

MULTI-PHYSICS COUPLING METHOD AND APPLICATIONS OF FLUID-STRUCTURE INTERACTION ON LNG STORAGE TANKS

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Abstract. The Liquefied Natural Gas (LNG) storage tank is stored in specially engineered and constructed double-walled structure which are essential for receiving and safe storage of the liquid gas. The 160000m³ LNG storage tank has 800mm thick post-tensioned concrete walls on the exterior and the inner tank is made of a special steel/nickel alloy to accommodate cold LNG. In this study, a finite element modeling method for fluid-structure interaction (FSI) is proposed and the multi-physics coupling method of the fluid and structure is used to investigate the aseismic behavior of the 160000m³ LNG storage tanks. By using this modeling method of FSI, a finite element model for the tank is established mainly by the FLUID80 elements and SHELL181 elements based on software ANSYS. The characteristics of natural vibration for the LNG tank is obtained by taking the reduced method for modal analysis. The results show that there are generally three kinds of vibrational mode types including convective mode, circular multi-wave mode and impulsive mode. Several published experimental results have been used to verify the multi-physics coupling method and the results are almost identical with the computational results. As one of the applications of the FSI method, the dynamic responses of the LNG tank structures under seismic excitation can be obtained 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. The results of research can provide a reference for the design and construction of LNG tank structures.

1 INTRODUCTION

Over the past few decades, world consumption of liquefied natural gas (LNG) has increased more than five-fold and it is predicted that this growth will continue to be very strong. The growing demand from large markets such as China and India combined with the increasing popularity in a large number of other smaller markets has resulted in the development of many new LNG facilities throughout the world. The LNG is stored in specially engineered and constructed double-walled storage tanks which are essential for

receiving and safe storage of the liquid gas. The growing world-wide use of LNG has seen the development of significant LNG storage tank facilities for LNG exporters and importers. However, unexpected structural failure of such huge structures by earthquakes may result in not only severe environmental contamination but also tremendous loss of human and financial resources. In order to ensure the safety of the LNG storage tanks, an earthquake-proof structural design is a matter of primary concern. For such an earthquake-proof design, the accurate free vibration characteristics analysis and seismic analysis with reliable earthquake record are of a great importance.

Arya *et al.* ^[1] have studied the dynamic characteristics of liquid containers fixed at the base and free at the top. Virtual mass due to the liquid has been considered but sloshing effect has not been taken into account. Veletsos and Yang ^[2] developed flexible anchored tank linear models and found that the pressure distribution for the impulsive mode of rigid and flexible tanks were similar, but also discovered that the magnitude of the pressure was highly dependent on the wall flexibility. The fluid tank system was treated as a single degree of freedom system in terms of the lateral displacement of the tank at the free surface level. The fluid inertial effect was considered by means of an added mass. The study has been restricted for impulsive load only. Haroun ^[3] have studied the dynamic characteristics of a ground supported cylindrical tank due to earthquake motion. Natural frequencies of vibration and the associated mode shapes are found though the use of a discretization scheme in which the elastic shell is modeled by finite elements and the fluid region is treated as a continuum by boundary solution techniques. Babu and Bhattacharyya ^[4] developed a numerical scheme using finite element technique to calculate the sloshing displacement of liquid and pressure developed due to such sloshing. Using the developed computer code, they found that the pressure developed in a liquid filled container due to sloshing and the displacement of the container wall considering fluid-structure interaction effect.

This paper presents a finite element (FE) method for the analysis of the storage tanks mainly by using the FLUID80 elements and SHELL181 elements based on software ANSYS ^[5]. Besides, this modeling method for fluid-structure interaction (FSI) is verified by several published experiments. The free vibration characteristics analysis and seismic analysis have been done as the applications of this method, and the results of research can provide a reference for the design and construction of LNG tank structures.

In this study, the time history response of the LNG storage tank is obtained using the transient dynamic analysis technique. The unidirectional horizontal seismic excitation is applied to the structure by using El-Centro earthquake motion and Taft earthquake motion. The study includes the coupling between the impulsive response of the liquid and the shell and also the sloshing effects. An accurate model is also established considering the influence of pile-soil interaction, compared to the model of the tank fully anchored to the rigid foundation.

