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Al-Qadisiyah Journal for Engineering Sciences

Journal homepage: https://qjes.qu.edu.iq

Research Paper

Optimal shape of concrete tanks under seismic load considering soil-structure interaction

Abdulameer Qasim Hasan

Environmental and Pollution Department, Technical Engineering College, Southern Technical University, Basra, Iraq.

ARTICLE INFO

Article history:
Received 29 February 2024
Received in revised form 08 May 2024
Accepted 13 July 2024

keyword:
ABAQUS
Concrete tank
Dynamic analysis
Seismic load
Structure behavior

ABSTRACT

Most water stations use concrete tanks to store water, and the tanks may be above or below ground level. In designing tanks, many engineering requirements are taken into account to ensure the structural safety of the tank and the absence of water leakage. The research aims to study the response of different shapes of concrete tanks (square, rectangular, circular, and hexagonal), that based on clay soil and subjected to an earthquake wave (type El Centro), by studying some engineering variables related to tanks and soil. ABAQUS program was used to analyze the tanks, and used different analysis cases like Dynamic Explicit, geotechnical and soil analysis. The study concluded that there are advantages and disadvantages for each of the studied shapes. It is preferable to use circular tanks because they have a high resistance to shear forces, bending moments, stresses, lateral strength, and have small soil consolidation compare with the other tanks, but the bad characteristic is that cracks are high. Also, It is also preferable to avoid using a rectangular tank due to its poor response to seismic loads.

1. Introduction

All structures are subject to earthquake loads, which is one of the most dangerous load imposed due to the movement of the soil under the foundation. Concrete tanks are durable and fire-resistant, and their construction life is longer than other types of tanks. It's among the facilities that are high risk under the influence of these loads. Due to the appearance of cracks that may lead to the failure of the entire tank as a result of water leakage. There is a lot of research regarding the behavior of the effect of earthquakes and horizontal loads on concrete, steel tanks, and others material [1–5]. Vladimir V.and Djordje L., A studied the response of circular tanks above ground level under the influence of horizontal and vertical seismic waves, the ratio of water height and radius (H / R) is the main factor in the analysis and the research was matched within the provisions of ACI and the mandatory provisions of Eurocode 8. The survey showed that the basic shear strength and the impulsive period of the vibrations and the overturning moments increase with the increase of the ratio H/R and that the convection of the vibrations is a constant value of $H/R \geq 1.5$. Also, the seismic response of the tank structure depends mainly on the impulsive mode. And that the increase in the ratio H / R controls the shear strength and overturning moments[6]. Abdulameer Q. Used the ANSYS program to study the behavior of a single tank and a group of tanks (empty and full) under the influence of free vibration and under the influence of earthquakes in Basra Governorate / Iraq. The inflection point was known in both the bending moments and the shear forces resulting from the earthquake effect. Also, the behavior of a group of tanks is less than that of the singular tank, and the hoop pressure, displacement, and moments increase in the individual tanks [7]. Abdulameer Q. and Rafi. M. discussed the effect of the interaction between a fuel tank and a group of horizontally loaded piles. Some variables were taken, including the state of the plastic soil and the state of the tank empty, half full, and full. The study focused on the main factors, including hoop pressure, bending moments, shear forces, and pressure distribution on the walls. It was concluded that the critical state in the response of the tank is when the tank is full [8]. Norbert J, and Lenka U., used the finite elements in the study of the response of a concrete rectangular drinking water tank. They used an acceleration scheme for a natural earthquake for loading and taking into account the damping. The method of direct integration with time was used in the ANSYS program. A difference was observed in the resulting distortions and the bending moments in the walls between the method of loading the response spectrum (accelerometer) and the spectroscopy over time,[9]. Chae Lee and Jin Lee Discuss the response of rectangular tanks above the soil surface under the influence of ground motion in three directions, considering the concrete in a non-linear state. The study summarized the main factors, including When designing tanks, the material should be considered in a non-linear state, because this increases the response of the tanks and increases the appearance of cracks in concrete. Also, the hydrodynamic pressure decreases significantly when compared with the linear material and consequently, the overturning moments and shear [10]. The importance of this research into choosing the appropriate shape for concrete tanks from among a group of shapes (square, rectangular, circular, and hexagonal). Whereas all tanks are equal in base area and height. All tanks are based on clay soil and non-linear materials used to represent the soil and concrete. The appropriate tank shape is chosen according to some variables, including displacement, shear forces, bending moments, stresses, lateral pressure distribution on the tank, cracks in the tanks, and consolidation in the soil.

