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Study the Behavior of Ground-Supported Cylindrical Tanks Considering the Soil Structure Interaction Using Finite Element Method FEM

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Abstract:

The ground-supported Cylindrical Steel tanks are widely used in industrial and service domains to store various types of liquid. As a result of neglecting the interaction between the fluid and tank from one side and the interaction between the tanks and soil beneath them from the other side, it will likely be exposed to huge damages during and post-earthquakes. In this paper, the fluid-tank system considering Soil Structure interaction (SSI) has been studied. The 3D model has forming for the soil, tank and fluid in the finite element program (ABAQUS) to examine the two types of tanks. Two types of soil (hard−Conglomerate & silty gravel) and the frequency content of several earthquake records have been investigated. The results have apprenticed that the shear force of the water tank in the silty gravel soil is increasing by about 60% in the hard soil and may decrease by about 10% - 20%. These ratios vary depending on the Frequency content of the seismic record and the role of properties of silty gravel soil in the amplification of the forces and displacement. The increase in wall displacement may arrive at 3 times in silty gravel soil in comparison to hard one. Also, the increase in displacement is accompanied by an increase in the stresses in the tank elements. In addition, the liquid wave height (sloshing) increases by a higher ratio in the case of silty gravel soil than in hard one. The results emphasize the necessity of considering the type of foundation soil for underground reservoirs and the seismic characteristics of the applied recordings. Additionally, it highlights the importance of improving the soil layers on which the foundations of the reservoirs are established, particularly for silty gravel soils.

Keywords: Ground Cylindrical Tank, Finite Element Method, Soil_ Structure Interaction (SSI), Fluid_ Structure Interaction (FSI), Seismic Analysis.

دراسة سلوك الخزانات الأرضية الاسطوانية باعتبار أثر التفاعل المتبادل منشأ –تربة باستخدام طريقة العناصر المحدودةFEM

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الملخص:

تستخدم الخزانات الأسطوانية المعدنية الأرضية على نطاق واسع في المجالات الصناعية والخدمية من أجل تخزين أنواع مختلفة من السوائل. تتعرض الخزانات لأضرار جسيمة أثناء حدوث الهزات الأرضية وبعدها.ذلك نتيجة لإهمال التفاعل بين السائل والخزان من جهة، والتفاعل بين الخزانات والتربة المستندة عليها من جهة أخرى. في هذا البحث، تمت دراسة جملة خزان – سائل مع الأخذ في الاعتبار أثر التفاعل المتبادل بين التربة والخزان (SSI). تم نمذجة موديل ثلاثي الأبعاد يتضمن الخزان والسائل ضمنه وحقل التربة واختباره في برنامج العناصر المحدودة(ABAQUS) وذلك لنموذجين من الخزانات. أيضاً تم دراسة أثر نوعين مختلفين من التربة (تربة صخرية –كونغلوميرات & تربة بحصية سيلتية).

إضافة إلى ذلك، تم تطبيق ثلاث تسجيلات زلزالية للتحقق من أثر خصائص هذه التسجيلات على سلوك الجملة المدروسة. أظهرت النتائج أن قوى القص لخزان المياه في التربة السيلتية تزداد بنحو 60٪ عنها في التربة الصخرية، وعلى العكس قد تنخفض بنحو 10٪ –20٪. هذا الاختلاف في الزيادة أو النقصان يعود الى تأثير تردد الزلزال المطبق ودور خصائص التربة السيلتية في تضخيم القوى والانتقالات. وقد تصل الزيادة في انتقالات الجدران إلى ثلاثة أضعاف في التربة اللينة مقارنة بالتربة الصخرية. كما أن الزيادة في الانتقالات بكون مصحوبة بزيادة الإجهادات في عناصر الخزان. إضافة إلى ذلك، فإن ارتفاع موجة السائل يزداد بنسبة أعلى في حالة التربة السيلتية عنه في التربة الصخرية. تؤكد النتائج على ضرورة الأخذ بعين الاعتبار نوع تربة التأسيس للخزانات الأرضية والخصائص الزلزالية للتسجيلات المطبقة. إضافة إلى أهمية تحسين طبقات التربة التي تؤسس عليها الخزانات وخاصة طبقات التربة السيلتية البحصية.

الكلمات المفتاحية: خزان أسطواني أرضي، طريقة العناصر المحدودة، أثر التفاعل المتبادل بين التربة والمنشأ، التفاعل المشترك بين السائل والخزان، تحليل زلزالي.

Introduction:

Ground-supported tanks play a vital role in social and industrial applications such as storage facilities and distribution systems. Controlling the seismic behavior of these private structures is essential for ensuring their safety and performance during earthquakes. Disasters in different regions showed Several tanks have been severely damaged during past earthquakes like the Turkey and Syria 2023 earthquake, where common states of tank failure (cracks in floor and walls, the collapse of the connection systems, buckling of wall). One of the important things in this type of structure, studying the interaction between the fluid and the tank, or what is called fluid-tank interaction (FSI). In addition, the soil-structure interaction (SSI) is a major topic usually illegible in research. This topic has been discussed in this study, where SSI is a main factor that influences the response of ground tanks to seismic forces. The interaction between the tank structure and the supporting soil can significantly impact the dynamic behavior of the tank systems.