2 FINITE ELEMENT METHOD

The general purpose software ANSYS is used to implement FE analyses. As the thickness of the outer tank is 800mm which is very little compared to the height and diameter of the out tank, a 160000m³ liquid-filled LNG tank is modeled and FE analyses are conducted using SHELL181 elements for the structure of tank and FLUID80 elements for the LNG.

The FLUID80 element uses the displacements as the variables in the fluid domain. These elements are considered as an extension of structural solid elements in which the element shear modulus is set to zero and the fluid bulk modulus K is used to establish the elastic stress–strain relations. FLUID80 elements are particularly useful in modeling fluids contained within vessels having no net flow rate and can be employed for transient as well as free vibration analyses. Also it is particularly well suited for calculating hydrostatic pressures and fluid–solid interactions including acceleration effects, such as in sloshing problems, as well as temperature effects. The stress–strain relationships used to develop the stiffness matrix and thermal load vector are as follows:

$$\begin{Bmatrix} \varepsilon_{\text{bulk}} \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{xz} \\ R_x \\ R_y \\ R_z \end{Bmatrix} = \begin{Bmatrix} 3\alpha\Delta T \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix} + \begin{bmatrix} \frac{1}{K} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{S} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{S} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{S} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{B} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{B} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{B} \end{bmatrix} \begin{Bmatrix} P \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{xz} \\ M_x \\ M_y \\ M_z \end{Bmatrix} \quad (1)$$

Where: $\varepsilon_{\text{bulk}}$ =bulk strain= $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}$, α =thermal coefficient of expansion, ΔT =change of temperature from reference temperature, K =fluid elastic (bulk) modulus, P =pressure, γ =shear strain, $S=K \times 10^{-9}$ (arbitrarily small number to give element some shear stability), τ =shear stress, R_i =rotation about axis , $B=K \times 10^{-9}$ (arbitrarily small number to give element some rotational stability), M_i =twisting force about axis i .

A damping matrix of the element is also developed based on:

$$\begin{Bmatrix} \dot{\varepsilon}_{\text{bulk}} \\ \dot{\gamma}_{xy} \\ \dot{\gamma}_{yz} \\ \dot{\gamma}_{xz} \\ \dot{R}_x \\ \dot{R}_y \\ \dot{R}_z \end{Bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{\eta} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{\eta} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{\eta} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{c} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{c} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{c} \end{bmatrix} \begin{Bmatrix} P \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{xz} \\ M_x \\ M_y \\ M_z \end{Bmatrix} \quad (2)$$

Where: η =viscosity, $c=0.00001 \times \eta$, and the $(\dot{\quad})$ represents differentiation with respect to

time.

The element also includes special surface effects, which may be thought of as gravity springs used to hold the surface in place. This is performed by adding springs to each node, with the spring constants being positive on the top of the element, and negative on the bottom. This expression is generalized to be as follows:

$$K_s = \rho A_F (g_x C_x + g_y C_y + g_z C_z) \quad (3)$$

Where: A_F = area of the face of the element, g_i = acceleration in the i direction, C_i = i th component of the normal to the face of the element.

When coming to the multi-physics coupling method of modeling the LNG tank and contained LNG, this paper introduces the direct coupling method as following. Shell element should be meshed in such a way that the location of each node of the fluid element on the interface coincides exactly with that of the corresponding shell element. Then, these coincident nodes must be coupled in the direction normal to the interface in order to get equal displacements in the radial direction for both fluid and shell nodes located on the interface. Tangential relative displacements, however, should be possible to happen and therefore, no coupling needs to be assigned in any other direction.

When considering the influence of pile-soil interaction, the most reliable method for evaluating the survivability of structures under extreme earthquake shaking is to carry out inelastic dynamic analyses of detailed structure-foundation models, using several earthquake records selected on the basis of site-specific seismicity studies. For systems with a large number of degrees of freedom, however, solutions of this type can be extremely expensive. Therefore, the discrete-element formulations have been used in the finite element model, in which the near-field soil can be divided into layers and nodal points may be selected along the piles at the middle of each layer^[6]. The near-field soil elements (spring-dashpot elements) can simulate the force-deformation characteristics of the surrounding soil and energy dissipation due to material and radiation (geometric) damping.