2. Methodology

2.1 Problem

Four concrete tanks are used to store drinking water with same base area, square 8×8 *m*, rectangular 5.65×11.3 *m*, circular with a diameter of 9.03 *m*, and hexagonal with a side length of 4.96 *m* as shown in Fig. 1.

*Corresponding Author.
E-mail address: a.almubarak@stu.edu.iq ; Tel: (+964 770 901-4140) (Abdulameer Hasan)

https://doi.org/10.30772/qjes.2024.147340.1146
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Nomenclature:

List of variables:

C	Cohesion (kPa)
D	Diameter (m)
E	Young modulus (MPa)
G	Shear modulus of elasticity (MPa)
H	Height (m)
K	Third stresses invariant parameter
M	Critical state ratio
P	Pressure (MPa)
P_o	Pre consolidation pressure (MPa)

Greek Symbols:

ν	Poisson's ratio
γ	Density (kg/m^3)
β	Wet cap parameter
α	Friction coefficient of soil
κ	Logarithmic elastic bulk modulus
λ	Logarithmic hardening modulus
μ	Dynamic viscosity $(kg-s/m^2)$
Δ	Dilation Angle deg.

Sub Scripts:

a_0	Initial over consolidation parameter
e_0	Initial void ratio
k_0	Coefficient of earth pressure
e	Eccentricity
fbo	The initial equi-biaxial compressive yield stress
fco	The initial uniaxial compressive yield stress

All tanks with a height of 10 m and a water height of 8.5 m, resting on the two layers clay soil in the case of plastic, the first 2 m dry clay soil and the other is saturated clay soil. The water level is shown in Fig. 2. The tanks were subjected to an earthquake of the El Centro type for fifty seconds. It is required to know which tank is most suitable and highly efficient for earthquake resistance, in terms of studying some variables such as shear forces, bending moments, pressure distribution, lateral displacement, and stresses in the tank, as well as knowing the cracks in the tank and soil consolidation.

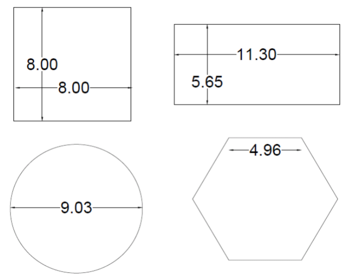

Figure 1. Schematic of the base dimensions of selected tanks tested.

2.2 Modeling

ABAQUS engineering software is used to model the problem in this work. Concrete was represented by a non-linear three-dimensional brick element C3D20, steel was represented by a non-linear three-dimensional beam element, and the soil was represented by a non-linear, porous brick element C3D20P, ensuring that consolidation occurred in the clay soil. Figure 3 shows the finite element modeling in ABAQUS. To simplify the problem, the steel was embedded in the concrete; the tank foundation is raft footing extends by 1 m around the tank wall, it is also embedded in the soil. For soil, The soil dimensions were assumed to be 10 times the smallest dimension of tank on all sides [11, 12].

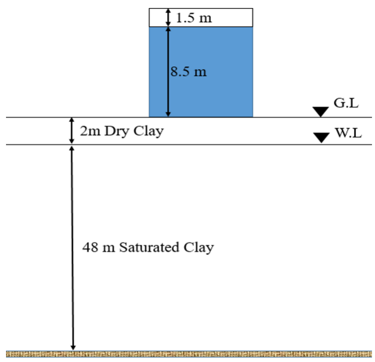

Figure 2. Schematic of the soil profile under the tanks.

