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Dynamic Analysis of a Recessed Reinforced Concrete Rectangular Water Tank under Blast-Induced Ground Motion Effect

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Abstract

Construction, mining, oil, forestry, and agriculture all use blasting processes both in our country and in the world. A wide range of civil engineering projects, including homes, roads, railroads, dams, and airports, use blasting technology. The blasting process provides some advantages, but it also has drawbacks. Blasting has negative impacts such air shock and ground motion. This investigation concentrated solely at ground motion induced by explosion. Utilizing the well-known MATLAB programming language, BlastGM software was implemented to obtain ground motion acceleration-time information. This software uses the maximum acceleration value and the ground motion acceleration time envelope curve to determine the acceleration-time changes of blasting-induced ground motions. Furthermore, this software uses the ground motion acceleration-time values to determine the shock's reaction spectrum. This study looked at how a recessed reinforced concrete (RC) rectangular water tank was affected by ground motion based on by blasting. In Turkey, these tanks are built very frequently. For these tanks, the impact of ground motion brought on by blasting is crucial. ANSYS software produced the recessed RC rectangular water tank's three dimensional (3D) finite element model (FEM). Furthermore, the recessed RC rectangular water tank's maximum stresses and displacements were examined. The study's findings demonstrate that the recessed RC rectangular water tank is greatly impacted by blast-induced ground motion.

Keywords: recessed RC rectangular water tank, blast-induced ground motion, finite element method, modal analysis, shock response spectrum

Patlatma Kaynaklı Yer Hareketi Etkisindeki Gömme Bir Betonarme Dikdörtgen Su Deposunun Dinamik Analizi

Öz

Patlatma işlemi, ülkemizde ve dünyada yapı, maden, petrol, tarım ve orman alanlarında kullanılmaktadır. Patlatma teknolojisi konut, karayolları, demiryolları, barajlar, havalimanları gibi çoğu inşaat mühendisliği uygulamalarında yaygın olarak uygulanmaktadır. Ancak, patlatma işleminin olumlu tarafları olmasına rağmen, olumsuz tarafları da bulunmaktadır. Patlatma, yer hareketi ve hava şoku gibi olumsuz etkiler meydana getirmektedir. Bu çalışmada, sadece patlatma kaynaklı yer hareketi incelenmiştir. Yaygın olarak kullanılan MATLAB programlama dili ile yer hareketi ivme-zaman bilgisinin elde edilmesi için, BlastGM yazılımı uygulanmıştır. Bu yazılım, yer hareketi ivmesinin zaman zarf eğrisini ve en büyük ivme değerini kullanarak patlatma kaynaklı yer hareketlerinin ivme-zaman değişimlerini elde etmektedir. Ayrıca, bu yazılım, yer hareketi ivme-zaman değerlerinden patlama şokunun tepki spektrumunu da elde etmektedir. Bu çalışmada, patlatma kaynaklı yer hareketinin gömme betonarme dikdörtgen su deposuna etkisi incelenmiştir. Bu depolar, Türkiye'de çok sık inşa edilmektedir. Bu nedenle, patlatma kaynaklı yer hareketinin etkisi bu depolar için önemlidir. Gömme betonarme dikdörtgen su deposunun üç boyutlu sonlu eleman modeli, ANSYS yazılımı ile elde edilmiştir. Bununla birlikte, gömme betonarme dikdörtgen su deposunun en büyük gerilmeleri ve yer değiştirmeleri incelenmiştir. Bu çalışmanın sonuçları, patlatma kaynaklı yer hareketinin, gömme betonarme dikdörtgen su deposunu önemli derecede etkilediğini göstermektedir.

Anahtar Kelimeler: gömme betonarme dikdörtgen su deposu, patlatma kaynaklı yer hareketi, sonlu elemanlar yöntemi, modal analiz, şok tepki spektrumu analizi

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Introduction

The tunneling process for major technical projects like dams, roads, railroads, and underground infrastructure now inevitably involves blasting. To get materials from quarries for those mentioned constructions as well as for all other construction purposes, blasting activity is also executed. Because of this, as technology advances, blasting is more preferred in civil engineering applications. For the majority of structures that are proposed to be built, a blasting study must be designed and carried out. Prior to blasting, the location of the blasting center and the impact on existing structures must be taken into account. It is possible to predict how blasting may impact dwelling regions' structures with early planning. As previously mentioned, blasting offers time and cost savings in the majority of civil engineering applications. However, blasting has a lot of drawbacks in addition to its advantages. Negative impacts include air shock, ground displacement, and the ejection of natural materials (rock particles, ground particles) during the blasting process. Ground motion, one of blasting's adverse impacts, was investigated in this study. Damage to a masonry structure and the ground caused by blast-induced ground motion can be seen in Figure 1 (Köksal & Karaca, 2018).

Figure 1. Damages Resulted From Blasting-Induced Ground Displacement (Köksal & Karaca, 2018)

In the technical literature, there are many studies dealing with effect of blast-induced ground motion on the structures. Wu and Hao (2005) formulated simultaneous air blast and ground shock forces that are readily applicable to structural response analysis of adjacent structures. Wu et al. (2005) analyzed the damage and 3D dynamic response of masonry and masonry-infilled RC frame structures to ground excitations caused by blasting. Lu and Wang (2006) described the structural effects of above-ground explosions, emphasizing the relative significance of global dynamic response and localized damage on the overall behavior of a structural system, as well as the role of ground vibration in the process. Özmen (2006) demonstrated the effects of blast-induced and earthquake-induced ground motions on structural systems that have two and multiple degrees of freedom and utilized the finite element method to calculate the acceleration-time changes of ground vibrations caused from different explosives. In order to establish safe ground vibration levels for residential buildings and other structures in mining zones, Singh and Roy (2010) explained the impact of blast-induced ground vibration on the potential for damage to residential structures. Hao and Zhou (2011) predicted the reaction of stiff structures to ground shock numerically and theoretically. Köksal and Karaca (2020) investigated how blast-induced ground motion affected the RC retaining walls' dynamic response. Moghadam et al. (2022) studied the explosion effect, splash waves and water surface tension on the walls of above-ground cylindrical RC water storage tanks. Raikar and Kangda (2024) intended to implement passive control techniques in the form of fluid viscous dampers in order to counteract blast-prone ground vibrations and lessen the possibility of damage to water tank structures. Alipour et al.