Many research has been conducted on storage tanks, with a particular emphasis on finite element modeling (FEM) that incorporates soil-effects structure interaction (SSI). Alexandros [14] examined the of dynamic soil-structure interaction on the performance of the Fluid-tanks system. This study shows that a soft soil layer contributes to the increase of sliding and uplifting for two tank boards and slender. It is noteworthy that the interaction between the fluid and the tank is modeled using a spring-mass system by the Eurocode Code. Erkman [6] evaluated of liquid content volumes and soil types of the seismic response. Additionally, the impact of the friction coefficient in terms of base sliding and uplifting has been investigated. Maedeh et al., [9] focused on investigating the impact of soil effects on the natural period of elevated tanks. They discussed the significance of fluid-structure-soil interaction in determining the natural period of elevated tanks, emphasizing the need to account for dynamic soil stiffness changes during seismic events. The Maedeh's study concluded by reporting that the analytical models provide good estimations of natural periods compared to finite element results, especially for soft soil conditions. Chirag N. Patel et al., [11] study the seismic response of the evaluated water tank considering SSI. Their study focused on analysing the seismic behavior of elevated water tanks by considering the dynamic interaction between the tank, foundation, and supporting soil. The study compared responses like base shear, overturning moment, top displacement, and sloshing displacement to clear the effect of soil structure interaction. Livaoglu [8] explored the influence of foundation embedment on the seismic behavior of fluid-elevated tank-foundation-soil systems. This investigation delves into the intricate dynamics of fluid-elevated tank-foundation-soil systems under seismic loading, underscoring the importance of incorporating fluid-structure-soil interaction effects into the analysis. Vern [17] investigated the behavior of liquid storage tanks under bi-directional earthquakes and explore the implementation of base isolation devices to manage the tank responses. The study utilizes a nonlinear time history analysis using ABAQUS software with the ALE method to model the fluid. The research focuses on various response parameters such as sloshing height, base shear, overturning moment, and Von isolation to control stresses in the tank while addressing the amplification of sloshing waves. However, this study does not consider the effect of supported soil beneath the tanks.

The objectives of this study of a cylindrical steel ground-supported tank are: (i) to understand the effect of entire the soil structure interaction in studying the liquid tank system on the seismic response; (ii) to study the change of shear forces, sloshing height, and displacement of the wall when the soil beneath the foundation has changed and its effect on the design works. For that, a finite element method is used to consider the complete fluid-tank-soil system (FSI & SSI). The interaction between the liquid and the tank (Fluid Structure interaction FSI) using the ALE method. The 3D model is implemented in the FEM program Abaqus. Two slender ratios for two tanks (T1 =0.36 & T2=0.82) in the sewage treatment plant are investigated. Also, two types of soils have been examined according to the classification of soil in the Syrian code (Sc, Sd) from real sites in Damascus. In addition, the effect of frequency content for three seismic excitations is investigated. Researchers can profite valuable insights into how the ground tank responds to ground motions, leading to more accurate and reliable seismic design practices.

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1. Fluid -Tank System:

Dynamic analysis of fluid storage tanks is a complex problem involving fluid-structure interaction. The simple mechanical models of liquid-tank systems have been developed to evaluate hydrodynamic forces based on numerous analytical, numerical, and experimental studies. All reference models for ground-supported tanks (two SDOF systems) are based on the work of Housner. Until now, simple models have not captured the realistic behavior of the interaction. For complex models, the last models can be insufficient and inaccurate. Therefore, numerical approaches have been developed. For that the FEM method is adopted.

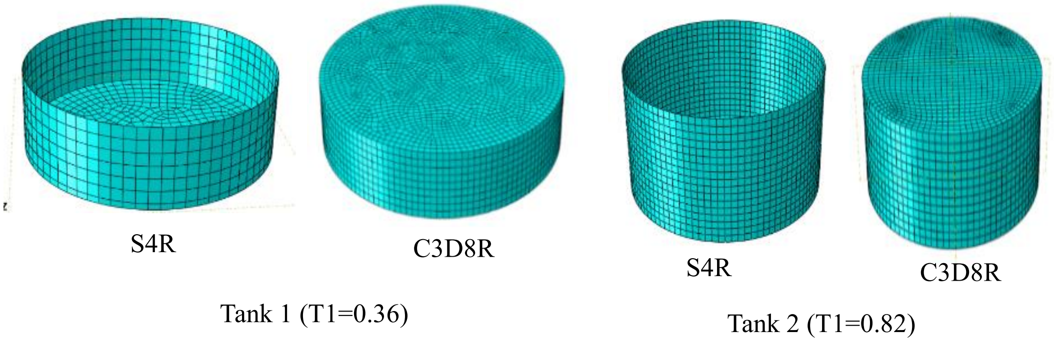

Fig (1)Two model of tank T1 & T2 with the element type and mesh in FEM.

In FEM formulation, the definition of (FSI) at the interface between structural and fluid elements is required to couple tank and liquid displacements. ALE has been used to model this interaction. ALE method is a numerical technique used to model fluid-structure interactions by allowing for the independent movement of the mesh and the material, effectively combining the advantages of both Lagrangian and Eulerian approaches. This method is particularly useful in applications involving large deformations and free surface flows, as it enables accurate simulations of complex interactions between fluids and solids. Fig.1. illustrates the element types and the mesh of it. Liquid in the storage tanks is assumed to be incompressible, non-viscous, and non-rotational for the seismic problems of tanks. All properties of the fluid to model it are shown in Table.1.