2.3 Material

Table 1 and Fig. 4 show the concrete material in an elastic and plastic state [13–15] and Table 2 and Fig. 5 show the steel material in an elastic and plastic state [16, 17]. Soil plasticity represents by the cam clay model to study the effect of porosity on the consolidation and pore water pressure, Table 3 shows the soil material in the elastic and plastic state [18–23].

2.4 Load

The main load represents by the applied earthquake (El Centro wave) in the horizontal direction for fifty four seconds, Figure 6 shows the El Centro wave, Also the pressure of water on the tank base and walls is used in calculations in addition to gravity weight [24].

2.5 Analysis

A set of analyzes was conducted to find all the variables required in this work. The first analysis was Dynamic Explicit to calculate the response of the tank, and then it used the geostatic analysis and the soil analysis to find the poor water pressure and soil consolidation. For analysis, it is used the seismic wave in the x-direction, but the rectangular tank the seismic load is applied in two cases, the first is in the long direction and the other is in the short direction. Table 4 show the tank name and tank symbol used in this study.

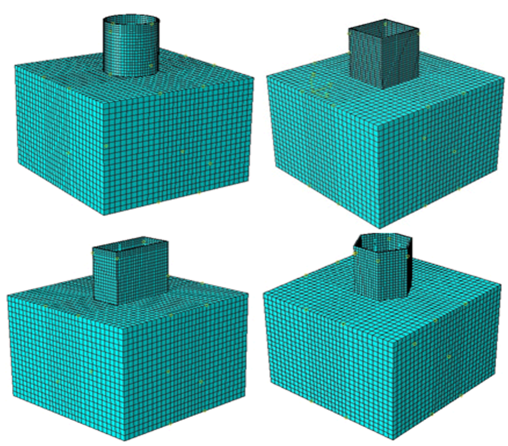

Figure 3. Finite element modeling of deferent Tanks in ABAQUS.

3. Verification

S. Klishin and A. Revuzhenko [25] do an experimental cylinder tank with a radius of 1m and height of 1 m, the concrete material used a density of 2500=kg/m^3 and an elastic modulus of 10 GPa with a fixed base. The tank is filled with water by using equal batches and calculating the vertical pressure Pz according to some factors used in the study. The relation between normal stress and H/D (water depth to tank diameter) and the relation of Pz/γ and the filling height H/D are used to verify in this study. Good results are shown in Fig. 7 and Fig. 8 between experiment and analysis results.

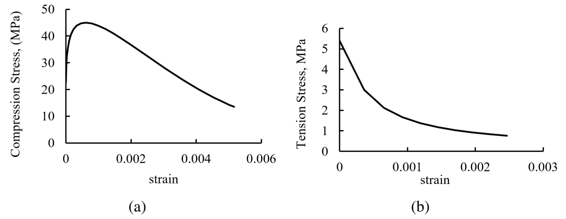

Figure 4. Concrete response in compression and tension.

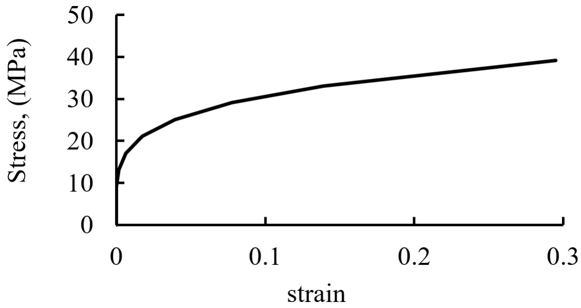

Figure 5. Steel response in compression and tension.

