



## Research Article

# Blast-induced ground motion effect on dynamic response of a cylindrical vertical water tank with piled raft foundation

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## ABSTRACT

This paper studies to estimate the dynamic behavior of a demineralized water tank with a piled raft foundation system considering soil-pile-structure-fluid interaction to shock-ground motion. A three-dimensional finite element model of a coupled system is constituted in ANSYS software. Interaction between pile and soil is represented with the frictional contact element. The frictionless contact elements are utilized to model between the water and tank shell to allow for displacement of the free surface adjacent to the tank wall. Shell elements are used for the tank body and its vault. The dynamic analyses of the tank including soil-pile-structure-fluid interaction are presented by using shock response spectra. Ground shock acceleration time histories, generated by using a developed computer program based on Fortran programming language, produce shock response spectra. The effects of the different charge weights and distances from the charge center are examined in the analyses. Also, the effect of the water fill level in the tank and the number of piles is also investigated. The results of the research are presented with the directional displacements and equivalent stresses. It seen from the analyses that the dynamic responses of the tank increase with the charge weight, while decreasing with the charge center distance. Moreover, the water fill level and the number of piles extremely affect the displacement and stress values of the coupled interaction system.

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## 1. Introduction

Circular storage tanks, such as reinforced concrete/steel water tanks, are widely used to store water, oil and gas. These type tanks transfer loads from liquid and self-weight to a foundation and layers of soil or rock. Storage tanks located in soft soil can easy to be threatened by earthquakes, traffic load, explosion induced ground vibrations. In such situations, it is necessary to study dynamic responses of storage tanks in soft soils during ground motion. A conventional raft foundation under storage tanks constructed in soft soils does not provide adequate support, it can be enhanced by the addition of piles to the reduction of settlement and increase in bearing capacity of the raft.

Limited studies were carried out in analyzing storage tanks considering soil-pile-structure-fluid interaction under seismic excitation. The first study titled "Foundations for Cylindrical Storage Tanks" belongs to Roberts (1961). This study investigated the effect of the types of foundations used for a variety of soil conditions. These foundation solutions include the use of a sand pad, concrete or crushed rock ring wall, an interlocking sheet pile ring wall, and a pile foundation with a crushed rock pile cap. Xinliang and Xuecheng (1992) simulated the soil-pile system as an anisotropic elastic solid. They developed special software to analyze the dynamic behavior of liquid-structure-pile-soil interaction system. Dieterman (1993) presented the effects of the liquid and foundation including pile-soil interaction on the structural

dynamics using an analytical model. Higuchi et al. (2000) described the results of shaking table tests on LNG facilities on the reclaimed land using the centrifuge apparatus. The study investigated the seismic responses of multi-layered grounds and piled foundations of LNG facilities. Ruifu et al. (2011) studied the seismic response of an isolated vertical, cylindrical, extra-large liquefied natural gas (LNG) tank by a multiple friction pendulum system (MFPS). The results showed that the isolation system has excellent adaptability for different liquid levels and is very effective in controlling the seismic response of extra-large LNG tanks. Yamashita et al. (2014) confirmed the validity of the foundation design. They performed field measurements on the foundation settlement and the load sharing between the piles and the raft from the beginning of the construction to 80 months after the end of the construction. Ximei et al. (2014) conducted the dynamic responses of the LNG tank structures under seismic excitation considering the influences of pile-soil interaction, liquid level of LNG, the site classification, direction and intensity of earthquake, and the leakage of LNG liquid. Park et al. (2017) purposed a dynamic centrifuge model test method for the accurate simulation of the behaviors of a liquid storage tank with different types of foundations during earthquakes. The study investigated the effects of the soil-foundation-structure interactions of a simplified storage tank under two different earthquake motions, simulated using a shaking table installed in a centrifuge basket. Cheng and Jing (2017) proposed two simplified methods to quantify the stability of composite foundation treated with a large number of compaction piles. Kim et al. (2017) investigated the cathodic protection design improvement. In this study, the current distribution was studied using the Boundary Element Method (BEM) and the Finite Element Method (FEM) numerical analysis methods. End of the study, it was implemented that the construction cost was reduced significantly without any under-protection area on the steel piles. Ha et al. (2017) performed the dynamic centrifuge tests to observe the seismic behaviors of the liquefied natural gas (LNG) storage tank with different foundation conditions. Two typical foundation types were used as shallow foundation and pile foundation. The accelerations at soil surface, slab and structure were compared. Fiore et al. (2018) researched the influence of sloshing effects and of the soil-structure interaction. Also, the tank founded on piles, soil-structure interaction is taken into account by computing the dynamic impedances. Sahraeian et al. (2018) performed dynamic centrifuge model tests to investigate the mechanical behavior of oil tanks supported by piled raft foundation on liquefiable saturated sand and non-liquefiable dry sand. In the tests, two types of foundations were modelled for oil storage tanks, namely, slab foundation (SF) and piled raft foundation (PRF). Purnama et al. (2018) carried out the study on improvement of foundation structure system with concrete slab supported by piles on the outside around and "Sistem Cakar Ayam" that spread evenly in the area of the foundation. The numerical study of the proposed improvement of structure model was conducted using SAP2000 and ABAQUS. Zhang et al. (2018) studied the seismic response of the tank-fluid system

considering soil-structure interaction. A three-dimensional FEM model of soil-pile-structure-fluid interaction system was built based on ANSYS software, in which, the structure and fluid interaction are considered by Lagrangian fluid FEM approximation.

In underground mining and civil engineering, drilling and blasting are generally using excavation techniques. Ground shock and vibrations have been a major problem for the surrounding structures such as buildings, bridges, dams and tunnels, etc. This type of vibration threat can cause cracks or other kinds of damages in buildings and other types of structural systems. Only recently, a limited number of studies have been performed to define the potential threat of blast type loadings on above structures. Some valuable researches are regarding dynamic analyses of water storage tanks against blast ground motion (Blair et al., 2007; Hacıfendioğlu et al., 2012).

There is no enough study about the dynamic response of the soil-pile-structure-fluid interaction system under blast ground motion. This study presented the dynamic behavior of a demineralized water tank with a piled raft foundation subjected to blast ground motion, with 3D modeling in ANSYS software (2013). Shock spectra are utilized to determine dynamic response calculations of the coupled system subjected to blast loading. In the analyses, three different charge weights with three different charge centers are taken into account for parametric studies.

## 2. Shock Response Spectrum

Controlled blasting techniques may be useful in stages of construction of some structures, tunnel, embedded foundations, etc. or rock removal, quarrying and preparation of finished slopes, because of the extreme complexity of each setting. While surface blasting produces ground motion and airwaves, underground blasting produces only ground motion waves, which cause ground vibration. The analyses of this study include underground blasts. Blasting-induced ground motions under controlled explosions are measurable excitations. However, these excitations occur at different frequency amplitude depending on soil types, blast distances and charge weights. The difficulty of determining the time histories of ground motions due to blast loads is obvious. In such a situation, utilizing the response spectrum method, which is generalized shock excitation, instead of time history analysis having various amplitudes can be convincing for engineers.