Table(1)the properties of fluid

$Viscosity\ (pa.s)$	$EOS\ (Us-Up)$			**Density ($\mathbf{kg/m3}$)**
	C_0	s	$Gamma\alpha_0$	
0.001	1450	0	0	1000

The studied tank consists of steel wall S275 with a density of 7850 kg/m^3, young module with 210 GPA and the foundation from concrete (density of 2400 kg/m^3) and a young module with a 27.8 GPA. Table .2 shows the dimension of the two models of tanks under investigated.

Table(2) the Dimension of Tanks

Model of Tank	$\boldsymbol{H/R}$	$\boldsymbol{Radius\ (m)}$	Height of Wall (m)	Height of Fluid (m)	Thickness of wall (mm)
T1	0.36	11.0	6.0	4.0	10
T2	0.82	8.00	8.0	6.5	10

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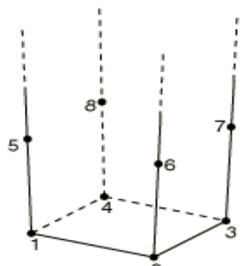
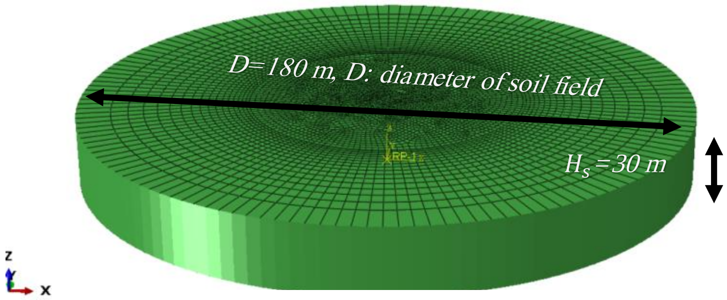
2. Soil -Tank interaction:

In previous investigations (e.g., Veletsos and Tang, 1990) & (Veletsos et al., 1992), analyses were performed using two-dimensional models to represent the soil–fluid–lank interaction. In addition, these studies use the spring -the dashpots system to define two systems soil -tank and fluid -tank (simplified approach).

In this study, the FEM method has been used to evaluate the dynamic response of the tank supported on the ground. The difficulty is in determining the size of the soil domain. For adoption, the artificial boundary is defined for the soil field to prevent the reflected wave from returning to the structure. However, there is not a whole solution because relatively many types of soils have high wave velocities.Fig.2. shows the semi-infinite element type (CIN3D8) that used to define the border elements of the soil domain. Many researchers conduct studies to optimize the soil field dimension. Rayhani et. al, [10] carried out comprehensive numerical analysis and centrifuge tests and recommended to take the length of the soil field in FEM model about 5 times the width of the tank. The results showed that increasing that distance more than five times the structure width doesn't effect the results of the seismic response. Also, El-Hoseiny et al, [4] recommended the maximum bedrock depth thirty meters in the numerical analysis, which is in good agreement with most global seismic codes that consider the properties of the top thirty meters of the soil profile to evaluate local site effects.



Fig(2) infinite element in Abaqus (CIN3D8R) [1]



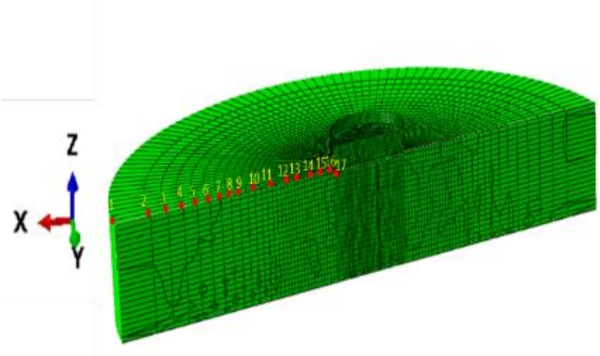
Fig(3) the mesh and dimension of soil domain in FEM

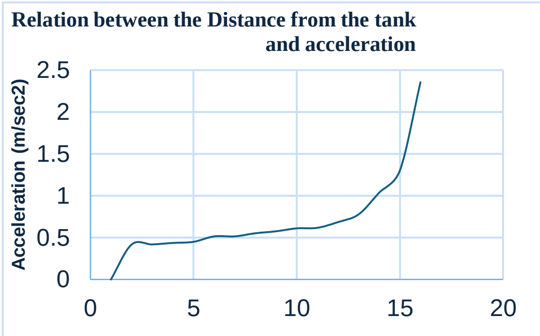
Also, according to the recommendations of Wilson,[7] & Sextos et. al,[] the dimensions of soil don't less than 3 times the width of the structure in two transitional directions. In addition to considering the previous recommendations about the dimensions of soil domain. Three models with different sizes were investigated, (5D, 7.5D, 10D). Then, the results were compared to determine the effect and reflection of the field dimensions on the accurate results. Fig3. Shows

the dimensions that are used in these studies (about 9 times of diameter). The size of the mesh is 1 meter at the region close to the tank and gradually increased from 1 to 5 at the border (Fig.4). The artificial boundaries are working in absorbing the effects of the seismic wave when it reaches. In addition, it contributes to the movement not being reflected so as not to affect the values of the displacement, stresses, and forces.