(2025) investigated the blast effect on hoop stresses and displacements created on the wall of over-ground RC water tanks by using ABAQUS software.

Material and Method

Blast-Induced Ground Motion Modelling

Examining blasting-induced ground motions reveals that they are exceptionally frequent and transient. The behavior of these ground motions is influenced by numerous factors. These criteria include the explosive weight, blast center depth, vertical distance between the center and the structure, and the geotechnical characteristics of the rock and ground.

Investigations into the impacts of earthquake-induced ground motion on buildings are ongoing both nationally and internationally. Either historical earthquake records or artificial earthquake records are used in these studies' dynamic analyses. Researchers additionally draw close attention to how existing structures are affected by ground movements brought on by blasting, which is widely used nowadays. Therefore, just as dynamic analysis of structures performed for earthquakes, dynamic calculations for blasting must be conducted carefully. The recessed rectangular RC water tank is located vertically R away from the blasting center in Figure 2.

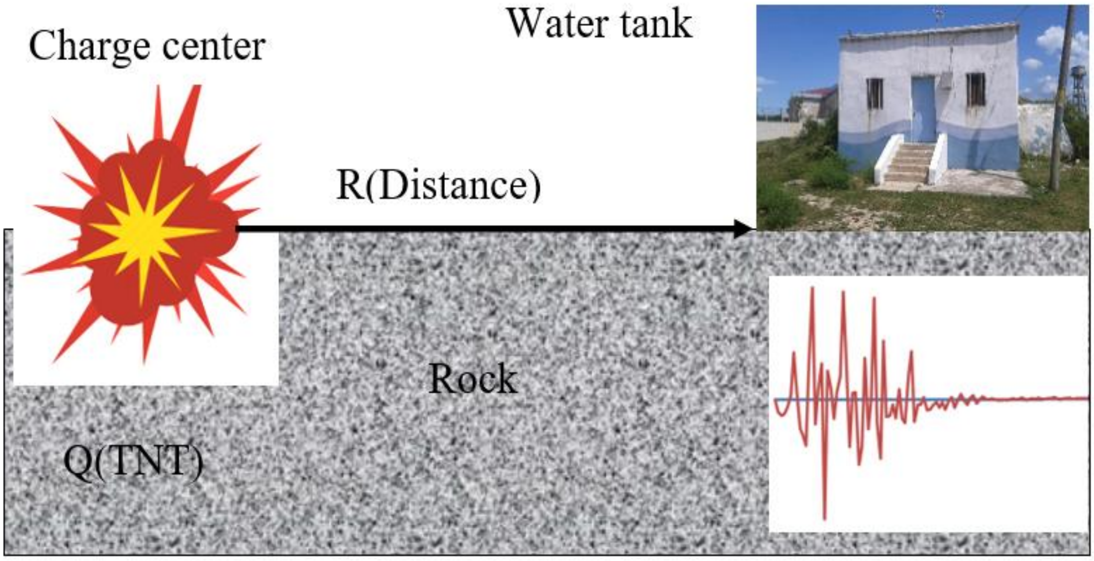


Figure 2. The RC Water Tank at a Perpendicular Distance R From The Blasting Center, The TNT Explosive, and The Blasting Center

The vertical distance to the explosion center, the peak acceleration value based on the explosive weight, and the blast pressure time envelope curve can all be used to model blast-induced ground motion (Wu & Hao, 2005). The non-stationary random process approach can be used to develop a model of ground motion caused by blasts Ruiz and Penzien (1969). To estimate ground motion acceleration values that characterize blast-induced ground motion, a software program known as BlastGM (Artificial Generation of Blast Induced Ground Motion) has been developed by Köksal (2013). The weight of the explosive and the distance perpendicular to the blast center are used to create artificial acceleration values. It is also possible to acquire velocity, displacement, and blast pressure values that vary with time.

In this study, direct effect ground motion was represented using empirical equations derived from earlier field studies. Time-dependent acceleration recordings of granite soil are produced by using Equation 1 to express direct impact ground motion Wu and Hao (2005).

$$PPA = 3.979 \cdot R^{-1.45} \cdot Q^{1.07} (g) \tag{1}$$

where PPA is the maximum particle acceleration, R is the vertical distance from the blast center (m), Q is the weight of the TNT explosive (kg), g=9.81 m/s^2 is the acceleration of gravity.

The weight of the explosive, the vertical distance from the explosion center, and the ground characteristics can all be taken into consideration when calculating the maximum accelerations of direct effect ground motions using Equation 1. Acceleration-time values that indicate ground motion are essential for the dynamic analysis of many civil engineering structures. However, for safety and economic reasons, conducting the required experimental research for blasting presents certain challenges. Therefore, it becomes necessary to create blast-induced ground motions artificially when it is needed to investigate the impact of such motions on structures. In this study, the developed software was used to artificially obtain acceleration-time values that can be considered in situations where the dynamic effects of blasting cannot always be determined experimentally.