Underground shock ground motions are determined from an empirical formula. These equations are for TNT detonations at or near the ground surface. The charge weight and distance from the explosion are effective for the ground shock parameters. Eq. (1) demonstrates maximum horizontal acceleration (PPA) of the ground surface for rock media (Hao and Wu, 2005).

$$PPA = 3.379R^{-1.45} Q^{1.07} \quad (\text{g}) \quad (1)$$

where  $R$  is the distance (in meters) from the point of the explosion and  $Q$  is the TNT charge weight (in kilograms).

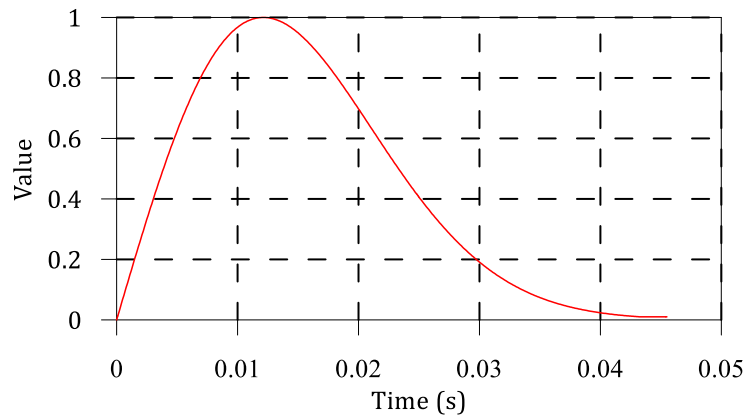
A computer program based on Fortran programming language was developed to simulate shock response spectra producing from the ground shock acceleration time histories. Ground shock accelerations are simulated by using a non-stationary random process method. To this process, time-dependent ground motion accelerations are produced by help of the parameters of a deterministic shape function of time (i.e. a time-intensity envelope function)  $p(t)$  and stationary white noise  $w(t)$  of intensity  $S_0$  (Bolotin, 1960; Jennings et al., 1969; Ruiz and Penzien, 1969). To determine non-stationary blast ground motions, Amin and Ang (1998) generated a formulation as follows:

$$a_b(t) = p(t) w(t)_{sta} \quad (2)$$

A time-intensity envelope function and frequency characteristics are crucial parts of a non-stationary stochastic process, well-known an earthquake ground motion is given as an example. The time-dependent envelope function  $p(t)$  obtained from the Hilbert transform (Hahn 1996) of blast ground motion may be represented as an exponential function given by Eq. (3) (Hao and Wu 2005).

$$p(t) = \begin{cases} 0, & t \leq 0 \\ m t e^{-nt^2} & t > 0 \end{cases} \quad (3)$$

where  $m$  and  $n$  depend on the non-stationary ground motion and  $e$  is the base of the natural logarithm. The general envelope function of blast ground motion is depicted in Fig. 1.



**Fig. 1.** Envelope function of shock ground motion.

PSD functions used to represent the blast ground motion which was thought of as a stationary random process  $w(t)_{sta}$  have been proposed by Wu and Hao (2005). The power spectrum based on Tajimi (1960) and Kanai (1957) studies is adopted for blast ground motion as follows:

$$S(f) = \frac{1+4\xi_g^2 f^2 / PF^2}{(1-f^2 / PF^2)^2 + 4\xi_g^2 f^2 / PF^2} \quad (4)$$

where  $PF$  is the principal frequency,  $\xi_g$  is the soil damping coefficient,  $S_0$  is the intensity of the ideal white noise excitation at the bedrock-overburden interface. The principle frequency can be formulated as follows:

$$PF = 465.62 \left( \frac{R}{Q^{1/3}} \right)^{-0.13} \quad (5)$$

$$0.3 \leq R/Q^{1/3} \leq 10 \quad (\text{Hz})$$

A constant value  $\xi$  is taken as 0.6.  $S_0$  is calculated by

$$S_0 = 1.49 \times 10^{-4} R^{-2.18} Q^{2.89} \quad (\text{m}^2/\text{s}^3) \quad (6)$$

Power spectral density functions are constituted by the frequency range of 0.3–10 Hz (Wu et al., 2005; Wu and Hao, 2007; Singh and Roy, 2010). The waveforms of

bedrock acceleration are derived from a second-order differential equation as given by Eqs. (7) and (8).

$$\ddot{x}(t) + 2\xi_g \omega_g \dot{x}(t) + \omega_g^2 x(t) = -a_b(t) \quad (7)$$

$$\ddot{x}(t) = -2\xi_g \omega_g \dot{x}(t) - \omega_g^2 x(t) \quad (8)$$

where  $a_b(t)$  is a stationary Gaussian white noise process;  $\omega_g$  is natural frequency;  $x$  is the first filtered response.

The shock response spectrum is calculated by considering a transient shock input signal which is generally provided as the time evolution of displacement, velocity or acceleration. A series of SDOF linear oscillators (like a mass-spring system) with increasing natural frequencies is used to build a shock response spectrum. The calculation uses an amplification factor  $Q=10$  corresponding to a viscous damping ratio of 5% (Tuma et al., 2011).

Shock response spectrum with damping can be defined as:

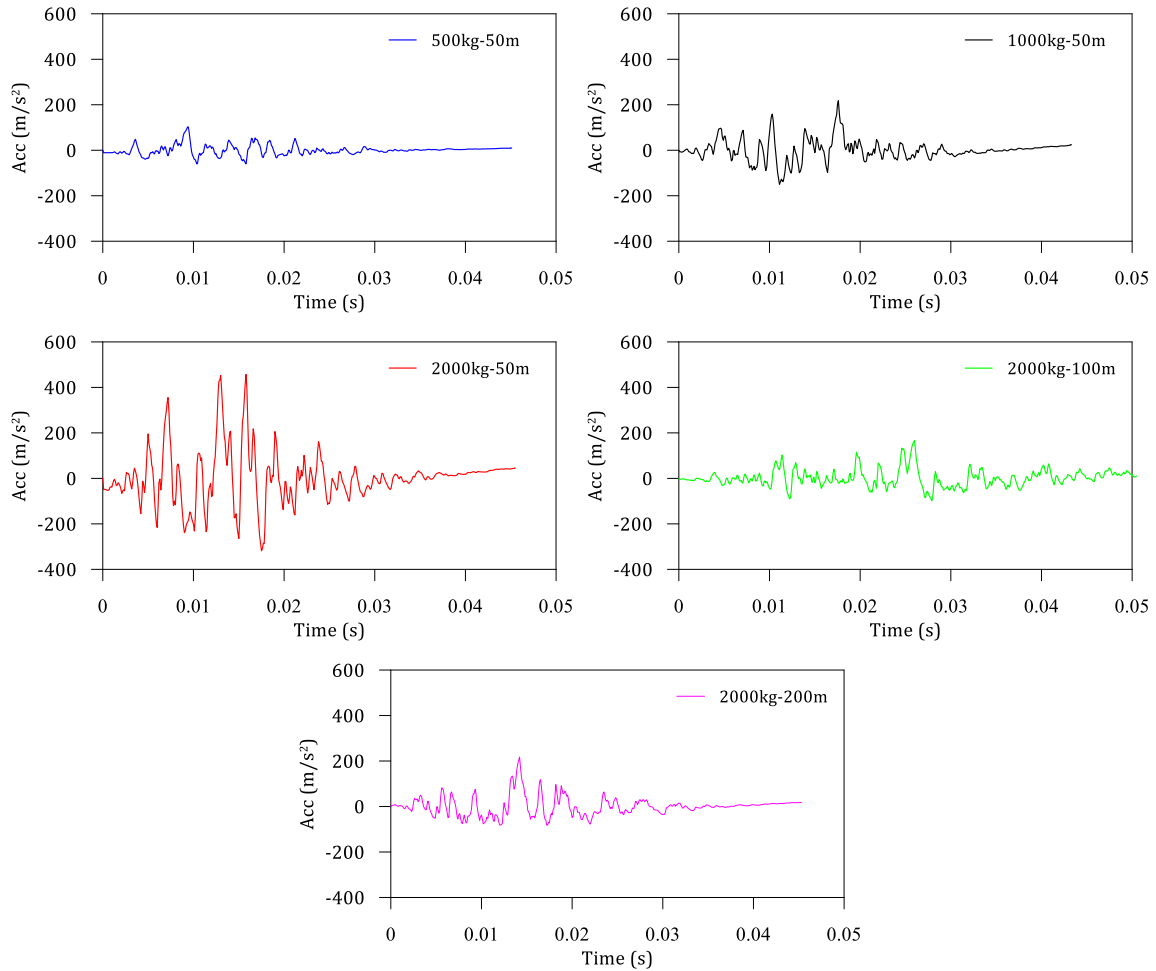
$$S_l = \left| \omega \int_0^t \ddot{x}(\tau) e^{-\xi \omega (t-\tau)} \sin \omega (t-\tau) d\tau \right|_{max} \quad (9)$$