The BEAM188 element is used for modeling the piles of the LNG tanks, additionally, the COMBIN39 elements and COMBIN14 elements are used as the spring-dashpot elements for calculating the pile-soil interaction. When calculating the force-deformation characteristics of the surrounding soil, the API RP 2A-WSD^[7] is used. The lateral bearing capacity for soft clay, stiff clay and sand is provided by constructing lateral soil resistance deflection (p - y) curves using stress-strain data from laboratory soil samples. The free-field amplification is carried out separately by the software DEEPSOIL and then use the resulting motions at the elevations of the near-field elements as input.

3 FINITE ELEMENT METHOD VERIFICATION

To verify the finite element method, the free vibration response of a small-scale aluminum cylindrical tank is obtained using the current finite element method and the results are compared with the experimental values obtained by Wan Shui^[8]. In his study, the free vibration results of the tank shown in Figure 1 were obtained by experimental method. The material properties of the tank: young's modulus is 60 GPa; poisson's ratio is 0.35; density is 2800 kg/m³. Other geometric properties not given in Figure 1 are as follows: the width of stiffening rib is 28 mm; stiffening rib thickness is 3 mm; shaft thickness: tank thickness is 1

mm; tank floor thickness is 3 mm. The finite element model is established based on the experimental tank used by Wan Shui.

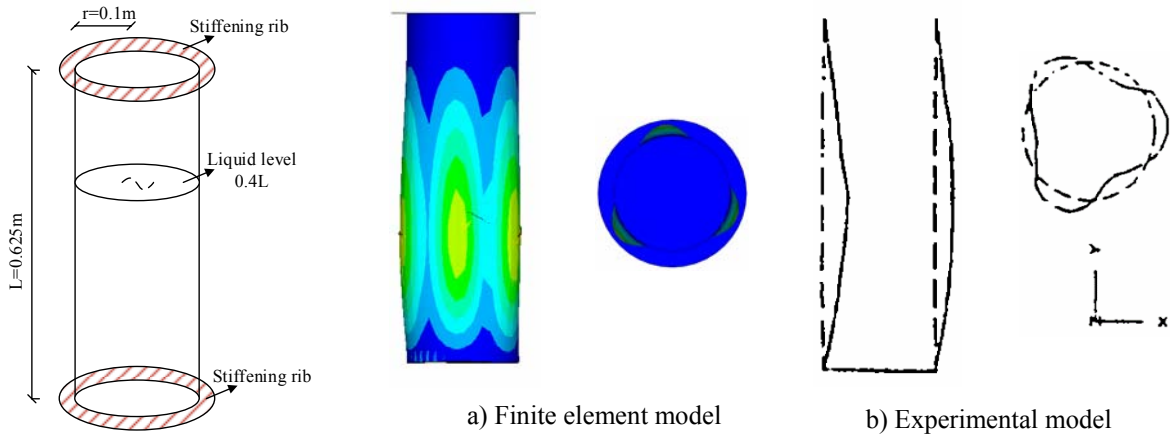


Figure 1: Tank model geometry

Figure 2: The results of finite element model and experimental model

As shown in Figure 2, the first mode of the liquid-shell mode is 129.98Hz for experimental result and 138.55Hz for numerical result, and the mode shapes are also almost the same. The obtained finite element results are in excellent agreement with experimental results verifying that the current method can be employed with high accuracy to study the fluid–structure interaction problems of liquid-containing structures.

4 FE MODEL FOR LNG TANK

The LNG storage tanks with the full capacity of 160000m³, which are the most common used in practice^[9], are specially engineered and constructed aboveground with double walls (800mm thick post-tensioned concrete walls on the exterior and the inner tank is made of a special steel/nickel alloy). The simplified geometry of the tank is indicated in Figure 3. As shown in the Figure 3, the height of inner tank is 36.315m, the diameter is 80m, and the thickness is about 20mm; the height of 800mm thick post-tensioned concrete outer wall is 82m. Besides, the top level of liquid is 34.978m when the LNG is stored in inner tank, and top level of liquid is 33.4m when the LNG is leaked into outer tank.

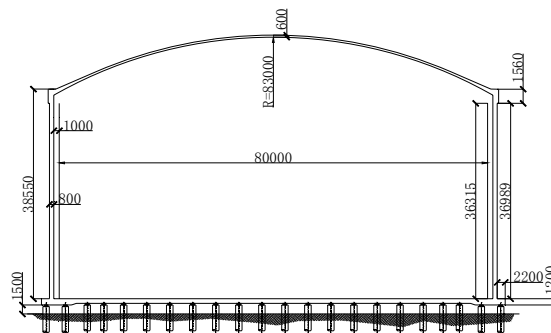


Figure 3: LNG tank geometry

As shown in Figure 3, there is a ring beam at the top of the outer wall, and four buttresses 90 degrees from each other. The dome of the tank is a concrete shell of 600mm thick. The foundation of LNG tank is pile foundation, and the bottom of the tank is elevated for 1.5m.