Ground motion caused by blasts is modelled using the non-stationary random process approach. The deterministic shape function (time density envelope function) p(t) and stationary process w(t) parameters are used in this method to compute ground motion acceleration values (Ruiz & Penzien, 1969). Equation 2 was also used to express blast-induced non-stationary ground motion (Amin and Ang, 1968).

$$a_b(t) = p(t) \cdot w(t) \tag{2}$$

In earthquake engineering, the shape function is utilized to identify the non-stationary aspect of seismic ground vibration in terms of timing. The Hilbert transformation yields the shape function for Equation 2 (Kanasewich, 1981). Likewise, the envelope of blast-induced ground motions can be exponentially modelled by this shape function. Equation 3 provides an expression for this function (Wu and Hao, 2005).

$$p(t) = \begin{cases} 0 & t \leq 0 \\ mte^{-nt^2} & t > 0 \end{cases} \tag{3}$$

The non-stationary aspect of ground motion is associated with the parameters m and n. t_p determines the parameters m and n, while e is the natural logarithm. The acceleration from t_a to its highest value is measured by time t_p (Wu & Hao, 2005).

$$t_p = \sqrt{1/2n} \tag{4}$$

$$m = \sqrt{2ne} \tag{5}$$

Equation 6 can be used to quickly figure out the arrival time of the vibration wave to a place on the surface that is R from the blast center based on the conducted experiments (Wu & Hao, 2005).

$$t_a = 0.91 \cdot R^{1.03} \cdot Q^{-0.02} / c_s \tag{6}$$

The P wave velocity of granite soil is denoted by c_s. Equation 7 provides the empirical relation for the predicted time t_p (Wu and Hao, 2005).

$$t_p = 5.1 \cdot 10^{-4} \cdot Q^{0.27} \cdot (R/Q^{1/3})^{0.81} = 5.1 \cdot 10^{-4} \cdot R^{0.81} \qquad \text{(s)} \tag{7}$$

It is evident that t_p solely depends on the distance R. The ground motion wave's duration is a crucial factor that influences the structural effect. The tremor wave duration in this study is defined as t_d, which is obtained using Equation 8.

$$t_d = t - t_a \tag{8}$$

A damped single-degree-of-freedom linear system, represented by the undamped angular frequency ω_0 and damping ratio ξ, is used to approximate the ground layer's filter effect. $a_g(t)$ ground motion acceleration is obtained by solving Equations 9 and 10 (Ruiz & Penzien, 1969).

$$\ddot{z} + 2 \cdot \xi \cdot \omega_0 \cdot \dot{z} + \omega_0 \cdot z = -a_b(t) \tag{9}$$

$$a_g(t) = -2 \cdot \xi \cdot \omega_0 \cdot \dot{z} + \omega_0^2 \cdot z \tag{10}$$

Obtaining Blasting Pressure and Ground Motion with BlastGM Software

In order to create artificial ground motion and blast pressure, a software named BlastGM has been created using the MATLAB programming language (Amin & Ang, 1968; Kanasewich, 1981; Köksal, 2013;

MATLAB, 2012). By entering the explosive weight, time step, and ground type (damping ratio, seismic velocity), this software creates artificial ground motion from blasting using Equations 1–10. The software is compatible with SI and American unit systems, as well as Turkish and English languages. Figure 3 displays the information entry, and Figure 4 also displays the software's flow diagram.