where,  $\ddot{x}$  is the base acceleration of an SDOF system as a function of time, and  $S_l$  is the spectral acceleration.

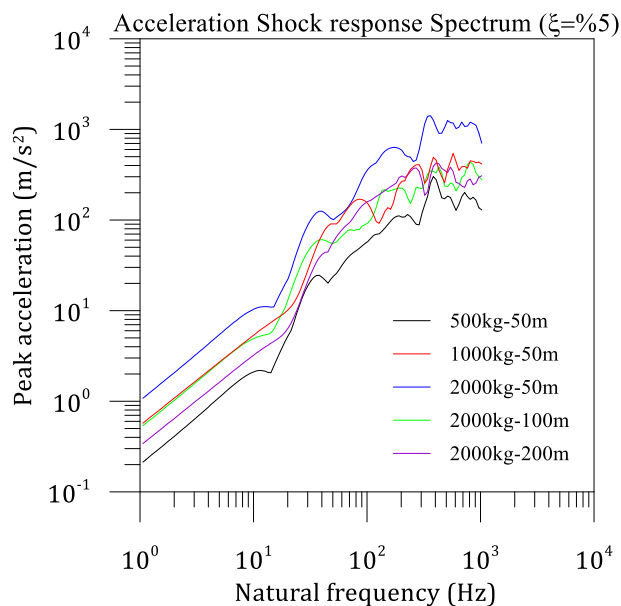
2000 kg, 1000 kg and 500 kg charge weights and 50 m, 100 m, and 200 m distances from the point of the

explosive are taken into account to analyze the demineralized water tank with a piled raft foundation subjected to shock ground motion. The shock response spectra depending on the time history ground motions

for each case are depicted in Figs. 2 and 3. In this study, the displacement and stresses obtained here are maximum values using the CQC modal combination methods.



**Fig. 2.** Acceleration time histories for different blast distances and charge weights.



**Fig. 3.** Shock response spectrum due to for different blast distances and charge weights.

### 3. Application

#### 3.1. Geometry and material properties

This study aims to investigate the dynamic behavior of the demineralized water tank with a piled raft foundation under blast-induced ground motion. The picture and a piled raft foundation system of the demineralized water tank are indicated in Fig. 4. Also, the geometry of the soil-pile-structure-fluid interaction system and the simplified geometry measures of the tank and soil layer are shown in Figs. 5 and 6, respectively. As indicated in Fig. 6, the inner diameter of the tank is 16.0 m, the height is 16 m. The maximum height of the water surface is 15.0 m. The tank wall is assumed as a constant thickness, which is 10 mm from the bottom to roof of the tank. The

tank was made of the stainless-steel material. The elastic modulus, Poisson’s ratio and density of the tank are 200 GPa, 0.3 and 7850 kg/m<sup>3</sup>, respectively. The density and Bulk modulus of the water are assumed as 1000 kg/m<sup>3</sup> and 2.07 GPa, respectively. To achieve the required settlement performance of the tank and to reach the most economic foundation design, the calculations were carried out with an optimal number of piles. The cast in place 19 concrete piles calculated according to the soil parameters and loads caused by tanks are 800 mm in diameter and are 19 m long. All piles are the same diameter. The tank is constructed on a reinforced concrete foundation with 19.0 m outer diameter and 80 cm height. The material properties of the concrete are as follows, the elastic modulus is 30 GPa, Poisson’s ratio is 0.18 and density is 2300 kg/m<sup>3</sup>.

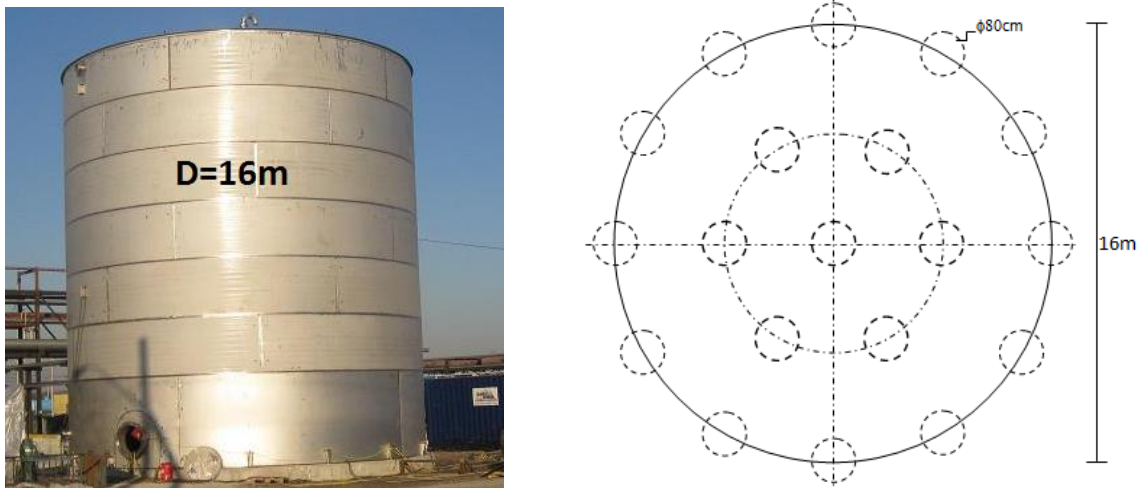


Fig. 4. Demineralized water tank with a piled raft foundation.