The Bulk modulus (K) of $3E9$ Pa and the density of 450 kg/m^3 are used for the LNG. Concrete and steel elements are modeled as nonlinear plastic material according to code for design of concrete structures ^[10] and code for design of steel structures ^[11]. The material properties of steel and concrete are indicated in Table 1.

Table 1: Material properties of steel and concrete

Steel material	Concrete material
Young's modulus = 206 GPa	Young's modulus = 32.4 GPa
Poisson's ratio = 0.30	Poisson's ratio = 0.2
Density = 7850 kg/m ³	Density = 2500 kg/m ³

According to the direct coupling method introduced previously, to couple the liquid nodes located at the wall of LNG tank with tank structure, first, the coordinates of the fluid and shell nodes should be rotated in the cylindrical coordinate system ensuring that all nodes are aligned perpendicular to the circle shell. Then, the rotated nodes can be coupled in the direction normal to the surface. Moreover, all fluid nodes located at the interface with the tank's floor should be restrained in vertical direction.

First, the tank is assumed to be fully anchored to the rigid foundation, as a result the tank model is of the hinged boundary condition at the base in model 1. Then, since the LNG storage tanks are mostly built on the seaside for the transport and safe storage of LNG, Pile foundations are generally used to support the tanks on soft soil with low bearing capacity. The pile-soil interaction is taken into consideration when establishing the model 2 of the tank, and in model 2 the LNG is leaked into outer tank completely. In this passage the soil is assumed to involve two kinds of soil, one is soft clay at the shallow depths and the other is sand at deep depths. The FE configuration of the LNG tank model 1 and model 2 are indicated in Figure 4 and Figure 5.

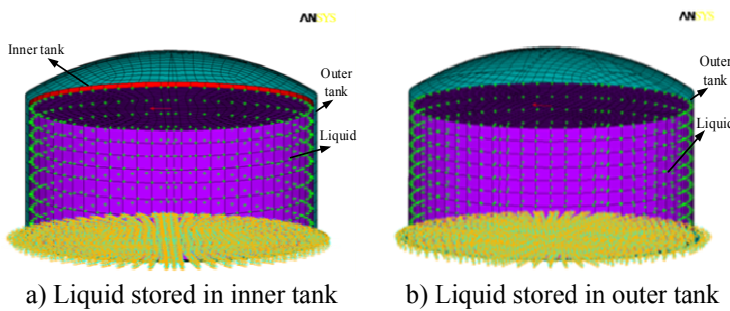


Figure 4: The FE model 1

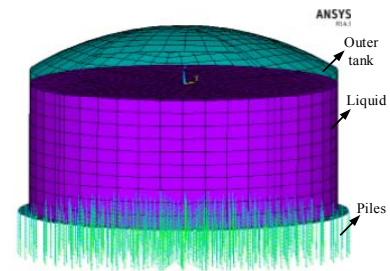


Figure 5: The FE model 2

5 RESULTS OF ANALYSIS

5.1 Free Vibration Analysis of Model 1

The calculated results of the model 1 through free vibration analysis are shown in Table 2, 3 and Figure 6, 7, 8.

The free vibrational modes of a cylindrical tank can be classified as sloshing, circular multi-wave and impulsive modes. The lower frequency sloshing modes of the contained liquid illustrated in Figure 6(a), 6(b), 7(a), 7(b) and 8(a), 8(b), besides the circular multi-wave types are shown in Figure 6(c), (d), 7(c), 7(d) and 8(c), 8(d) for which the deflection of the shell involves a number of circumferential waves. In addition to the mode types mentioned previously, there are the impulsive modes shown in Figure 6(e), 6(f), 7(e), 7(f) and 8(e), 8(f), which can be denoted beam-type modes because the tank behaves like a vertical cantilever beam as the impulsion of the contained liquid.