Fig (4) Parts and element of whole Model in Abaqus.

Another test was conducted to verify the dimensions of the selected soil field is test accelerations of the soil field according to the distance from the tank. Fig.5 shows a gradual decrease in acceleration values is observed from the structure to the boundary. The infinite elements should effectively minimize the acceleration to a value close to zero at their boundaries, indicating that they are functioning as intended to absorb the seismic energy. This indicates that the selected soil field and its dimensions are sufficient to obtain acceptable results.





No. of point	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Distance (m) from edge of tank	64	54	49	44.6	40.62	37	33.8	30.9	28.3	23.8	18.7	14	11	7	4	1
Values of ACC (m/sec2)	0.00	0.42	0.43	0.44	0.45	0.51	0.51	0.57	0.58	0.68	0.62	0.68	0.78	1.04	1.20	2.35

Fig (5) Location of points on the soil surface and the values of acceleration.

2.1 Tank-soil Couple:

To examine the interaction effects of the model from soil and tank, the inequality's Veletsos for inertial interaction compliance must be satisfied according to Eq. (1) [14]:

$$\textbf{(1)}\quad \frac{h}{V_S.T}\sqrt[4]{\frac{h}{r}} > 0.125$$

Table(3) properties of soils

Soil type	*Vs (m/sec)*	*Density (kg/m3)*	Ed (Mpa)	Poisson ratio (v)	Internal cohesion angle (°)	Dilation angle (°)	Cohesion Stress (Kpa)
S1	700	2350	2880	0.27	36	6	196.2
S2	200	2000	238	0.3	25	0	55

The h (m) represents the height of the tank, r (m) is the radius of the tank foundation, Vs (m/sec) is the shear wave velocity of the soil and T(Sec) refers period of the tank in fixed state, In the studied cases, after apply the invariants of this inequality is equal to 0.27 and 0.40 for Tank T1 and Tank T2, respectively. Therefore, since the inequality is not satisfied for the soil structure model, the interaction effects can be further explored. The tank-soil interaction is considered using type "surface to surface" contact formulation with friction coefficient (µ) equal to 0.484 for soil type S1 and equal to 0.311 for the soil type S2 between soil and tank surface.

2.2 Soil properties:

The Mohr-Coulomb criterion is used to describe and model the nonlinear behaviour of soil. Although there are advanced collapse criteria for soil, the applications of such models may create significant complications in dynamic analysis. Therefore, the Mohre-Coulomb criterion was adopted in this study to create a balance between accurate and inexpensive analysis. To evaluate the effect of the characteristics of the soil on the seismic response of ground cylindrical tanks, two types of soil were adopted in this paper, soil (S1) The height of the soil layer is (Hs=30 m). The fundamental period is equal to (T=4H/Vs). The damping ratios (ξ) can be assumed of two types of Soil at 5% and the same value of the earthquake. Damping arises from the main components of the soil (viscosity, plasticity) and has a major role in determining the mode of the dynamic response under seismic loads. In Abaqus, the damping is in the form of Rayleigh damping coefficients. The damping matrix as in Eq. (2) in Rayleigh damping is a linear combination of mass-proportional and stiffness-proportional terms:

$$[C] = \alpha[M] + \beta[K] \qquad \text{bb} \qquad \textbf{(2)}$$

[C] present the damping matrbbbix, [M] the mass matrix, and [K] the stiffness matrix. The Rayleigh damping coefficients (α, β) are used to specify the model damping ratio. These coefficients are calculated from relation Eqs. (3) and (4) Ju & Ni [13]:

$$\alpha = (2\omega_1\, \omega_2\, (D_1\, \omega_2 - D_2\, \omega_1))/((\omega_2^2 - \omega_1^2)) \qquad \textbf{(3)}$$

which has the shear wave velocity (Vs=700 m/sec) can be classified as S_C according to the Syrian Code. On the other hand, S2 which has the shear wave velocity (Vs=200 m/sec) can be classified as S_D according to the Syrian Code. Table.3 shows the two types of soils S1 & S2 have been examined in this study.

$$\beta = (2(D_2\, \omega_2 - D_1\, \omega_1))/([\pi(\omega_2^2 - \omega_1^2)]) \qquad \textbf{(4)}$$

$\omega_1 = 2\pi f_1$, $\omega_2 = 2\pi f_2$,where ω_1, and ω_2 are the soil and earthquake frequency respectively. D_1 and D_2 are the soil and earthquake damping ratios, respectively.

In this paper, the gravity load of fluid, tank, foundation, and soil field is defined. In addition, the seismic excitation applies as boundary condition at the bottom surface of the soil domain, the three seismic records are investigated to study the seismic response and the effect of interaction between the soil and structure. Fig.6. [17] present the seismic records Northridge, IONIAN, and San Francisco have different values of peak ground acceleration (PAG): 0.56, 0.24 and 0.105, respectively.