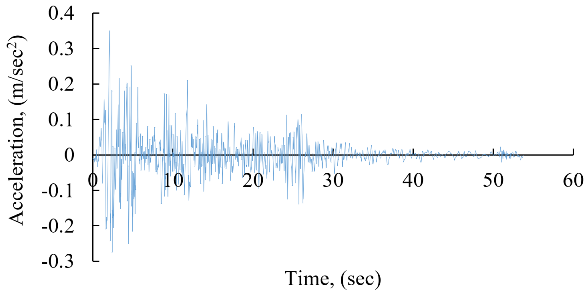

Figure 6. Shows the El Centro wave used in the work.

4. Results and discuses

4.1 Maximum Displacement on tank head

Figure 9 shows the maximum displacement in all tanks under seismic load, taken for 20 seconds to show the response clearly, its show that rectangular tank (REY-X) have a maximum displacement of 50.2 *mm* on the long side of the rectangle, while the minimum displacement occurs in circular tanks (CIX-X), this means that circular tank is very rigid because the curvature in-wall, the other tanks is having close value to the circular tanks.

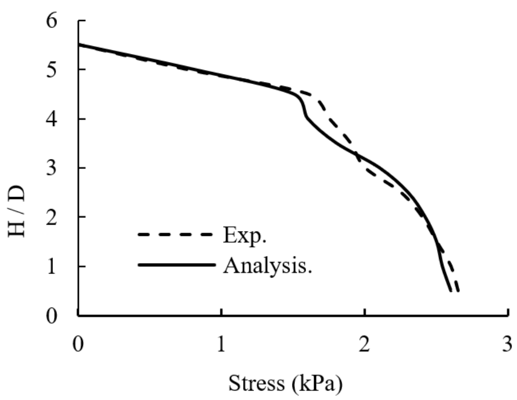

Figure 7. Relation between normal stress and H/D.

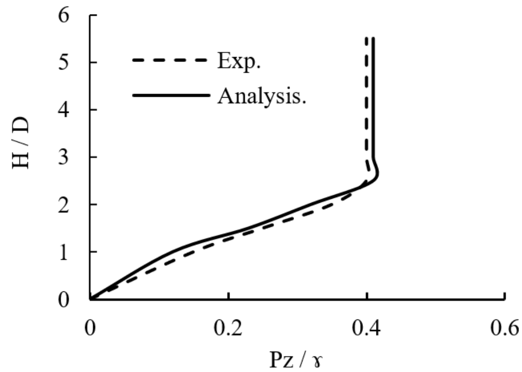

Figure 8. Relation of Pz/γ and H/D.

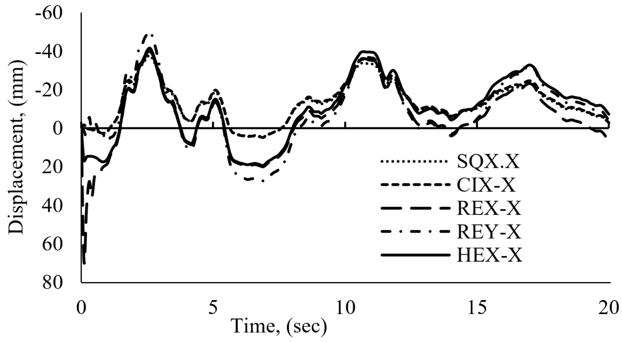

Figure 9. Maximum displacement in all tanks.

4.2 Maximum Deflection in-tank Base

The maximum deflection in the tank base can be shown in Table 5, from this result, the minimum deflection occurred in the square tank (SQX) while the maximum deflection happened in the rectangular tank (REY). Hexagonal tanks and circular tanks have close value to rectangular tanks.

4.3 Displacement along tank wll

Figure 10 and Fig. 11 represent the maximum displacement along the tank wall in x and y directions respectively. The rectangular tank (REX) has the maximum displacement in the x-direction while the rectangular tank (REY) has the maximum displacement in the y-direction, but the square, circular and Hexagonal tank has the minimum close value of displacement in the x and y directions. The displacement in the rectangular tank is too much from the head to the base, this occurs on the large side of the tank because support is far from this side.