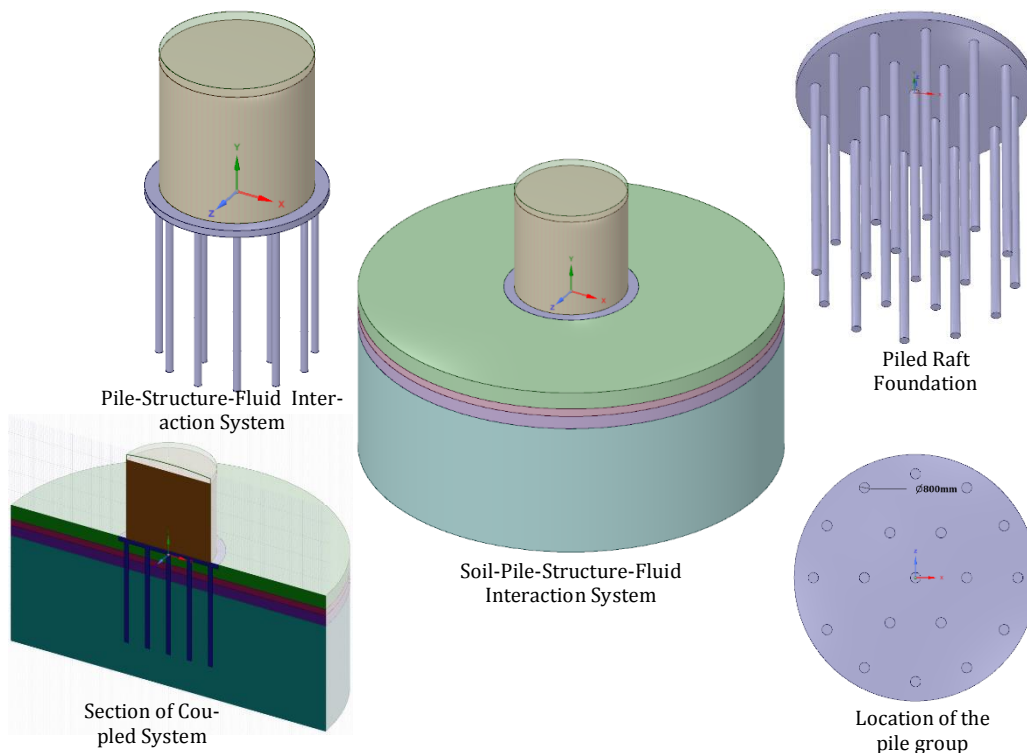


Fig. 5. The geometry of soil-pile-structure-fluid interaction system.

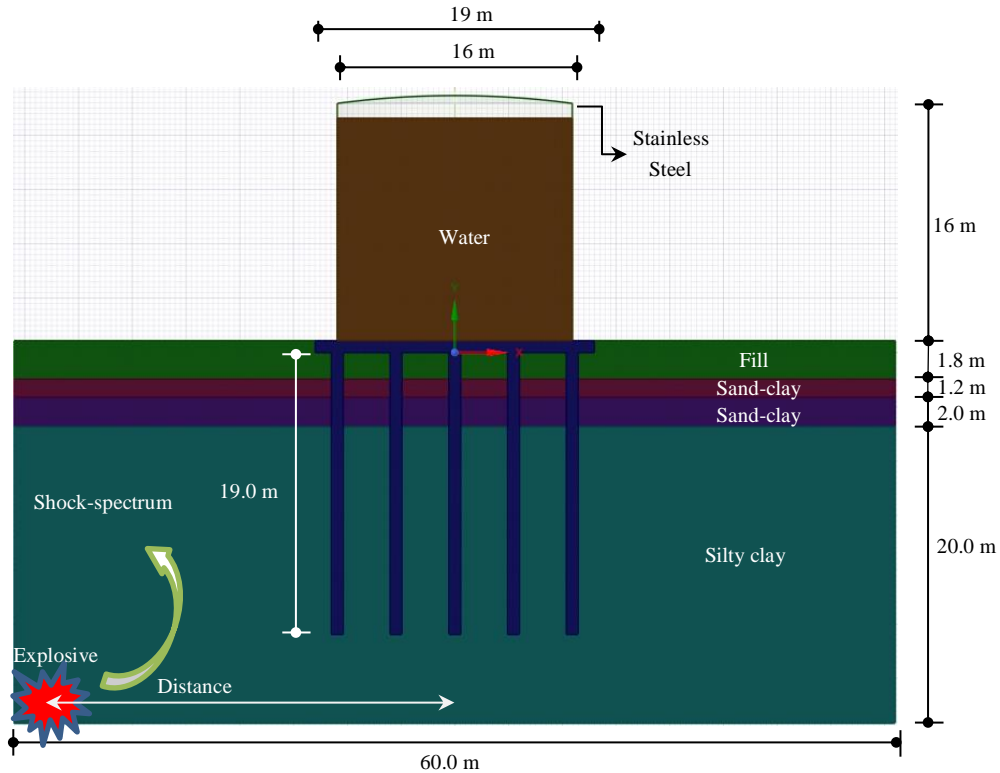


Fig. 6. Demineralized water tank with a piled raft foundation.

In the coupled system, the pile, soil and concrete foundation all use solid elements, simulation of the incompressible fluid in the tank is represented with the fluid element. The tank and its vault use shell elements. The frictional contact element (CONTA174) are utilized to provide the interaction between the pile and soil. CONTA174, which is used for general rigid-flexible and flexible-flexible contact analysis, is an 8-node element. The elements can be appropriate to represent contact and sliding between 3D surfaces. In this system, the isotropic friction model was used with a variable coefficient ranging between 0.35 and 0.55 and a starting value of 0.45 that corresponds to the coupling materials. The friction coefficient values of the fill, sand-clay and silty-clay soil types are assumed as 0.40, 0.35 and 0.50, respectively. The frictionless contact elements are utilized between the water and the tank shell to allow for displacement of the free surface adjacent to the tank wall.

#### 4. Results of Analyses

The shock spectrum analysis of a demineralized water tank with a piled raft foundation to shock-induced ground vibration is carried out using the finite element analysis package (ANSYS 2013). This study investigates the effect of the shock-induced ground motions on the dynamic response of the considered coupled system for the different charge weights and distances from the charge center by using the shock response spectrum method. In addition, the effects of the water fill level of the tank reservoir and the number of piles are studied as a parametric model.