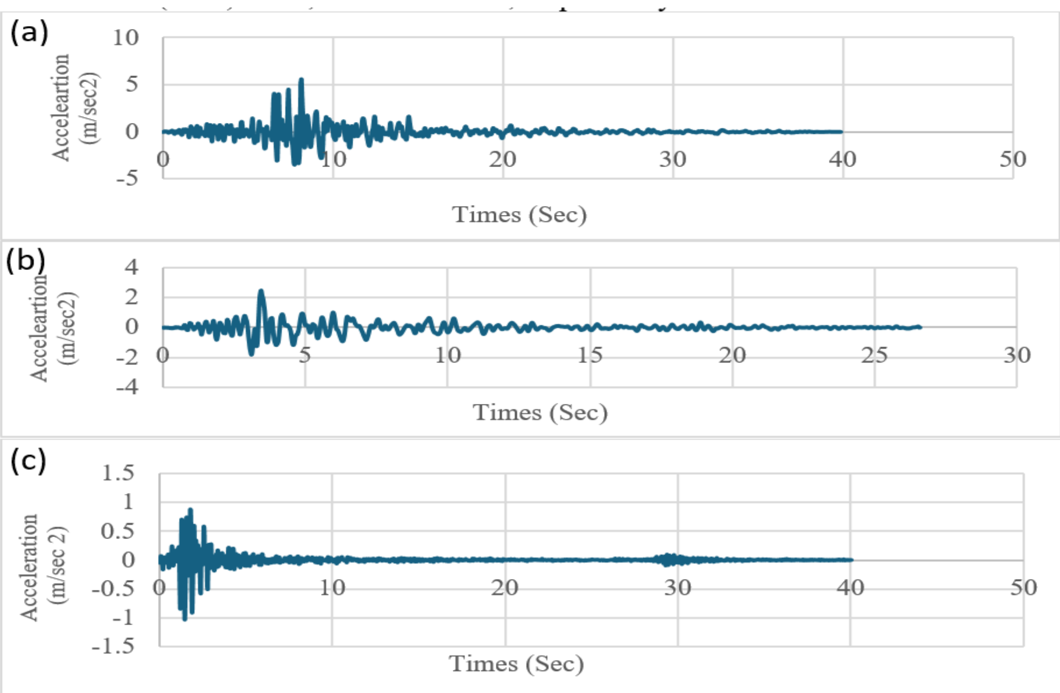


Fig (6) The seismic records (a) Northridge – (b) IONIAN (c) San Francisco [17].

3. Discussion of Result

3.1 shear force:

The comparative analysis of shear forces for cylindrical tank models situated on hard soil (S1) versus silty gravel soil (S2) under seismic excitation reveals significant insights into the influence of soil characteristics on tank performance. Considering the effects of soil structure interaction in dynamic analysis, cylindrical water tanks have become a critical issue to ensure economical and safe design. As can be seen in Fig.8 Shear forces of the studied cases decrease with the increase of soil flexibility due to the increase in the natural period of structures. But this result should not be generalized when considering the frequency content, damping properties of earthquakes and soil, and the interaction between the fluid and the tank.

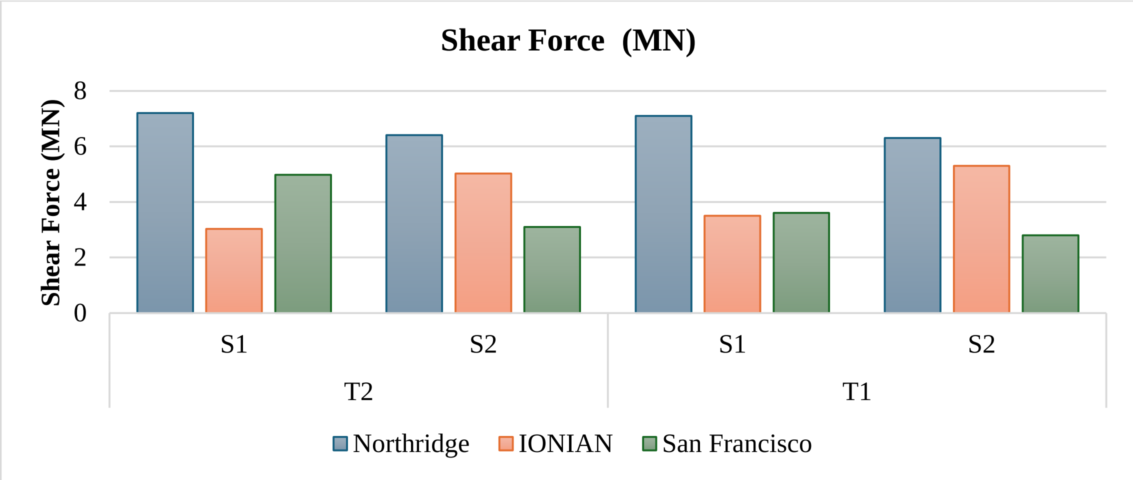


Fig (7) Shear Force for T1 & T2 for two types of Soil during three seismic records.