4.4 Shear force along tank wall

The maximum shear force during seismic load in x and y directions are shown in Fig. 11 11 and Fig. 12. At the head all tanks have a close value because all tanks are open, the hexagonal tanks have maximum shear force but the circular tank has an approximate constant shear force from depth 2 *m to* 6 *m* from the top of tank, It is the lowest shear force compared to all types of tanks. Rectangular tanks (REX and REY) have a close value in shear force, while square tanks have a variable value. The reflection point in shear force (along the x and y direction) is the same in all tanks it's about (1.7 *to* 2 *m*) from the tank base. All values for shear force in the x and y direction have a close value, because the water pressure is equal on the walls for all tanks.

4.5 Bending moment along the tank wall

The maximum bending moment during seismic load in x and y directions are shown in Fig. 14 and Fig. 15. From the head to the two-thirds of the tank wall, all tanks have close value because all tanks are open. The rectangular tank (REX-X) has a maximum bending moment at the two-thirds wall length unlike the hexagonal tank has a minimum bending moment in the x-direction, while in the y-direction, the rectangular tank (REY-X) have maximum value and the circular tank has a minimum value of bending moment. The reflection point in bending moment in the x-direction is about (0.5 *to* 3 *m*) from the tank base and in the y-direction is about 2 *m* because no loads in the y-direction.

4.6 Stress along the tank wall

Stress in the x and y-direction along the tank wall under seismic load is shown in Fig. 16 16 and Fig. 17, at the head and base of the tank the stress has a minimum value for all tank shapes while the maximum stress occurs in the mid-wall. The circular tank (CIX) has the minimum stress in the x and y direction but the rectangular tank (REX) has maximum value in the x-direction and the rectangular (REY) has maximum stress in the y-direction. The square and hexagonal tanks have the same response under seismic load due to the closeness of the geometric shape, which led to an equal distribution of pressures on the walls of the tanks.

4.7 Lateral Pressure along the tank wall

It is important to know the lateral pressure that occurs in the tank wall under seismic load, Fig. 18 and Fig. 19 summarize the lateral pressure in the tank wall. A circular tank (CIX) represents the ideal distribution of lateral pressure and has a minimum value in the x and y direction while the rectangular tanks (REX and REY) have maximum lateral pressure in the x and y direction respectively. The square and hexagonal tanks have the same response under seismic load in the x and y-direction for the same reason explained in the previous item.

4.8 Consolidation under tanks

The consolidation of soil under tanks is shown in Fig. 20, the curve represents the relation between logarithm time and Consolidation under the tank. Initially, all tanks have a closed value of Consolidation but at last rectangular tanks have maximum Consolidation of about 48.3 mm but the circular tank has minimum Consolidation of 37.1 mm, and the hexagonal tank has a value close to the circular tank.

4.9 Excess Pore water pressure in the soil

Because the level of water is near the ground level, the excess water pressure is very important to know the maximum and minimum pore water pressure on soil, Fig. 21 shows the excess pore pressure has the maximum value at the beginning and begins to decrease with time, also the figure summarizes that the seismic load occurs maximum pore water pressure under the rectangular tank due to the varying pressure distribution at the bottom of the tank and minimum pore water pressure under the circular tank. The variation between the maximum and minimum values is about 18%. Hexagonal tanks have a value close to circular tanks while square tanks have a value close to the rectangular tank.

4.10 Crack in tanks

Figure 22 show that the concrete crack occurs during the seismic wave and water pressure on the tank wall. All cracks in tanks happen in concrete, the cracks in rectangular have occurred in the middle of the long side and the crash is very high in the third part above the tank base, the cracks in circular tank occur along the circumference in the longitudinal side, the crack in the square tank is concentrate at the middle sides towards tank base, at last, Hexagonal tank has less cracking than the other tanks it occurs only in the edges of the tank, unlike the other tank the crack occurs in the middle side.

