THE EFFECT OF TOPOGRAPHIC IRREGULARITIES ON SEISMIC RESPONSE OF CONCRETE RECTANGULAR TANKS

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ABSTRACT

In this study, the finite element method is used to investigate the seismic behavior of concrete rectangular liquid tanks located on topographic irregularities in two-dimensional space with considering soil-structure-liquid interaction. In order to evaluate the effect of topographic irregularities, flat and inclined soil surfaces are taken into account. Also, two soil types corresponding with soft soil and stiff soil are studied. For evaluate the effect of earthquake frequency content, three different ground motions with various ratio of peak ground acceleration (PGA) to peak ground velocity (PGV) are applied in analyses. It is assumed that tank is rigid and fixed to the ground. Also, for considering the effect of the presence of liquid on the tank response, full tank and empty tank are studied. By using these different parameters, some comparisons are made on sloshing responses, tank wall displacement and base shear forces. The results showed that amplification due to topographic irregularities has significant effect on tank response. Furthermore, it is concluded that earthquake frequency content considerably affect the dynamic behavior of the liquid tanks.

Keywords: Seismic Response; Rectangular Tank; Soil-structure Interaction; Topographic Irregularities; Sloshing

1. INTRODUCTION

Liquid storage tanks are one of the most important structures which extensively used across the world during the recent decades. Since these structures are widely used in chemical fluids and water supply facilities, oil and gas industries and nuclear plants, safe design of these structures is essential. Evidence from recent strong ground motions showed that these structures were very vulnerable to seismic excitations. Collapse of the tank, uncontrolled fires, spillage or leakage of dangerous chemical liquids and shortage of drinking water were damages which reported from past earthquakes such as 1994 Northridge and 1999 Kocaeli (Cakir and Livaoglu 2012). Housner (1963) by using lumped mass approximation which herein hydrodynamic pressures were separated into impulsive and convective components, investigated the dynamic behavior of liquid storage tanks. Minowa (1984) by using experimental studies evaluated the seismic characteristics of various rectangular storage tanks. Livaoglu (2008), by using Housner’s two mass approximations, investigated the dynamic behavior of a rectangular tank and concluded that soil stiffness has significant effect on the base shear forces and displacements. Ghaemmaghami and Kianoush (2009) evaluated the effect of wall flexibility on the dynamic response of rectangular liquid storage tanks. Also, they studied the effect of earthquake frequency content on the dynamic response of rectangular tanks incorporating soil-structure interaction. Empirical evidence of recent earthquakes showed that topographic irregularities may induce amplification and even de-amplification ground motions. Numerical, analytical and experimental studies have been conducted both in the observation and evaluation of these effects. Studies performed by Trifunac and Hudson (1971), Boore (1972) and Celebi (1987), were the first studies in this field. Graizer (2009) studied the 1987 Whittier Narrows and the 1994 Northridge earthquakes and conducted

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that combined effects of topography and layering caused the observed amplification. Numerical studies by using different applicable approaches such as finite element method (FEM), finite difference method (FDM) and boundary element method (BEM) have been conducted in order to investigate the effect of topographic irregularities on the seismic response of different sites and structures. Oprsal and Zahradnik (2002) studied the seismic amplification of topographic irregularities by using finite difference method. Also, several researchers such as Wong and Jennings (1975), Nguyen and Gatmiri (2007) and Kamalian et al (2007) by using boundary element method, investigated the topographic effects on seismic motions. Examples of finite element method includes the works by Moczo et al (1997) and Athanasopoulos (2001).

Observations from recent earthquakes caused the researchers to investigate the effects of waves motion pattern on structures built on the slopes. With considering this fact that numerous liquid storage tanks are located on these sites, evaluating the seismic response of these structures are essential.

The aim of this paper is to evaluate the effects of surface topography on seismic response of concrete rectangular storage tanks incorporating soil-tank-fluid interaction. To this end, several parametric studies have been conducted in 2-D space using the finite element method.

2. PROBLEM STATEMENT

In this paper the parametric study was conducted using an implicit nonlinear finite element analysis software; ANSYS 17.2. In order to investigate the effect of topographic features on the seismic response of concrete rectangular storage tanks, two models are considered. At the first phase, the seismic behavior of the tanks located on top of the step-like slope are studied and in the second phase, the responses of the tanks located on the flat ground surface are investigated (see Figures 1 and 2).

![Figure 1. The schematic 2D model of the tank located on step-like slope](image)

Two different model configurations associated with slender and broad tanks are taken into account. For considering the effect of the presence of fluid on the tank response, empty tank and full tank are studied. Also, in order to evaluate the effect of earthquake frequency content on tank responses, three different ground motions with different frequency content are taken into account. Finally, results of both phases
would be compared to each other.