##### 4.1. The effect of charge weight

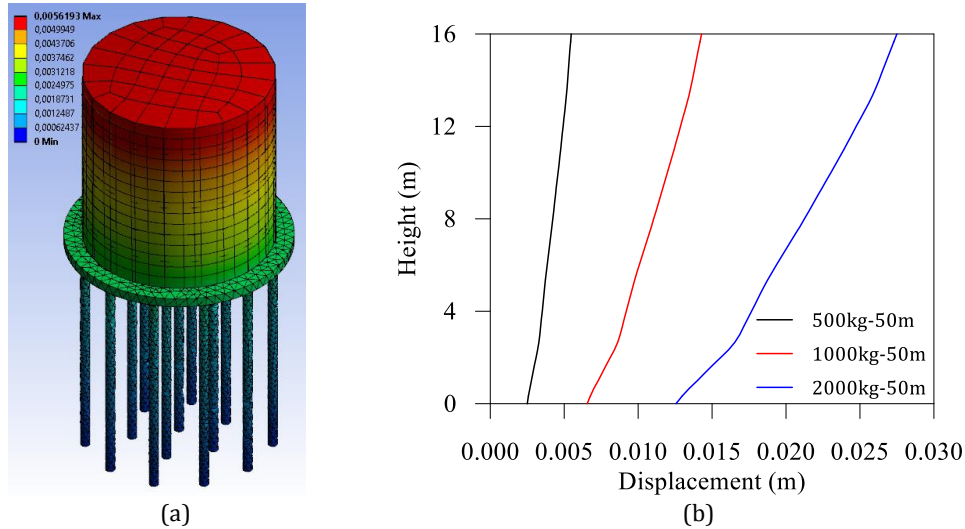
In order to the charge weight effects on the dynamic behavior of the demineralized water tank with a piled raft foundation system, the charge weight values of 500, 1000 and 2000 kg are taken into account. The distance from the charge center to the coupled system center is assumed as 50 m in all analyses in this section. The displacement and equivalent stress values of the tank are indicated in Figs. 8 and 9 for the charge weight values of 500, 1000 and 2000 kg, respectively.

Fig. 8(a) shows the displacement contour distribution on the tank consisting of a piled raft foundation. The displacement distributions for all of the charge weight values are close to each other, here, it was given only the displacement distribution for the charge weight value of 500kg. It can be seen that the displacement values increase with increasing the tank's height. Maximum displacements occur at the top of the tank. The displacement distributions along the tank's height with the various charge weights are shown in Fig. 8(b). Fig. 8(b) shows that the displacement values neatly increase with the tank's height. Also, it must be said that the charge weight values affect displacement values. Increasing the charge weight cause to increase the displacement values along with the tank's height.

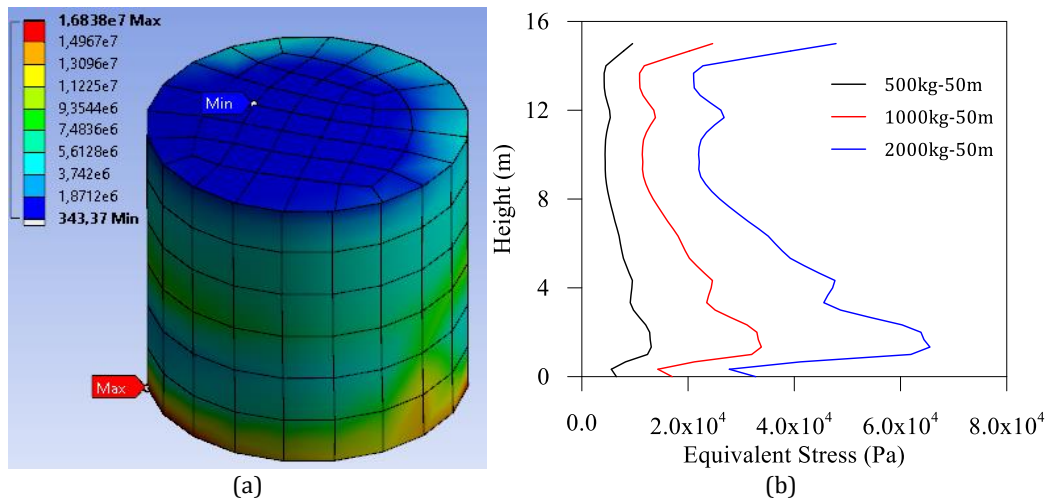
Fig. 9(a) and Fig. 9(b) indicate the Equivalent stress contour distribution (for 500kg) and along with the tank's height, respectively. It can be seen from Fig. 9(a) that the stress distribution contours at the bottom of the tank are generally higher than those at the top of the tank. As expected, the higher stress concentrations rise

near the bottom of the tank. The stress contour distribution graphics for the charge weights of 1000 kg and 2000 kg are almost the same. When compared the stress distributions for the various charge weight values, the difference between the stress values is extremely high.

Also, the stress distribution values near the top and bottom of the tank are highest. Clearly, it can be observed that the increase of the charge weight values causes to increase the stress values on all tank body and along with the tank.



**Fig. 8.** The displacement: (a) contour distribution; (b) along with the tank’s height for the charge weights of 500, 1000 and 2000 kg.

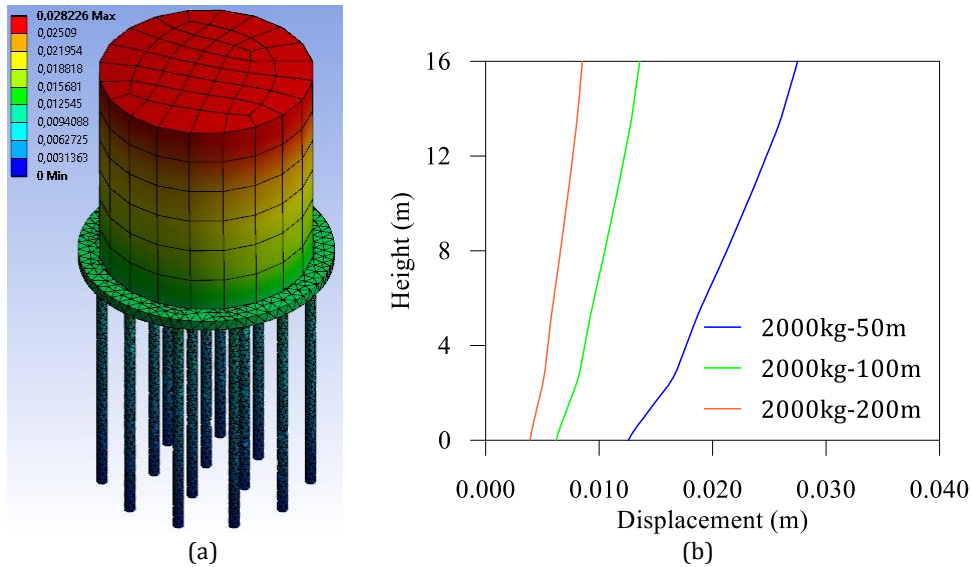


**Fig. 9.** The equivalent stress: (a) contour distribution; (b) along with the tank’s height for the charge weights of 500, 1000 and 2000 kg.