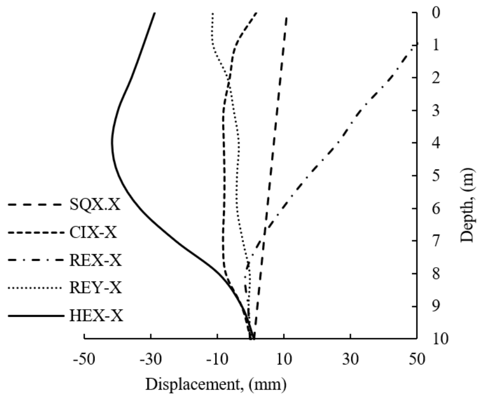

Figure 10**.** Displacement along depth, x-direction.

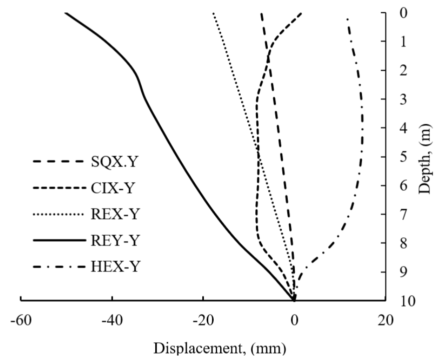

Figure 11**.** Displacement along with the depth, y-direction.

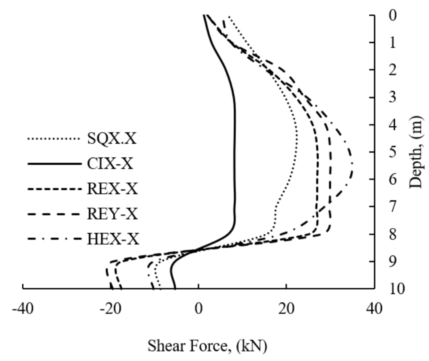

Figure 12**.** Shear Force along with depth, x-direction.

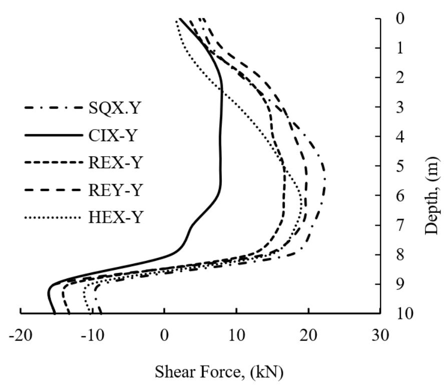

Figure 13**.** Shear Force along with depth, y-direction.

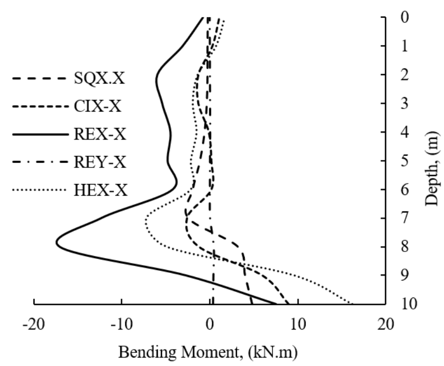

Figure 14**.** Bending Moment along depth, x-direction.

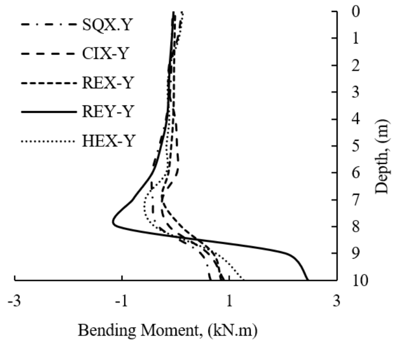

Figure 15. Bending Moment along with the depth, y-direction.