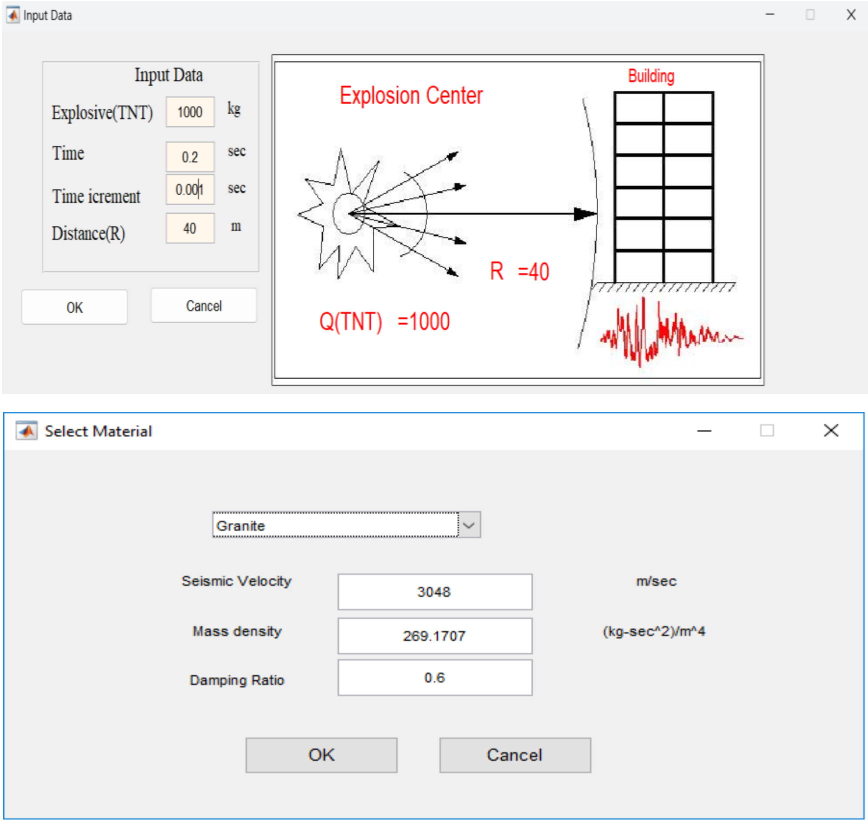


Figure 3. Screenshots of the BlastGM Software Login Details

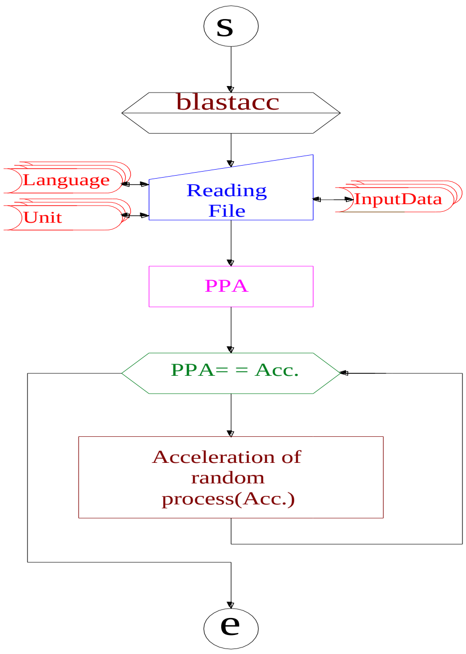


Figure 4. BlastGM Software Flow Diagram

Obtaining the Shock Response Spectrum

In the early 1960s, Shock Response Spectrum (SRS) analysis became a standard data processing technique. Assume that the base plate of a mechanical system with flexible mounting elements has numerous small tools or other components, such as substructures, attached on it. Stiffness and damping characteristics can be used to define it. The mechanical oscillator is a single-degree-of-freedom (SDOF) system that is produced by the mass of that substructure. The fundamental natural frequency and damping are the two primary parameters that show a SDOF system's free oscillation. The definition of damping is based on numerous criteria. Nonetheless, the damping ratio is usually set at a preset value as 5%. Equation 11 defines the spectrum of a damped shock response.

$$S_A = \left| \omega \int_0^t a_g(\tau) e^{-\xi\omega(t-\tau)} \sin\omega(t-\tau) d\tau \right|_{max} \tag{11}$$

SA represents both the spectral acceleration and the change in the single-degree-of-freedom system's fundamental acceleration with time (Tuma et al., 2011). Using the acceleration-time values derived from the solution of Equations 9 and 10, the response spectrum of blast-induced ground motion is determined. BlastGM software, which was created using the MATLAB program, was used to determine the acceleration-time values of blast-induced ground motion (Köksal, 2013). The Kelly-Richman technique (Kelly & Richman, 1971) was used to convert these acceleration data into values for the shock response spectrum. The BlastGM software's information inputs and the generated acceleration spectrum-frequency graph are displayed in Figure 5 (Irvine, 2013).

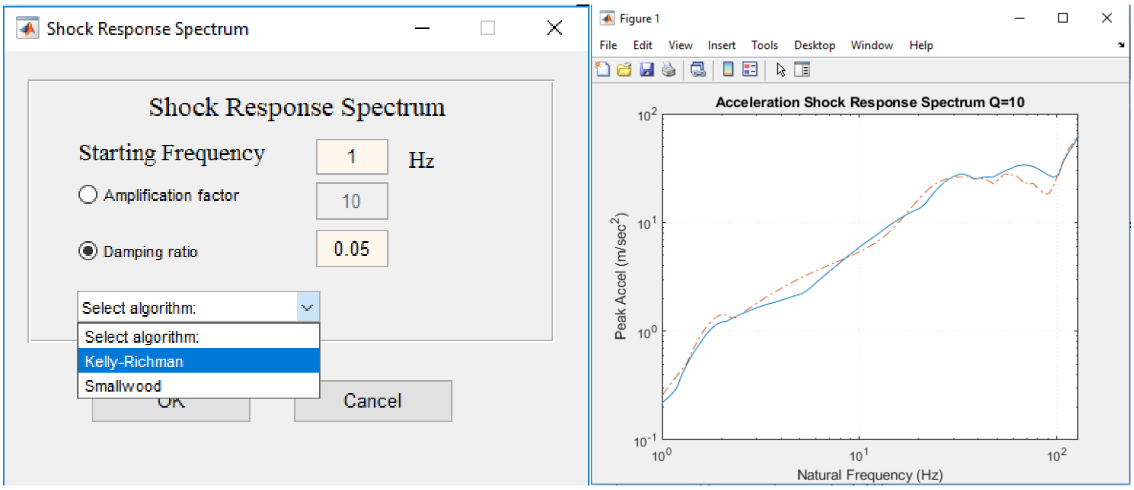


Figure 5. Login Information and Shock Spectrum Graph Screenshots in Blastgm Software

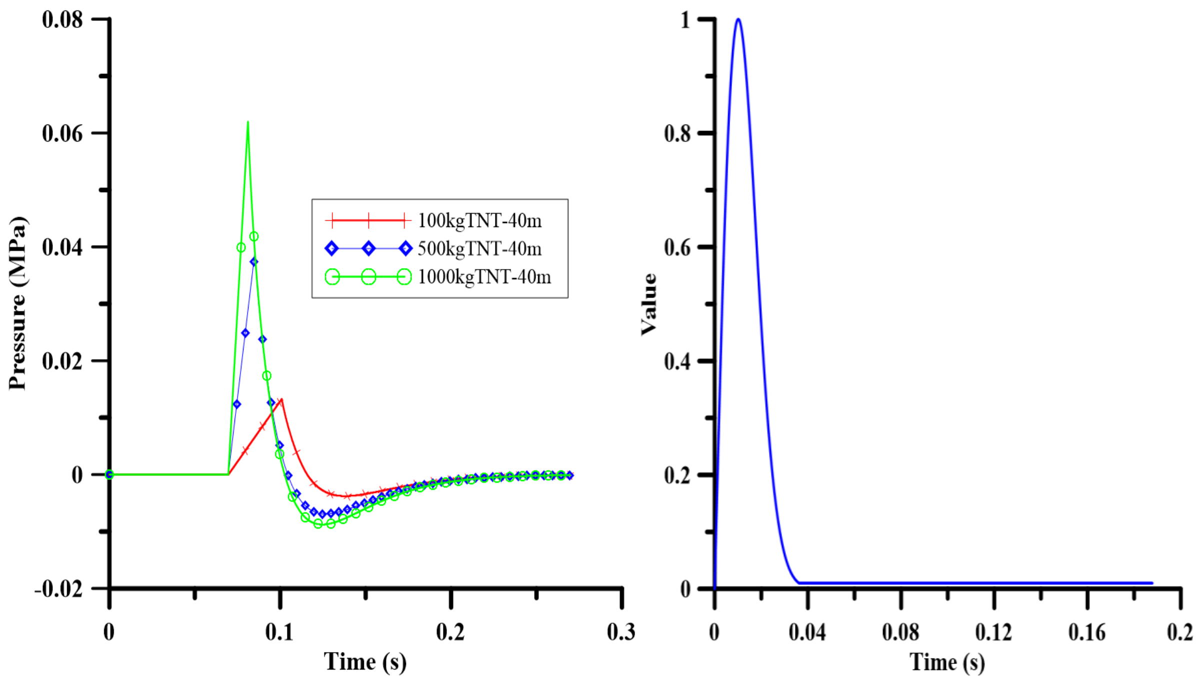
Dynamic Analysis of Recessed Reinforced Concrete Rectangular Water Tank