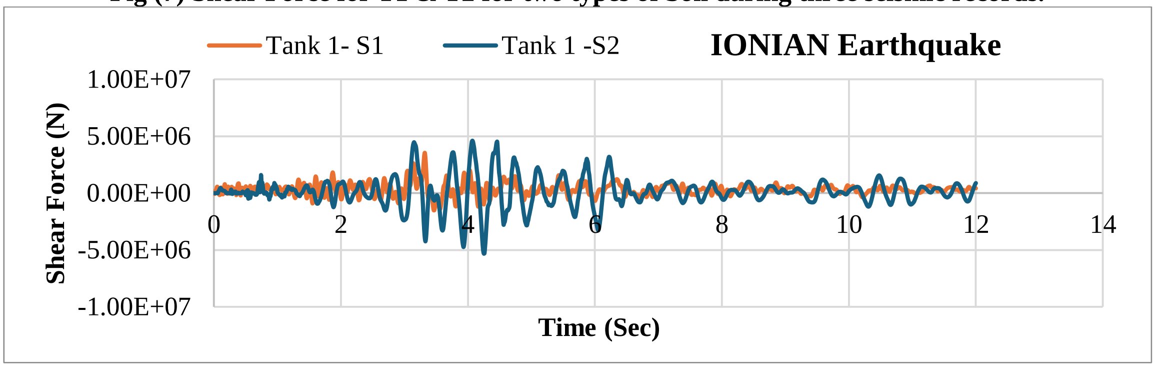
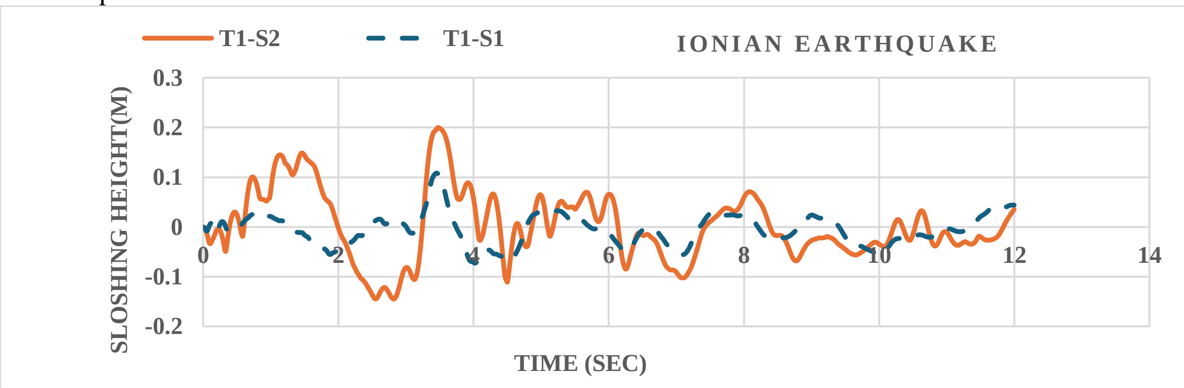


Fig (8.) The shear force during the period of IONIAN record Tank T1 two types of Soil.

Fig(7) shows the value of shear force for both types of Tanks (T1 & T2) and two types of soil S1 & S2. It was observed that the shear forces of the Northridge earthquake were larger than those of the IONIAN and San Francisco earthquakes for all studied cases of both soils S1& S2 and tanks T1 & T2 due to higher PGA of the Northridge earthquake. Compared to the values of Northridge, the decreased value was about 11 % in the silty soil from hard soil for both tanks (T1 &T2). These indicate effective energy dissipation mechanisms at play, particularly in the soil condition (S2). The reduction in shear force suggests that the Soil and Tank experienced some level of damping, which is beneficial for structural stability. Also, During the San Francisco earthquake, the shear force decreases in silty soil by about 22% for T1 and about 35 % for T2. Fig.8 shows a different response compared to the Northridge event while the shear force increases from S1 (hard soil) to S2 (silty gravel soil) by about 51% during the Ionian earthquake. During seismic events, such as the Ionian earthquake, the amplification effect significantly increases the base shear experienced by structures. The nature of the seismic waves generated by different earthquakes can also influence the response of tanks on varying soil types. The Northridge, San Francisco and the Ionian earthquake have different frequency content and ground motion characteristics.in this state, the Ionian earthquake produced certain frequency waves, these could resonate more effectively with the natural frequencies of structures built on silty gravel soil, leading to amplify and increase shear forces.

3.2 Sloshing Height:

In this research, the sloshing height at the left end of the free surface of the tank was examined. The analysis of sloshing height in cylindrical water tanks subjected to seismic excitation reveals significant differences between tanks situated on hard soil (S1) and silty gravel soil (S2) under the influence of the Northridge, San Francisco, and Ionian earthquakes. The results in Fig.10 indicate that tanks on silty gravel soil (S2) experienced markedly higher sloshing heights compared to those on hard soil (S1). The maximum value of sloshing height appears in the high slender ratio of the tank and in the records that have high peak ground acceleration (PGA). Fig.9 shows the change of sloshing height during the period of the Ionian earthquake for the tank T1. The maximum value for the soil S1 (11 cm) corresponds at the same time to the maximum value for soil S2 (20 cm) by increasing the ratio about 82%. This interaction between the tank and the surrounding soil can lead to a more significant relative movement between the tank and the ground, which can amplify sloshing. The dynamic response of the tank is affected by the soil's ability to absorb and dissipate seismic energy, which is less effective in silty gravel soils, leading to higher sloshing heights.in addition, the soil that has lower stiffness like (S2) allows for more deformation during seismic events, this flexibility can lead to increased lateral movements of the tank and amplifying the sloshing effect. The flexibility of tank's walls contribute to higher sloshing heights as the fluid interacts more dynamically with the tank structure.