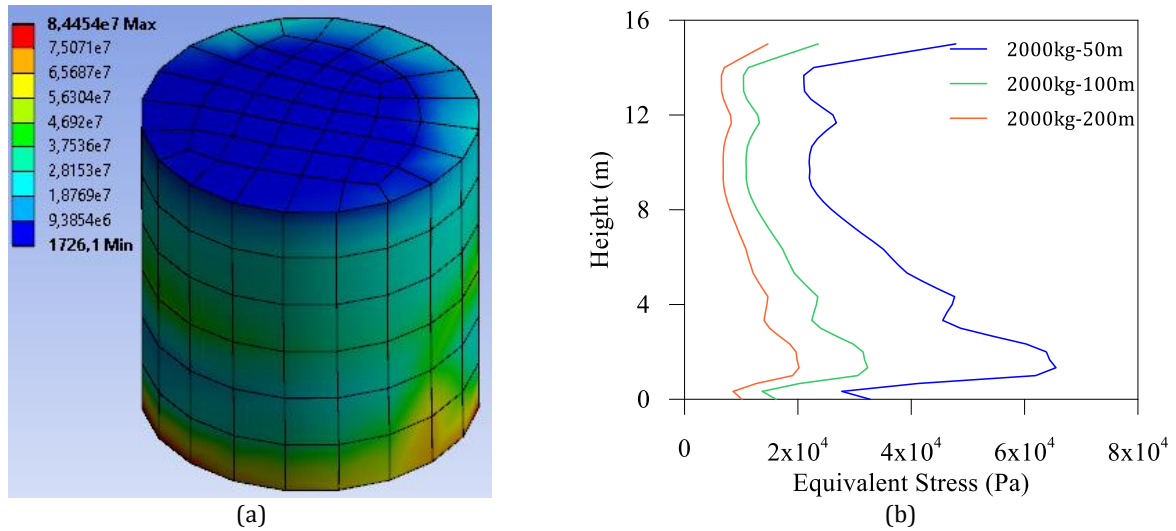
**4.2. The effect of charge center distance**

The charge center distance effects on the dynamic behavior of a demineralized water tank with a piled raft foundation system are estimated by using the different charge center distances. In this part, the charge center distances of 50 m, 100 m and 200 m are utilized with the charge weight of 2000 kg. The displacement and equivalent stress of the tank are indicated in Figs. 10 and 11 for the charge center distance values of 50 m, 100 m and 200 m, respectively. Fig. 10(a) and Fig. 11(a) only show the displacement and equivalent stress distributions for the charge center distance of 50 m, because of the fact that the result contours for the other distance values have almost the same distributions.

In Fig. 10(a), the displacement values along the tank’s height (Section 1-2) are the highest at the top of the tank while the lowest values at the bottom of the tank, also seen in Fig. 10(b). As observed in Fig. 11(a), the highest stress concentrations generally occur at the boom of the tank (junction point of the bottom of the tank and piled-raft foundation). It is also seen from Fig. 11(b), the stress values at the top and near the bottom of the tank are the highest values when compared to those of other height levels of the tank. The thing that needs to be mentioned from Fig. 10(b) and Fig. 11(b) is that both the displacement and equivalent stress values increase with decreasing the charge center distances.



**Fig. 10.** The displacement: (a) contour distribution; (b) along with the tank’s height for the charge weights of 50, 100 and 200 m.



**Fig. 11.** The equivalent stress: (a) contour distribution; (b) along with the tank’s height for the charge weights of 50, 100 and 200 m.

**4.3. The effect of water fill level**

In this section, the effects of water fill level on the dynamic behavior of the demineralized water tank with a piled raft foundation system are investigated. For this purpose, the water fill level height is assumed as 15 m from the bottom of the tank. As an external load, the blast charge weight and the charge center distance are taken as 2000 kg and 50 m, respectively. The water fill level cases in the tank are considered as 15 m (3/3 full), 10m (2/3 water fill level) and 5 m (1/3 water fill level). According to these cases, the displacement and equivalent stress distributions are presented in Figs. 12 and 13.

The displacement contour distribution and the displacements on Section 1-2 in the case of full water level, 2/3 water fill level and 1/3 water fill level in the tank with a piled raft foundation system subjected to blast ground motion are presented in Figs. 12 and 13. It can be

seen from the figures that the displacement values increase with the tank’s height. Maximum displacement values occur at the top of the tank. Also, it can clearly be observed that the displacement values increase with increasing the water fill level in the tank.

The equivalent stress contour distribution and the equivalent stress values on Section 1-2 in the case of full, 2/3 and 1/3 full of water in the tank are shown in Figs. 14 and 15. Fig. 14 shows that the Equivalent stress contour concentrations occur at the water fill levels and lower levels in the tank. While the stress concentrations in the case of 1/3 water fill level seem about 5 m tank’s height from the bottom, those in the case of 2/3 water fill level occur at about 10 m tank’s height. As can be seen in Fig. 15, the extreme jumps occur in the equivalent stresses at the level of 1/3 and 2/3 full of water. The stress values in the case of full of water can be ignored when compared to those of 1/3 and 2/3 full of water.

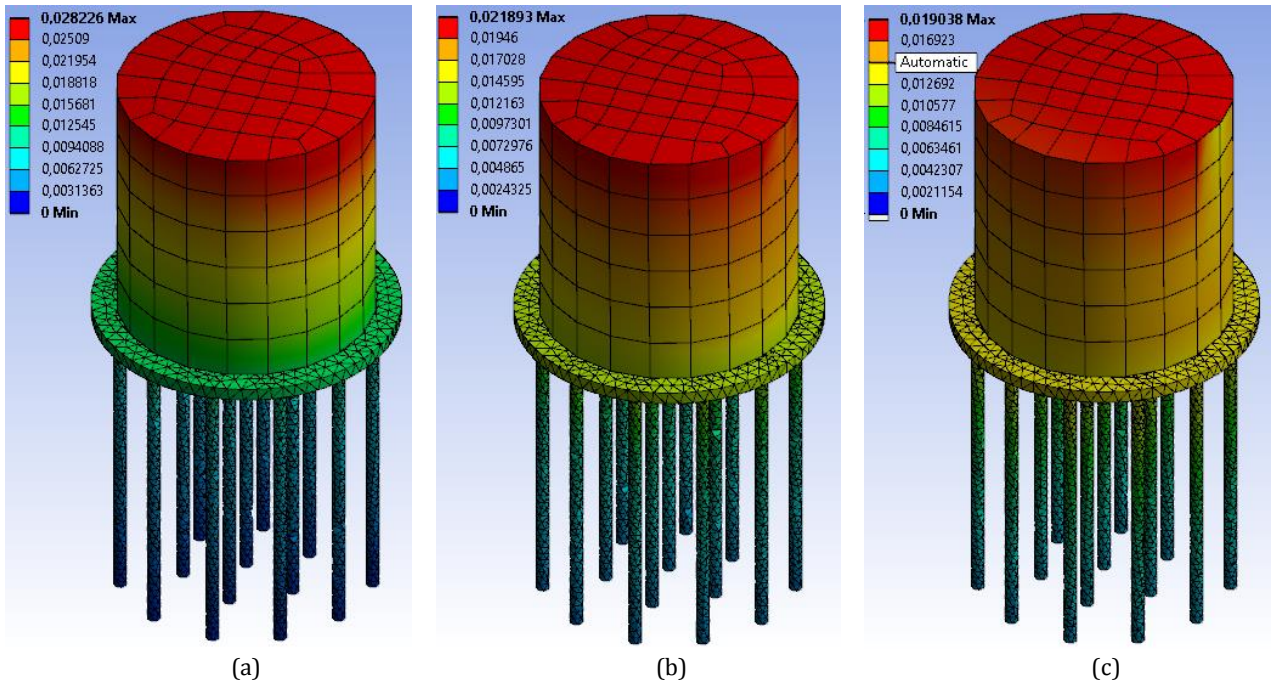


Fig. 12. The displacement contour distributions for (a) full, (b) 2/3 and (c) 1/3 of the water fill level in the tank.