The primary food source for people and other living things, water, is becoming less and more contaminated as the population grows. Since the beginning of history, humans have needed to conserve water. Our source of life, water, is the first thing that those individuals demand when unfavorable events like earthquakes, floods, fires, explosions, and epidemics occur. Clean drinking water must therefore be acquired in compliance with regulations and properly kept. To deliver the required pressure in the network, recessed RC rectangular water tanks have been built at elevated locations near city centers. In Turkey, State Hydraulic Works, Provincial Banks, Special Provincial Administrations and Municipalities use the typical projects of these tanks. The dynamic analyses of a 100 m^3 recessed RC rectangular water tank with two compartments under the influence of blast-induced ground motion was considered in this study. Figure 6 displays the cited tank's cross-section, actual view and FEM.

(a) (b) (c)

Figure 6. (a) Cross-section of the Tank (b) Actual View and (c) FEM.

BlastGM software was used to acquire these three ground motions resulting from blasting, which was supposed to have taken place on stiff soil using 100 kg, 500 kg, and 1000 kg TNT explosives at a distance of 40 m. using the above cited software, distinct response spectra for these ground motions were acquired. Only the x direction's response spectra were taken into account. Additionally, using the software mentioned above, pressure variations brought on by blasting and a typical time envelope function of blasting are depicted in Figures 7a and 7b, respectively.



(a) (b)

Figure 7. (a) Blasting Pressure Graph and (b) Time Envelope Function of Blast-Induced Ground Motion

Figure 8 displays the artificially produced time-dependent horizontal acceleration graph for 100, 500, and 1000 kg of TNT at a distance of 40 meters from the blast center using the BlastGM software.

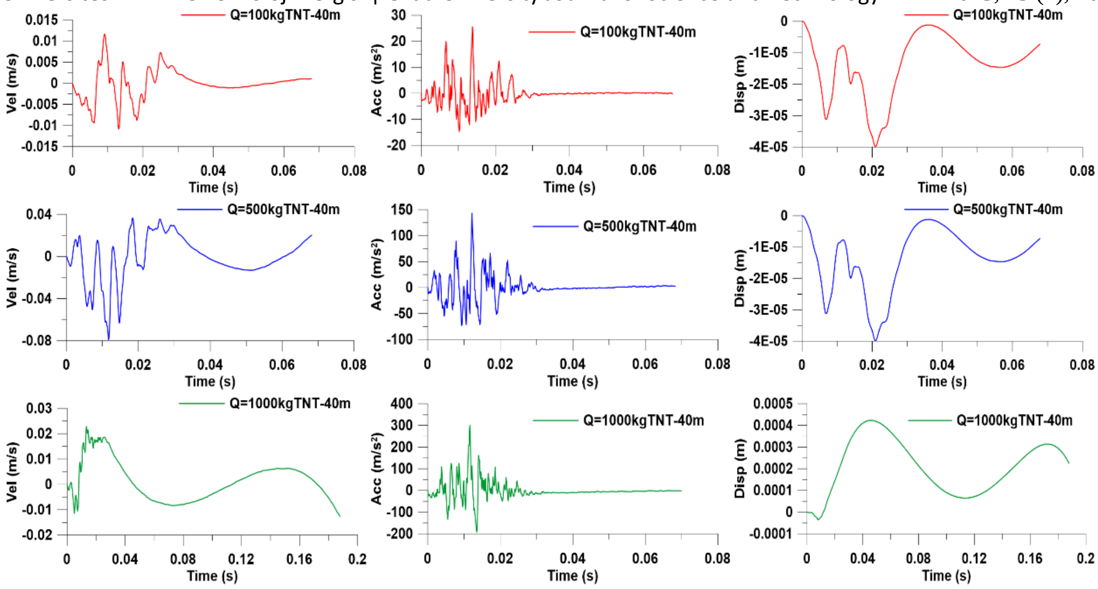


Figure 8. Horizontal Velocity-Time, Acceleration-Time and Displacement-Time Graphs Produced for 100Kg, 500Kg and 1000Kg TNT at a Distance of 40m from the Blast Center

At 40 meters from the blast center, Figure 9 displays the acceleration spectrum-frequency graph that was produced artificially using the BlastGM software for 100, 500, and 1000 kg of TNT.

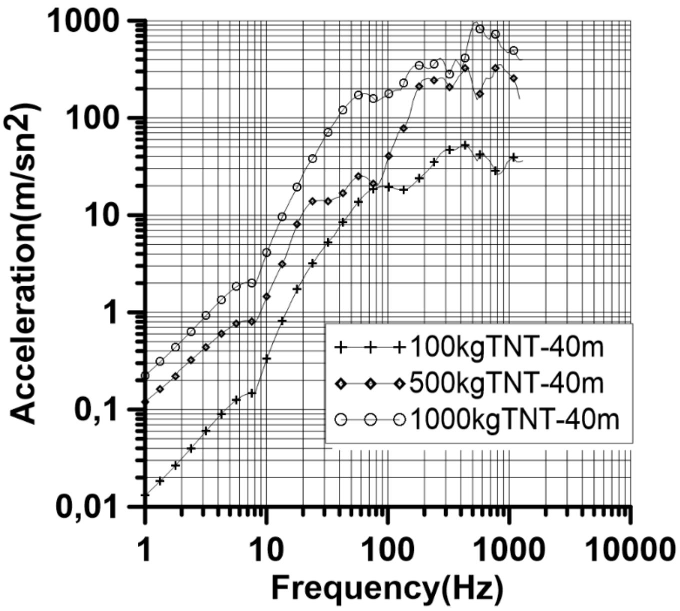


Figure 9. Acceleration Spectrum-Frequency Graphs Generated for TNT Weighing 100, 500, and 1000 Kg at a Distance of 40 Meters from the Blasting Center