Fig(9) The Sloshing Height during the period of seismic for T1 in soil types (S1& S2).

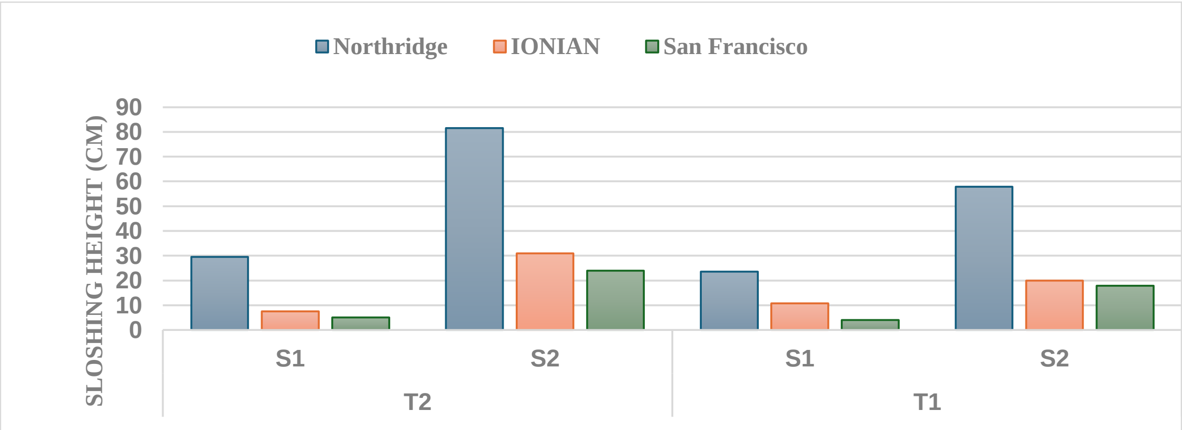


Fig (10)The Sloshing Height for T1&T2 for two types of Soil during three seismic records.

3.3 Displacement:

The maximum displacement responses at the selected node d at the top right wall (see Fig.13) of tank is calculated. Fig.11 presents the displacement of the tank wall in tank T1 for two soil conditions S1 & S2 during period of San Francisco earthquake. The maximum displacement for soil S1 is 0.9 cm at 0.67 sec, while in S2 arrived at 3.2 cm at 1.02 sec increasing about 3.5 times. Also, Fig.12 presents the values of maximum displacement wall for three seismic excitation, two types Tanks T1 & T2 and Two condition S1 &S2. All cases indicate to increase the displacement in silty soil by a high percentage. Many factors collectively contribute to an increase in the maximum displacement response in tanks founded on S2 soils during seismic events. The flexibility and lower stiffness allow for more significant relative movement between the tank and the soil beneath it under seismic loads. Also, the complex interaction between the fluid and the tank is very important. It contributes to the overall displacement response and leads to increased wall displacements. The fluid's inertia can exacerbate the effects of ground motion, particularly in softer soils where the tank may sway more freely.

In addition, silty soil can amplify seismic waves and cause larger forces to be transmitted to the tank walls, resulting in greater displacements compared to tanks on hard soil, where the seismic waves are less amplified. The dynamic response of tanks on soft soil is often characterized by longer periods of vibration. This can lead to resonance effects during seismic events, where the natural frequency of the fluid-tank system aligns with the frequency of the ground motion, resulting in amplified displacements.

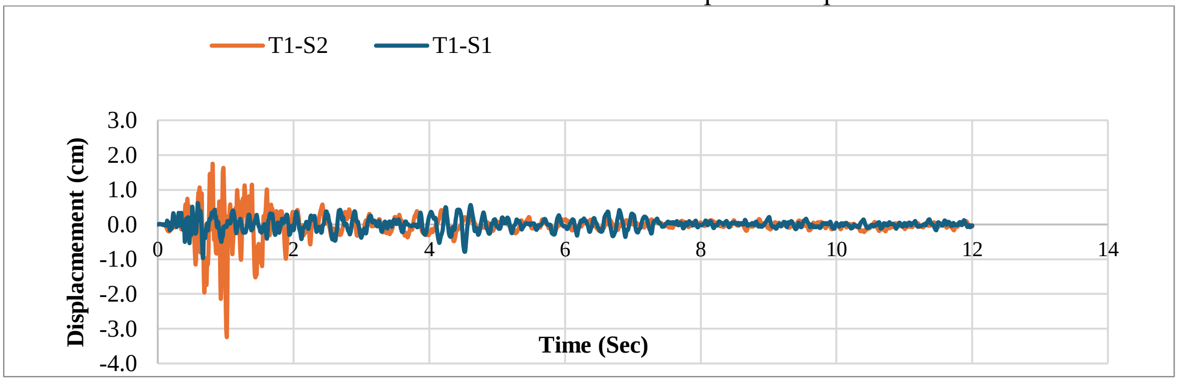


Fig 11) The displacement of tank walls T1 during the San Francisco earthquake.