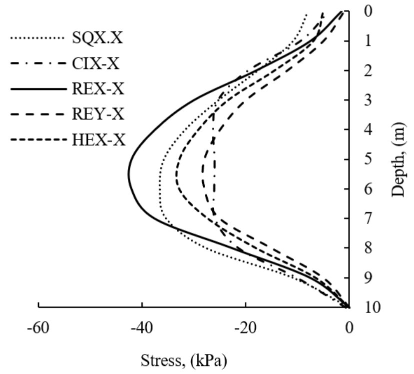

Figure 16. Stress along with the depth, x-direction.

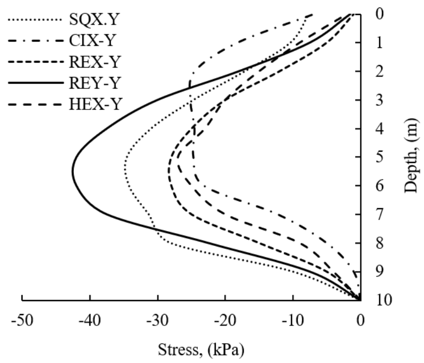

Figure 17. Stress along with the depth, y-direction.

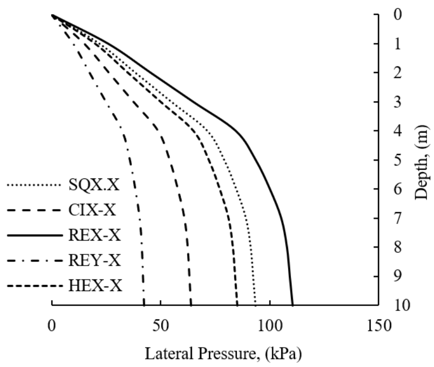

Figure 18. Lateral Pressure along with the depth, x-direction.

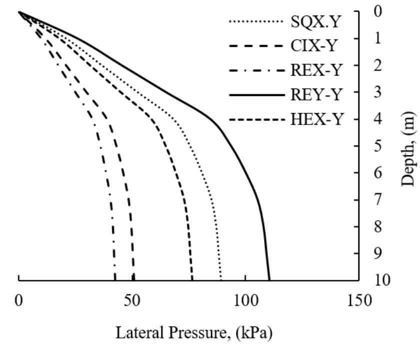

Figure 19. Lateral Pressure along with the depth, y-direction.

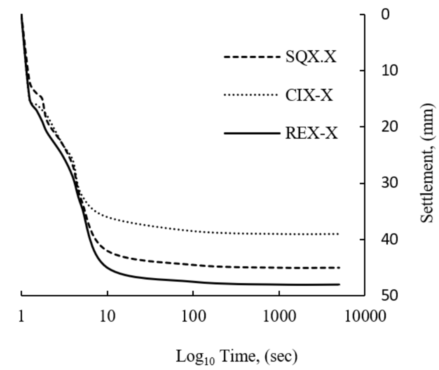

Figure 20. Consolidation of soil under tanks.

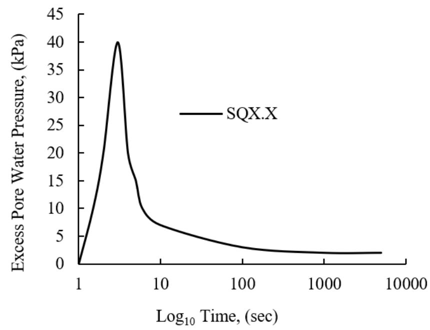

Figure 21. Excess pore pressure under tank.