3. NUMERICAL SIMULATION

3.1 Soil medium

In this study, soil is considered as a homogeneous, inelastic and semi-infinite medium. For evaluating the effect of soil stiffness, two types of soils are taken into account. The properties of selected soils are shown in Table 1.

Table 1. Properties of the soil types considered in this study

<table>
<thead>
<tr>
<th>Soil</th>
<th>Young modulus E (Mpa)</th>
<th>Shear modulus G (Mpa)</th>
<th>Density ρ (kg/m³)</th>
<th>Poisson’s ratio υ</th>
<th>Shear wave velocity Vₛ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>3330</td>
<td>1280.76</td>
<td>2000</td>
<td>0.3</td>
<td>800</td>
</tr>
<tr>
<td>S3</td>
<td>206</td>
<td>76.29</td>
<td>1900</td>
<td>0.35</td>
<td>200</td>
</tr>
</tbody>
</table>

The soil medium is modeled by using four-node isoparametric element (PLANE42). This element has swelling, plasticity, large deflection and large strain capabilities. Figure 3 shows the geometry of this element. Also, for simulating topographic irregularities, step-like slop with \( \frac{H}{B} = 2 \) (SL2) is considered. Herein, H is slope height and B is slope width (see Figure 4).

Figure 3. The geometry and coordinate system for the PLANE42 element

Figure 4. Dimensions of the considered step-like slope (SL2)

3.2 Boundary conditions

For absorbing propagated waves and prevent the reflection, spring-dashpot system are set on the model edges (see Figure 5). These boundaries are simulated by using spring-damper element (COMBIN14).
This element has torsional and longitudinal capability in 1-D, 2-D, or 3-D applications. The geometry and the coordinate system of this element are shown in Figure 6.

![Figure 5. Two-dimensional boundary conditions at the model edges](image)

![Figure 6. The geometry of the COMBIN14 element](image)

The following relations can be used for computing their coefficients (Wolf 1985):

\[
C_h = \rho \times C_P \times A
\]

\[
k_h = \frac{G \times A}{B}
\]

\[
C_v = \rho \times c_s \times A
\]

\[
k_v = \frac{G \times A}{L}
\]

Where \(k_h\), \(c_h\), and \(k_v\), \(c_v\) are horizontal and vertical components of stiffness and damping, respectively. Also, \(B\) is soil height, \(L\) is soil length, \(A\) is the element length which the spring-damper act on it, \(\rho\) is soil density, \(G\) is shear modules of soil, \(c_s\) is shear wave velocity and \(c_p\) is longitudinal wave velocity of soil.

### 3.3 Tank

Two different model of tank associated with slender and broad tanks are considered (see Figure 7). Also, for considering the effect of the presence of fluid on the tank response, full and empty tanks are studied.
The fluid domain is modeled by using four-node element (FLUID79). A schematic view of this element is depicted in Figure 8. The properties of considered tanks are shown in Table 2.

Table 2. Properties of considered tanks

<table>
<thead>
<tr>
<th>Tank Configuration</th>
<th>Tank Length (m)</th>
<th>Wall Height (m)</th>
<th>Fluid Depth (m)</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broad</td>
<td>10</td>
<td>5</td>
<td>4</td>
<td>T0.5</td>
</tr>
<tr>
<td>Slender</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>T1</td>
</tr>
</tbody>
</table>

3.4 Input motions

The ratio of peak ground acceleration to peak ground velocity is a good indicator of the frequency content (Zhu et al 1988). According to this criteria, earthquake records may be classified into three categories, low frequency content when $\frac{PGA}{PGV} < 0.8$, intermediate frequency content when $0.8 < \frac{PGA}{PGV} < 1.2$ and high frequency content when $\frac{PGA}{PGV} > 1.2$. In this study, for evaluating the effect of earthquake frequency content on the seismic response of storage tanks, three different earthquake ground motions are applied in finite element analyses. For comparing the models in the same conditions, all excitations are scaled in such a way that the PGA reach 0.1g. The characteristics of the selected input motions are shown in Table 3.

Table 3. The characteristics of considered ground motions
4. VERIFICATION

Since there are two cases of problems related to topographic irregularities and soil-tank-fluid interaction, thus two kinds of verifications have been carried out regarding these two subjects.

4.1 Topographic irregularities verification

As the first verification, a study of Dravinski and Mossessian (1987) was simulated in order to evaluate if the present model works well for simulating the amplification due to topographic irregularities. Figure 9 shows a semi-circular canyon subjected to ricker-wavelet in order to achieve to surface amplification.

Soil domain is considered homogeneous and shear wave velocity is taken as 120 (m/s). The dimensionless frequency η is selected as 0.5 ($\eta = \frac{\omega r}{\pi c_s} = 0.5$). Where $\omega$ is the angular frequency of the excitation and $r$ is the radius of the canyon. Figure 10 shows the results which is obtained from present study and also the results from Dravinski and Mossessian (1987). This figure shows a good agreement between the results.