The initial case involved modelling the tank using finite elements in ANSYS (ANSYS, 2024) software, fully empty and without accounting for soil thrust. Modal analysis was utilized to determine the tank's frequency ranges. The response spectrum analysis was performed with consideration for the obtained frequency ranges, and the highest horizontal displacements and stresses were analyzed. In the second scenario, the same analyses mentioned above were conducted again, but this time the tank was full of water and no soil thrust was taken into consideration. The tank's dimensions are height 3.90m, width 5.60m, and width 7.60m. The cited tank has a C25 concrete class with RC load carrying system.

ANSYS (ANSYS, 2024) software was used to model the recessed RC rectangular water tank using the finite element approach, as seen in Figure 6c. SOLID finite elements were used to simulate RC walls, floors, and foundations in the ANSYS (ANSYS, 2024) program, FLUID finite elements were used to describe water, and CONTACT elements were used to model structure-fluid interaction. It is expected that the stated tank has a built-in support that connects it to the stiff soil, which is considered to be homogeneous. The behavior of 3D SOLID elements was quadratic displacement. At every node, these elements possess three degrees of freedom. There are 45148 nodes and 5798 solid finite elements in the FEM, with a 200 mm solid element mesh selected. Table 1 provides information on the characteristics of the materials utilized in the analysis. It is assumed that the bulk modulus of water is 2.07 GPa and its density is 1000 kg/m^3.

Table 1. Material Properties

Material	Modulus of Elasticity (GPa)	Poisson's Ratio	Density (kg/m^3)
Reinforced Concrete	30	0.2	2400

ANSYS software was used for performing modal analysis of the cited tank in the empty state. The modal analysis revealed that the shapes of the 1st, 2nd and 3rd modes were in agreement with the literature (Köksal and Karaca, 2018; Köksal et al., 2023). The outcomes are displayed in Figure 10 and Table 2.

Table 2. First Three Frequencies of the Cited Recessed RC Rectangular Tank

Mode	Frequency (Hz)
1	57.917
2	63.366
3	69.424

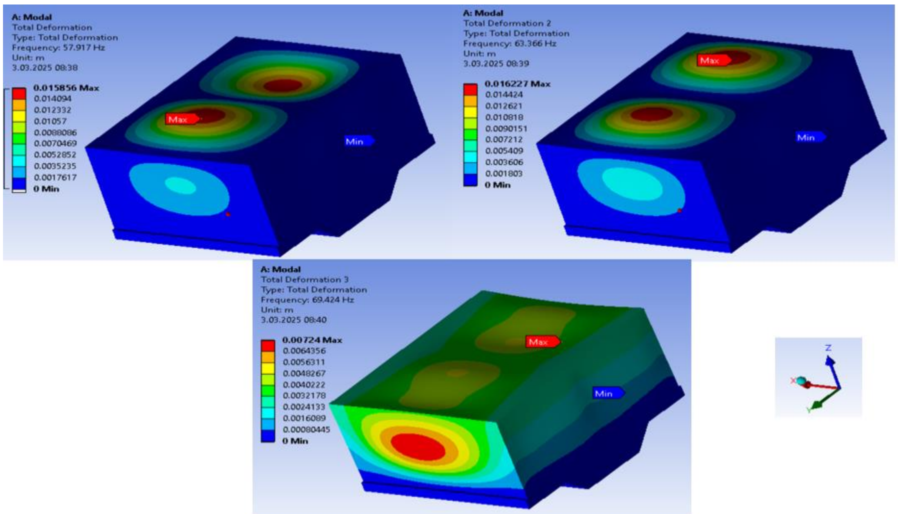


Figure 10. (a) 1st Mode Shape of the Empty Tank - f_1 = 57.917Hz, (b) 2nd Mode Shape - f_2 = 63.366Hz and (c) 3rd Mode Shape - f_3 = 69.424Hz

Response spectrum analyses were performed for ground motion at R = 40m using Q = 100kg, 500kg, and 1000kg TNT explosives following the modal analysis previously described. The findings from these analyses based on the tank's empty and full states are displayed in Figures 11-12 and 13-14, respectively.