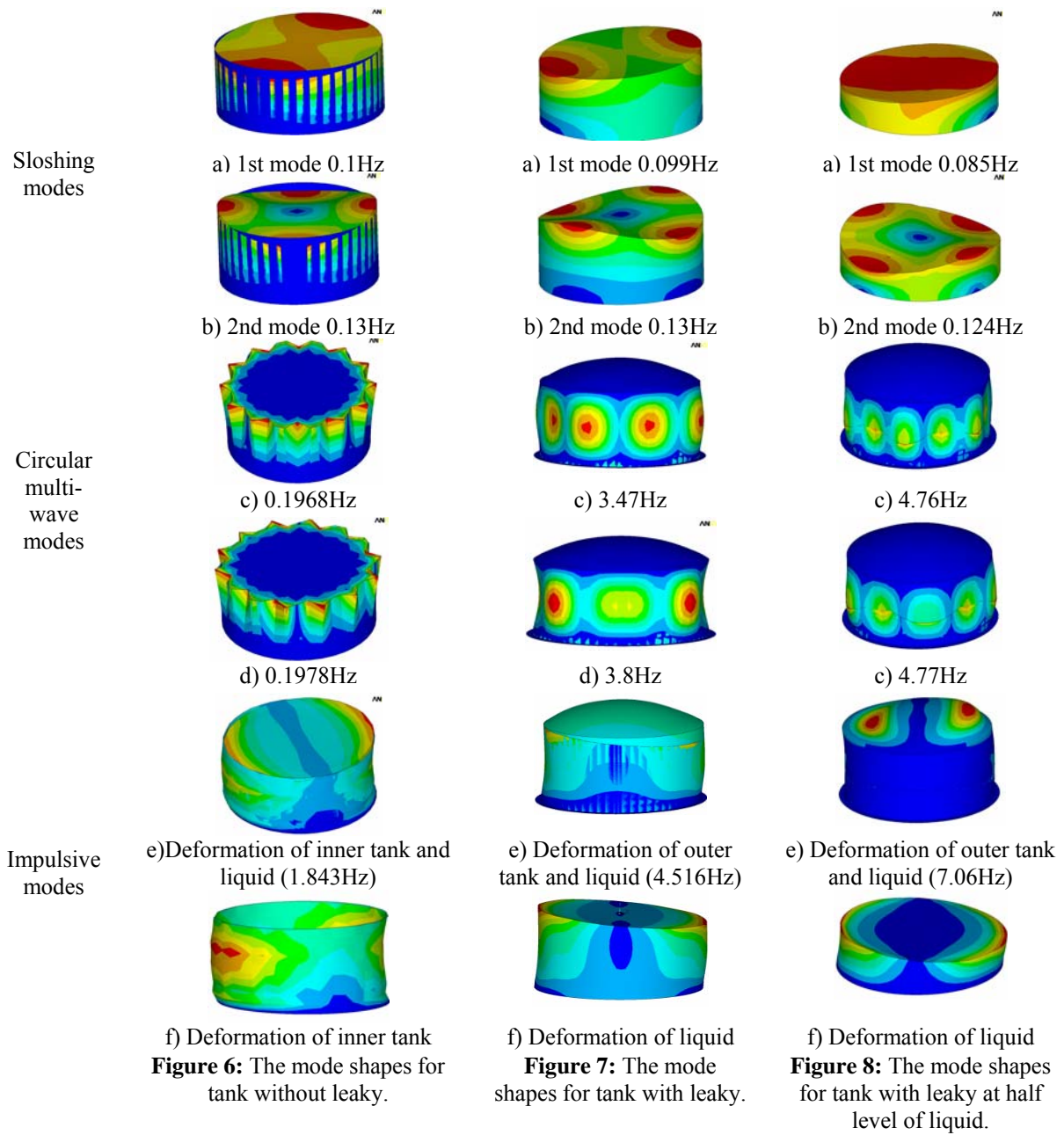
What's more, the fundamental sloshing and impulsive modes are identified as those with the largest effective mass in the horizontal X direction. In Table 2 and 3, as can be seen, the first sloshing mode and impulsive mode are the fundamental sloshing and impulsive modes of the tank.

Table 2: Free vibration analysis results for the tank model without leaky.