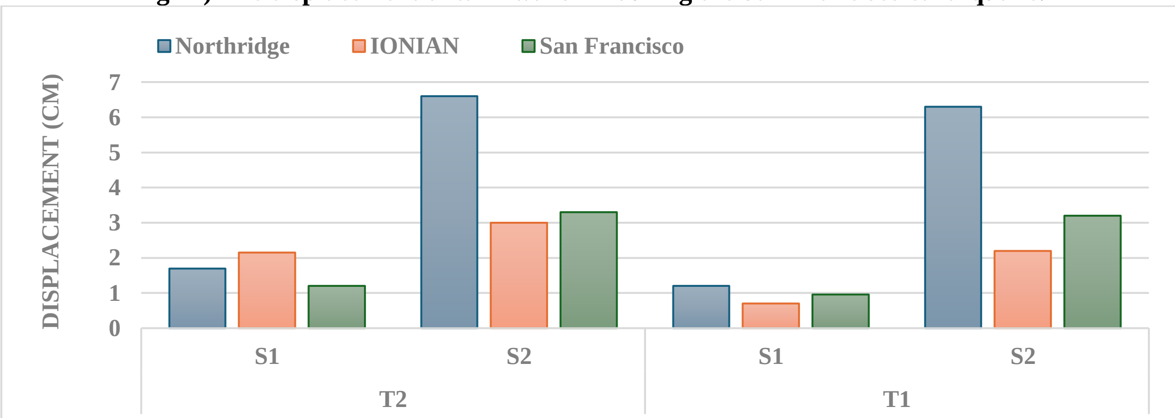
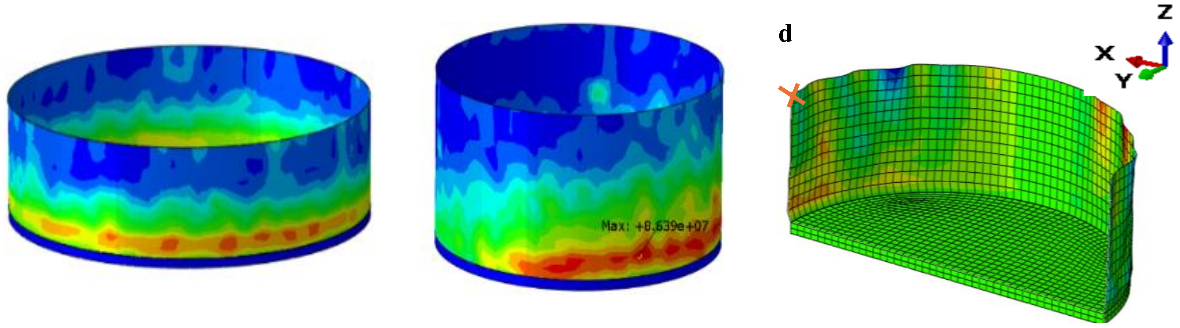


Fig (12)The displacement of tank walls for all studied cases.

While the displacement of the wall increases in the silty soil, the stress values increase also. Because the deformation of the wall tanks causes a high value of stress. The maximum value of the stress appears in the bottom part of the wall which can lead to local buckling phenomena (e.g., elephant foot failure that may occur during seismic events. The rapid changes in pressure and the inertial forces acting on the liquid can lead to increased local stresses and deformation at the base of the tank where the tank is supported. **These stresses can lead to elastic-plastic buckling)** for both T1 & T2. Fig.13 presents the numerical model which shows the stress concentration zones.



Fig(13) shown the zone of stresses in two tanks (T1 & T2) and the location of Node d.

According to previous results, this underscores the necessity for a nuanced understanding of soil-tank interaction and the interaction between the Fluid and tanks, as the choice of soil type significantly influences shear force, sloshing height, displacement and stress distribution, and overall structural performance during seismic events. In addition, the type of soil is probably the most critical parameter to be evaluated for the effect of soil structure interaction.

4. Conclusions:

In this paper, a Ground-supported steel cylindrical tank considering fluid -tank -Soil interaction was investigated. The finite element method by using explicit analysis in Abaqus is used. The result of two soil conditions and two different slender ratios (T1 & T2) and three seismic excitations are examined. The conclusion of this study can be summarized as the following:

1- The shear force for the tanks T1 and T2 during Northridge and San Francisco decreased in silty gravel soil from the hard one. The percentage of this decreased by about (11%) for both T1 & T2 and about (22%, and 35%) for T1 and T1 respectively. In contrast, during IONIAN earthquake, the shear force increases in silty gravel soil conditions by about 51%, and 62 % for T1 and T2 respectively. This difference clears the importance of the content frequency for seismic wave and the role of damping of soil in amplifying the forces.

2- The sloshing height at the free surface of the fluid is increased in silty soil (S2) by about 3 times for tank T1 and about 2.5 times for tank T2 in comparison to the hard soil (S1). The values of sloshing increased with an increase in the slender ratio of tanks and with an increase in the PGA of seismic excitation.

3- As the soil gets softer, the displacement increases in comparison to the hard one. This result shows that the silty gravel soil amplifies the deformation of the element tank during seismic events.

4- The results of the displacement of the tank wall at the top of the wall and displacement along the height of the wall have appeared to decrease the value of displacement for Soil S1 of Soil S2. The same percentage has been observed for all the studied records. Also, the stresses increased with the increase the displacement.

It is advisable to analyze and evaluate additional numerical examples across various soil types and seismic records to estimate the ratio of amplification in forces and displacement in many types of soil.

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