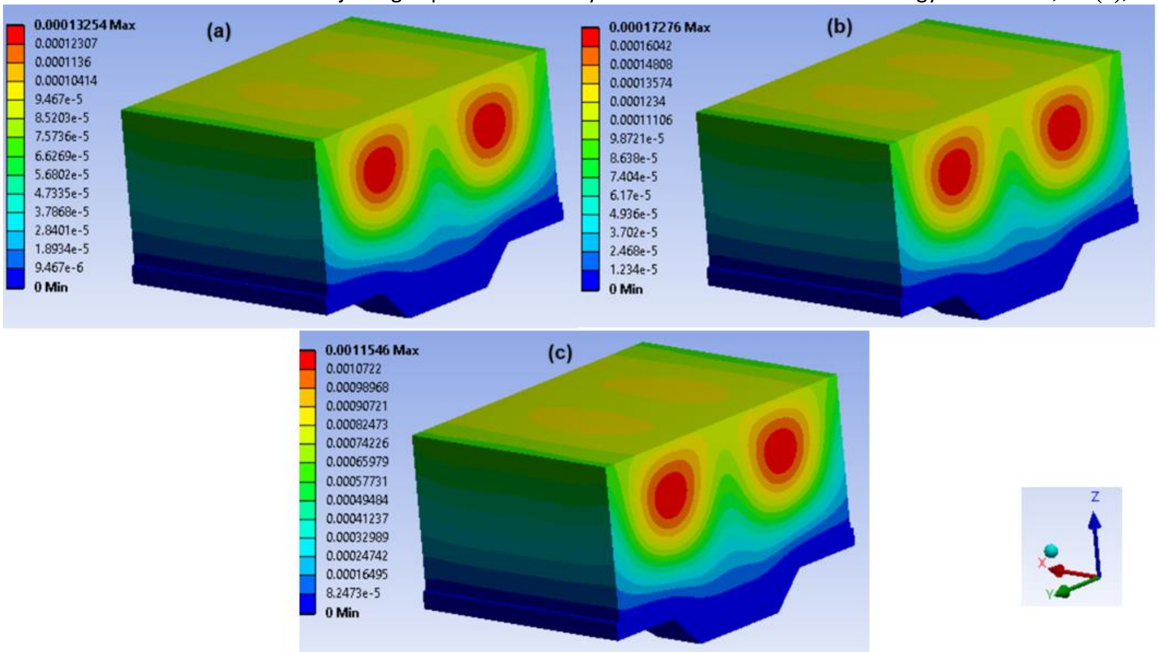


Figure 11. Displacements (m) in x Direction for R=40m in Empty Condition (a) Q=100kg TNT (b) Q=500kg TNT and (c) Q=1000kg TNT

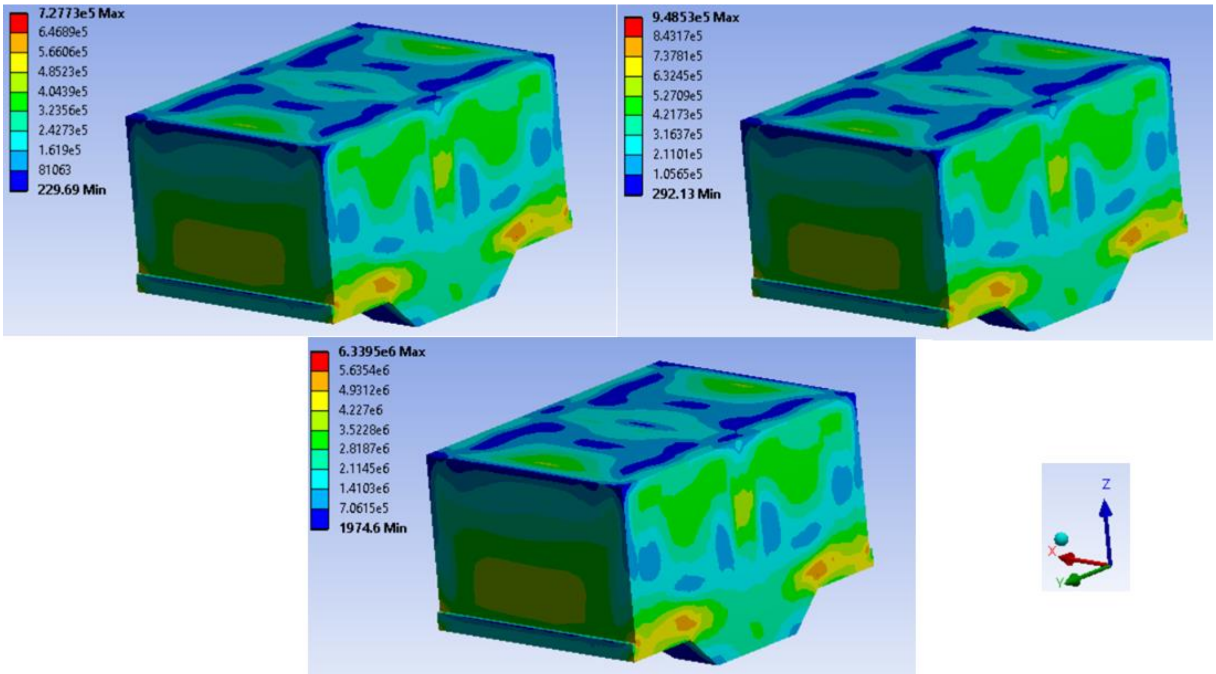


Figure 12. Von Mises Stresses (Pa) for R=40m in Empty Condition (a) Q=100kg TNT (b) Q=500kg TNT and (c) Q=1000kg TNT

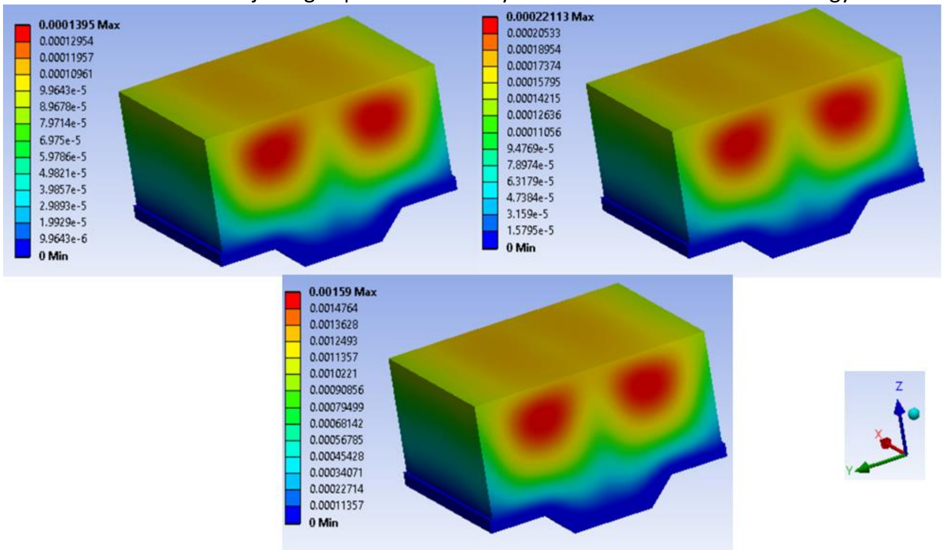


Figure 13. Displacements (m) in x Direction for R=40m in Full Condition (a) Q=100kg TNT (b) Q=500kg TNT and (c) Q=1000kg TNT