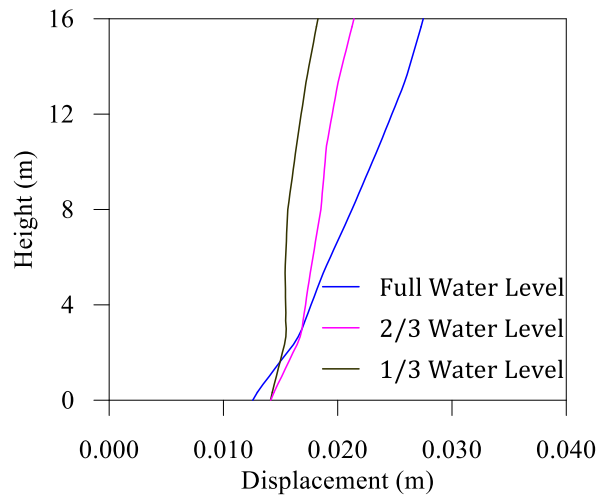


Fig. 13. The displacement values along with the tank’s height for full, 2/3 and 1/3 of the water fill level in the tank.

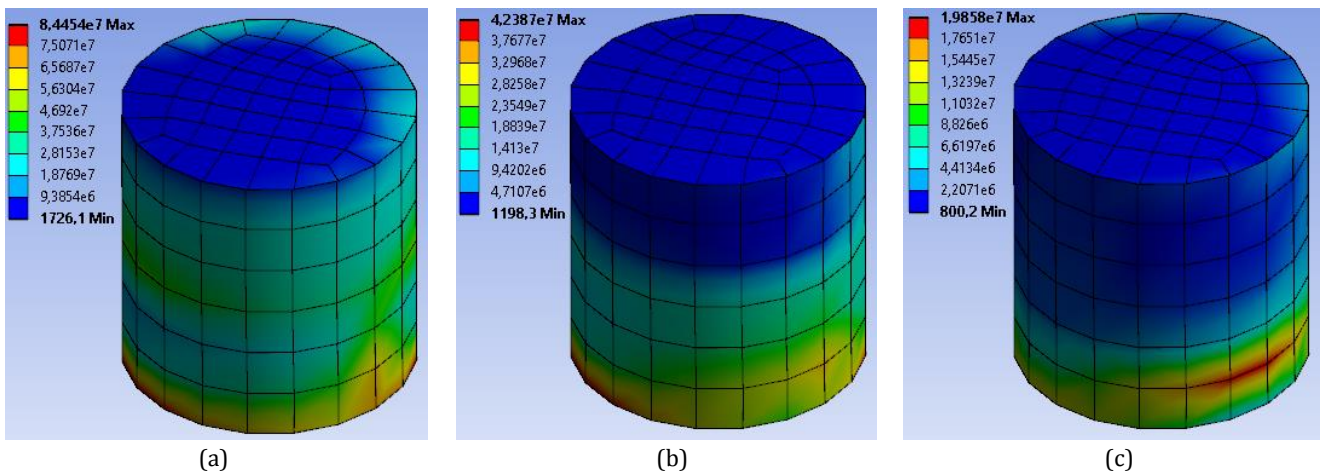


Fig. 14. The equivalent contour stress distributions for (a) full, (b) 2/3 and (c) 1/3 of the water fill level in the tank.

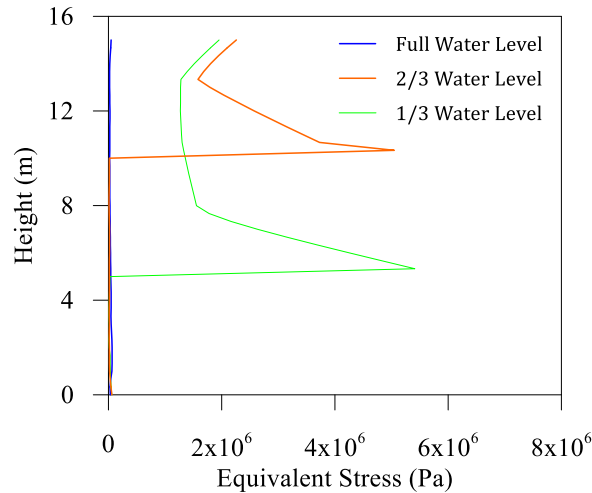


Fig. 15. The equivalent stress values along with the tank’s height for full, 2/3 and 1/3 of the water fill level in the tank.

4.4. The effect of the number of piles

This study also investigates the effect of the number of piles to estimate the dynamic behavior of the demineralized water tank with a piled raft foundation system. To this aim, it is first assumed that the tank is designed with a piled raft foundation consisting of 19 piles (model 1) on a soil whose properties are obtained experimentally. The number of piles is then assumed as 12 piles (model 2) and no-pile (model 3). The displacement and equivalent stress distributions are indicated in Figs. 16-19. In this section, the blast charge weight and the charge center distance are taken as 2000 kg and 50 m, respectively. The tank’s water level is assumed as 15 m.

Fig. 16 compares the displacement contour distributions on the tank in the case of 19 piles, 12 piles and no-

pile. The displacement values along the tank’s height are also presented in Fig. 17. As shown in these figures, the displacement values in the case of 12 piles are smaller than those of 19 piles. The displacements in the case of no-pile have maximum values when comparing the other cases. It is also seen in Fig. 17 that the displacement values on Section 1-2 increase with increasing the height of the tank. Figs. 18-19 show the equivalent stress contour distribution and the equivalent stress values on Section 1-2 in the case of 19 piles, 12 piles and no-pile. It is seen from the figures that the equivalent stress concentrations occur at the bottom of the tank for all cases. The stress distribution values near the bottom of tank have quite different. While the stress values in the case of no-pile are higher than those in the case of 12 piles. Minimum stress values in the same region of the tank take place in the case of 19 piles.