4.2 Soil-tank-fluid (STF) verification

The second verification is a study which has been conducted by Livaoglu (2008). In this study, concrete storage tank is subjected to 1999-kocaeli earthquake excitation. Geometry of the consider tank has been depicted in in Figure 11.
Figure 1. Geometry and characteristics of the considered rectangular tank (Livaoglu (2008))

Figure 12 shows the finite element model of soil medium and concrete rectangular tank in two-dimensional which are considered in this study. With considering 1999 Kocaeli earthquake as excitation and soil type 3, Figure 13 shows the sloshing response of the concrete tank which is investigated by present study and the results from Livaoglu (2008). This figure shows a good agreement between the obtained results.

Figure 12. Finite element model of two-dimensional soil medium and rectangular tank

Figure 13. Maximum sloshing response of present study and the results from Livaoglu (2008)

5. RESULTS AND DISCUSSIONS

According to Figure 14, comparisons between results in all models are made on sloshing response (section A), tank wall displacement (section B) and base shear forces of the tank (section C). It should be noted that maximum values of sloshing response and tank wall displacement are corresponding with points 1 and 2, respectively.
5.1 The effect of topographic irregularities on the sloshing response

Results corresponding with sloshing response of the tank located on step-like slope and the tank located on the flat ground surface related to broad tank and slender tank configurations are depicted in Figure 15 and Figure 16, respectively.

According to figures 15 and 16, in all cases of soil type 3 (S3), sloshing responses of the tank which is located on the slope is higher than the tank located on the flat ground surface. The maximum increment is related to the 1999-Kocaeli ground motion which is in low frequency excitation category. On the other hand, it would be well received that topographic irregularities doesn’t have significant effect on sloshing response in stiff soils such as soil type 1 (S1).
5.2 The effect of topographic irregularities on the tank wall displacement

Figures 17 and 18 show wall displacement values of broad and slender tank with considering full tank configuration, respectively. It should be noted that the results related to empty tanks are presented in figures 21 and 22 of Appendix.

As can be seen from the figures, in all cases maximum wall displacements of the tank which is located on the slope is higher than the tank located on the flat ground surface. This increment in low frequency excitation is more significant.

5.3 The effect of topographic irregularities on the base shear forces

Base shear forces values of the tank located on top of the slope and the tank located on flat ground surface related to full broad and full slender tank configurations are depicted in Figure 19 and Figure 20, respectively. It is worth mentioning that the results related to empty tanks are depicted in figures 23 and 24 of Appendix.

It is obvious that base shear forces of the tank which is located on the step-like slope is significantly higher than the tank located on the flat ground surface. Also, according to results from the different soil types, it would be well received that decreasing the soil stiffness leads to increasing the seismic amplification. Thus, soil type has been a considerable effect on the seismic amplification.
In order to assess the effect of topographic irregularities on seismic response of concrete liquid storage tanks, several time-history analyses are carried out with considering several parameters such as two soil type, two tank configuration and three ground motions. Also, for investigating the effect of the presence of fluid on the tank response, full and empty tank are taken into account. Soil-tank-fluid interaction is modeled using direct method with an appropriate boundary condition. Comparisons are made on the maximum sloshing response, maximum tank wall displacement and base shear forces.

Considering the effect of SSI, the results show that the sloshing response and tank wall displacement generally increased, when soil gets softer. The rate of this increment becomes larger under input motions with low frequency content. In the other words, the changes in the soil stiffness doesn't have considerable effect on tank wall displacement and sloshing response under high frequency earthquakes. Since the weight of the empty tank is less than full tank, in the same conditions, the maximum base shear of the full tank is higher than empty tank. Also, according to the hydrodynamic pressure, wall displacement of the full tank is higher than the empty tank. Since the predominant periods of low frequency excitations are close to those of liquid storage tanks, these excitations highly magnify the seismic response of the system. The results of this study show that amplification due to topographic irregularities increases all the responses of the tank particularly on the soil type 3. Sloshing response increases about 12.95% and 13.74% for broad and slender tank, respectively. Tank wall displacement increases approximately as much as 81.53% and 48.4% for broad and slender tank, respectively. Base shear forces are considerably affected by site amplification. In a way that this increment due to soil type varied from 103.36% to 703.71%.

It is clear that the seismic response of storage tanks depends on numerous parameters such as earthquake frequency content, tank configuration and soil conditions. This study shows that topographic irregularities due to site amplification has significant effect on seismic response of the tank which should be considered in current codes.
7. REFERENCES

ANSYS, R., ANSYS Mechanical APDL, Product Release 17.2 (2016).


8. APPENDIX

Figure 21. The maximum wall displacement of empty broad tank model

Figure 22. The maximum wall displacement of empty slender tank model

Figure 23. Comparisons of base shear forces of empty broad tank models

Figure 24. Comparisons of base shear forces of empty slender tank models