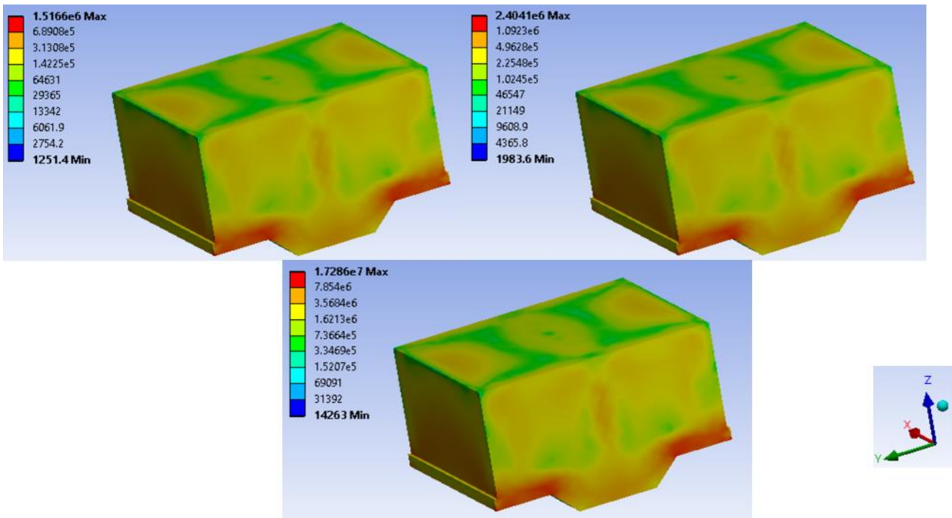


Figure 14. Von Mises Stresses (Pa) for R=40m in Empty Condition (a) Q=100kg TNT (b) Q=500kg TNT and (c) Q=1000kg TNT

Findings and Discussion

The blast induced ground motion effect on the recessed RC rectangular water tank model was analyzed with a total of six analyses with 100kg, 500kg and 1000kg TNT explosives at a distance of 40m for empty and full cases. As the analyses' results are analyzed, it is seen that when the tank is empty, the maximum displacement for Q=100kg, 500kg and 1000kg TNT are 0.00013254m, 0.00017276m and 0.0011546m, respectively. The maximum displacement for the full case at Q=100kg, 500kg and 1000kg TNT are 0.0001395m, 0.00022113m and 0.00159m. It can be clearly seen that for all weights of TNT, the maximum displacements occurred in full case are greater than the ones occurred in empty case. Also, for the empty and full cases considered, the von Mises stresses caused by the blast-induced ground motion with explosive weights of 100kg, 500kg and 1000kg were obtained. It is clearly seen from the Figures 12 and 14 that these stresses are obtained from the top of the foundation. For empty case, the maximum Von Mises stresses for 100kg, 500kg and 1000kg TNT are 0.73MPa, 0.95MPa and 6.3MPa, respectively. Moreover, for the full case considered, the maximum Von Mises stresses for 100kg, 500kg and 1000kg TNT are 1.52MPa, 2.40MPa and 17.28MPa, respectively. It can be clearly deducted from the results of the von Mises stress analyses that the maximum stress values obtained for the full case are approximately two times of the values obtained for the empty case.

Conclusions and Recommendations

In this study, dynamic structural analysis of a recessed RC rectangular water tank under the blast-induced ground motion (at 100kg, 500kg and 1000kg TNT weights) was performed for empty and full cases. The following conclusions can be drawn from the study.

Blasting on or close to the earth's surface releases an extensive amount of energy during the process that creates both direct-induced and air shock-induced ground motion. This study addresses ground motion caused by direct-induced ground motion caused by blasting. This ground motion is represented by utilizing Non-stationary Random Process method. Stiff soil experiments were used for investigating artificial ground motions. The BlastGM program was used to determine the blast's acceleration spectrum values with the help of the peak accelerations obtained during the experimental investigations. ANSYS software was used to model the cited tank using the Finite Element Method. Then, modal analysis and the related response spectrum analysis of the cited RC tank for different weights of TNT were performed. As a result of these dynamic analyses, it was determined that the maximum displacements of the full case of the cited tank increased by 5.25% for Q=100kg, 27.99% for Q=500kg and 37.71% for Q=1000kg compared to the empty case. Similarly, von Mises stresses of the full case increased by 108.22% for Q=100kg, 152.63% for Q=500kg and 174.28% for Q=1000kg compared to the empty case.

Moreover, the amount of explosive affected the maximum displacements and von Mises stresses. For the empty case, it can be clearly seen that the maximum displacements increase by 30.34% as the amount of explosive increases by 5 times and 771.13% as the amount of explosive increases by 10 times. Similarly, for the full case, the displacements increases by 58.52% as the amount of explosive increases by 5 times and 1030.79% as the amount of explosive increases by 10 times. The von Mises stresses for the empty case increase by 30.14% as the amount of explosive increases by 5 times and 763.01% as the amount of explosive increases by 10 times. In full case, the von Mises stresses increase by 57.89% as the amount of explosive increases by 5 times and 1036.84% as the amount of explosive increases by 10 times.

It can be deducted from the above findings when blasting processes are carried out close to water tanks, the case that the tank is full has the maximum displacements and von Mises stresses. Therefore, in addition to earthquakes, blast-induced effects on water tanks should be considered in the design phase in order to prevent local or fatal damages when displacements and stresses exceed the limit values. The findings in this study belong to one specific RC rectangular water tank under specified TNT weights. In order to generalize the results, different tanks should be analyzed under different amount of TNT weights.

Author Contributions

All authors have the same contribution in preparing this article. All authors have read and approved this article.

Ethic

There is no any ethical issue in publishing this article.

Conflicts of Interest

The authors declare no conflicts of interest.

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