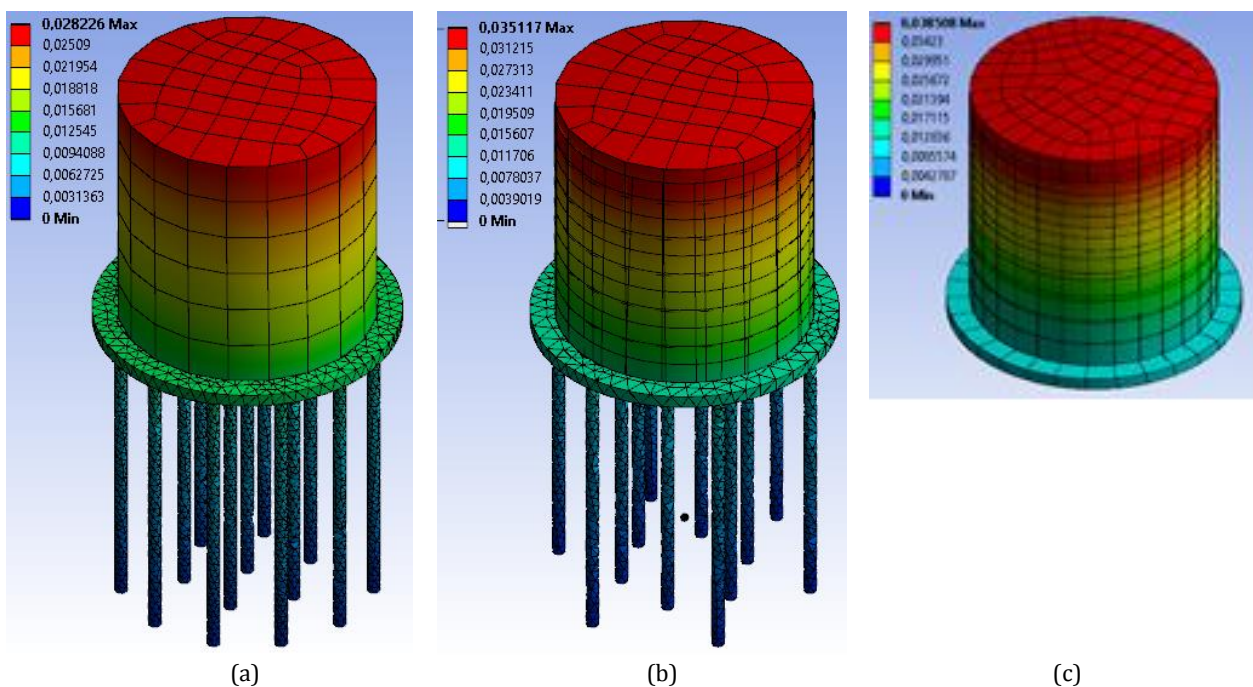


Fig. 16. The displacement contour distributions for (a) 19 piles, (b) 12 piles and (c) no-pile.

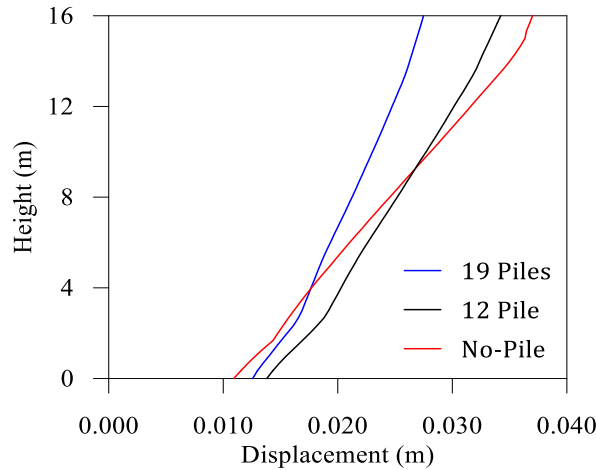


Fig. 17. The displacement values along with tank's height for 19 piles, 12 piles and no-pile.

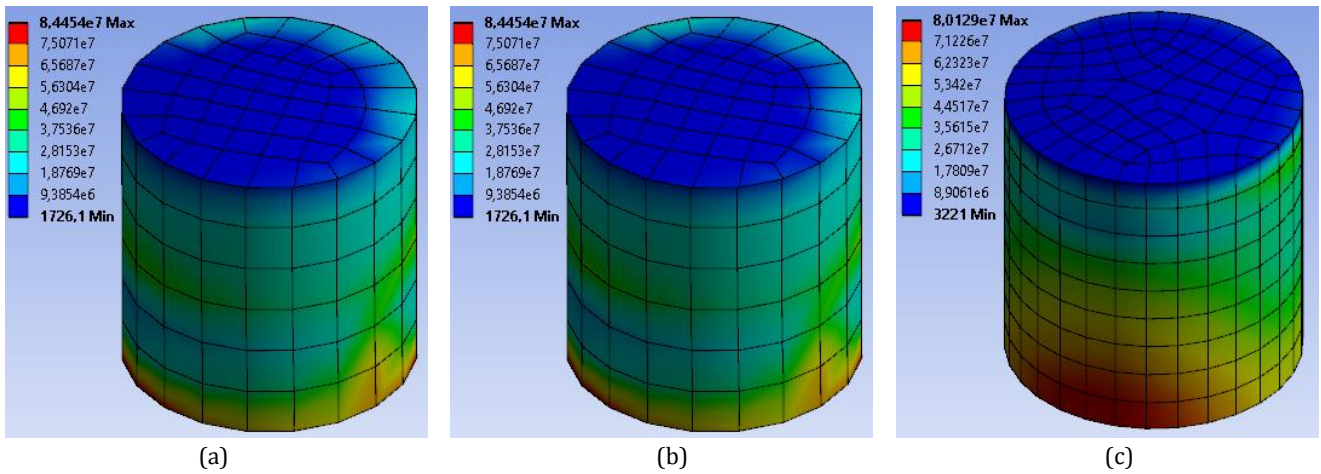


Fig. 18. The equivalent contour stress distributions for (a) 19 piles, (b) 12 piles and (c) no-pile.

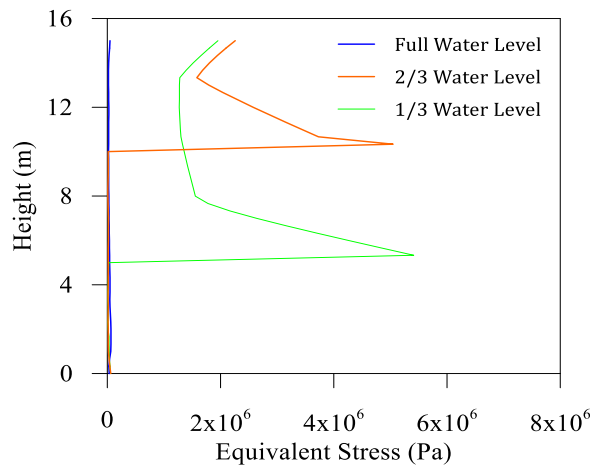


Fig. 19. The equivalent stress values along with tank's height for 19 piles, 12 piles and no-pile.

5. Conclusions

The current study mainly focuses on the effect of blast-induced ground motion on the dynamic behavior of a demineralized water tank with a piled raft foundation considering soil-pile-structure-fluid interaction. ANSYS software uses to establish the 3-D finite element

model of the soil-pile-structure-fluid interaction system. The shock response spectrum method determined from the blast ground motions are used to estimate the dynamic behavior of the soil-pile-structure-fluid interaction system.

Through the results determined the shock response spectrum analyses, there were observed that the charge

weight, charge center distance, tank's water level and the number of piles have extreme effects on the dynamic behavior of the demineralized water tank- fluid-soil-pile-interaction coupled system. While the displacement and stress values on the tank increase with the increase of the charge weight of the blast and water fill level, decrease due to the increase of the charge center distances and number of piles.

In general terms, it is observed that especially the maximum equivalent stress contour distributions are located at the middle and bottom part of the tank. Of course, the peak displacement values are expected to be at top of the tank. In addition, as a result of the analysis, it was observed that the water level change in the tank played an important role in the sudden stress change of the tank. It turns out that the displacement values also change visibly. The number and distribution of piles caused quite remarkable changes in the dynamic behavior of the water tank. Especially in the region where the water tank meets the basic part, there are significant differences in the stresses that occur.

As a result, although it is rarely encountered, besides the earthquake effect, perhaps blast ground motion should be taken into consideration in the design of such structures. Especially today, when the need for water has reached important dimensions, it is important to design such tanks in a reliable way.

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