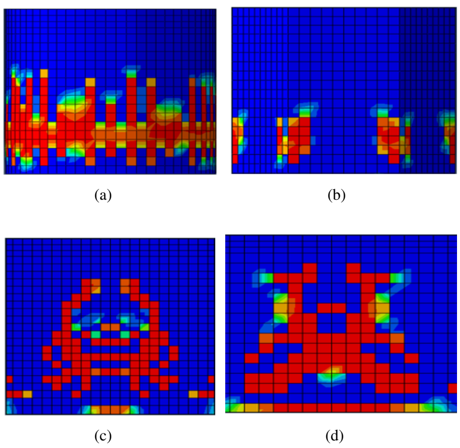

Figure 22. Finite element result of the crack and damage propagation in tanks.

Table 1. The physical elastic and plastic properties of concrete material.

Variable	Unit	Value
Mass Density	kg/m^3	24.00×10^2
Dilation Angle	Degree	35.00×10^0
Young's Modulus	MPa	21.50×10^0
Eccentricity	Unit-less	00.10×10^9
fbo/fco	Unit-less	01.16×10^0
K	Unit-lesss	00.667×10^9
Poisson's Ratio	Unit-less	00.18×10^0
Viscosity Parameter	Unit-less	79.85×10^{-4}

Table 2. Steel materials in an elastic and plastic state.

Variable	Unit	Value
Mass Density	kg/m^3	78.00×10^2
Young's Modulus	MPa	21.5×10^9
Poisson's Ratio	Unit-less	18×10^{-2}

Table 3. Soil material in the elastic and plastic state.

Variable	Unit	Value
Mass Density	kg/m^3	1400
Young's Modulus	MPa	09.70
Poisson's Ratio	Unit-less	00.35
Cohesion	kPa	18.80
Void ratio	Unit-less	00.80
M	Unit-less	01.10
λ	Unit-less	00.26
κ	Unit-less	00.02
β	Unit-less	01.00
a_0	Unit-less	04.50

Table 4. Tank name and tank symbol.

Tank code	Description
SQX	Square tank
CIX	Circular tank
REX	Rectangular tank long direction wave
REY	Rectangular tank short direction wave
HEX	Hexagonal tank

Table 5. Tank maximum deflection.

Tank	SQX	CIX	REX	REY	HXX
Deflection, mm	-12.56	-15.36	-15.02	-15.24	-14.15

5. Conclusions

From the result in the above item, it can be made a summary of this research as shown below.

- It is important to select the suitable type of tank according to the results from the above item (4).
- When designing tanks, rectangular tanks should be avoided because of the high displacement, shear force, bending moment, and stress.
- The appropriate and most efficient type is the circular tank, then the hexagonal and square tanks.
- It is preferable to use circular tanks because they have a high resistance to shear forces, bending moments, stresses, lateral strength, and have small soil consolidation compare with the other tanks, but the bad characteristic is that cracks are high.
- When executing the tanks, the rectangular and square tanks should be strengthened from the top due to the higher displacement from the tank head, unlike the circular and hexagonal tanks, which occur in the middle of the tank and the reason for this is due to the high rigidity of the last tanks.
- The largest deflection occurs in the rectangular tank, due to the distribution of pressure on the base varies according to the longest side. As for the square tank, the pressure is equal, so the effect is less under a load of seismic waves.
- The emergence of the highest cracks in the areas that contain the largest shear strength and bending moments and stresses, and the circular tank contains the largest cracks, although the shear strength and bending moments are less than the rest of the tanks.
- It is necessary to know the inflection points in the shear strength and bending moments and strengthen them to avoid failure in the tanks.
- The highest excess poor water pressure occurs at the moment of the earthquake, after which it begins to decline, and its effect remains with time.
- The amount of consolidation in the soil increases when the earthquake occurs due to the loosening of the soil particles under the tank.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

Funding source

This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgements

The authors would like to acknowledge.

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How to cite this article:
Abdulameer Qasim Hasan, (2025). ’Optimal Shape of Concrete Tanks under Seismic Load Considering Soil-Structure Interaction’, Al-Qadisiyah Journal for Engineering Sciences, 18(1), pp. 65-71. `https://doi.org/10.30772/qjes.2024.147340.1146`