Number	Mode Type	Frequency (Hz)		Effective mass (kg)
		FE	Ref. [12]	
1	Sloshing mode	0.1	0.1	2.98×10^7
2		0.134		2.19×10^{-9}
3		0.151	NA	1.8×10^{-10}
4		0.156		5.85×10^3
1	Circular multi-wave modes	0.1968	NA	7072.84
2		0.1978		16124.3
1	Impulsive modes	1.843	2.13	3.672×10^7

Table 3: Free vibration analysis results for the leaky tank model

Number	Mode Type	Frequency (Hz)		Effective mass (kg)
		FE	Ref. [12]	
1	Sloshing mode	0.099	0.1	2.003×10^7
2		0.132		3.88×10^{-11}
3		0.1493	NA	1.90×10^{-9}
4		0.1551		8004
1	Circular multi-wave modes	3.47	NA	8.52×10^{-5}
2		3.8		5×10^{-11}
1	Impulsive modes	4.516	5.26	5.63×10^7



As can be seen, the FE results are in reasonable agreement with those calculated from the reference [12], so the results are reasonable and reliable. Moreover, comparing the sloshing modes illustrated in Figure 6(a), 6(b) and 7(a), 7(b), both the mode shapes and the mode frequency are almost the same when calculating the sloshing mode of the inner tank and outer tank. The sloshing modes are mainly associated with the liquid level and the geometry of liquid contained in the tank, and don't care what the stiffness of the tank is.

As shown in Figure 8, when the LNG tank is leaky at half level of liquid, the height of liquid is 16.7m, the frequency of sloshing mode is 0.085Hz, 14% drop comparing with 0.099Hz of tank with leaky at top level. The mode of frequency 4.76Hz is circular multi-wave

mode, and the frequency of impulsive mode is 7.06Hz, increasing 56% comparing with 4.516Hz of tank with leaky at top level. The modes of LNG tank which is of leaky at half level are almost the same with the empty situation as the volume of liquid becomes smaller.

5.2 Free Vibration Analysis of Model 2

The FE model 2, as shown in Figure 5, takes both the fluid-structure interaction and the pile-soil interaction into account. As the sloshing modes don't change with different stiffness of the tank, the sloshing modes are the same when considering fluid-structure interaction of the structure.

First, the LNG tank model with only the pile of 1.5m out of the ground is under consideration using element beam188 for pile. The results are illustrated in Figure 8 and 9. The first liquid-shell mode is circular multi-wave mode with the frequency 3.316Hz, 4.3% drop comparing with 3.47Hz of model 1. The frequency of the impulsive mode is 4.06Hz, 10% drop comparing with 4.516Hz of model 1. In conclusion, the free vibration characteristic of the LNG tank structure with pile of 1.5m and without considering pile-soil interaction is similar to model 1.

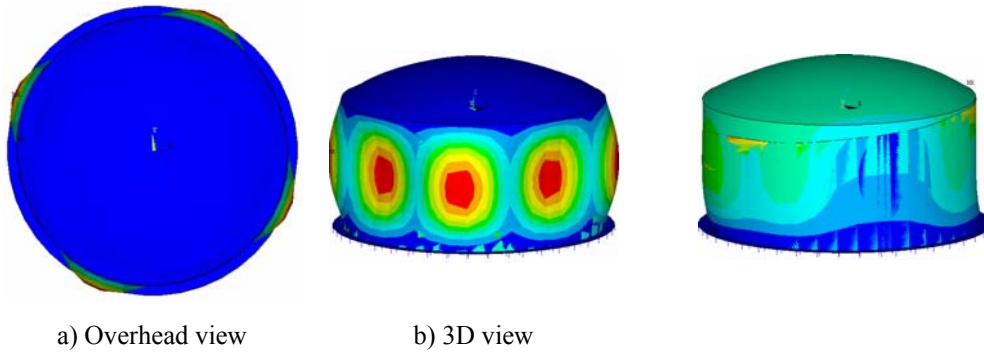


Figure 8: The first liquid-shell mode shape

Figure 9: The impulsive mode shape

Then, the whole pile is under consideration for the FE model, and the spring-dashpot elements are used for simulating pile-soil interaction. As mentioned previously, the length of the whole pile is 10m, and the soil contains soft clay at the shallow depths and sand at deep depths. Assume that the angle of internal friction of sand (φ) is 28~40 degree, the cohesion of clay (C) is 20-80KPa, and the depth of clay changes from 1m to 5m. The frequency of first liquid-shell mode is listed in Table 4 and the mode shape is shown in Figure 10.

Table 4: Frequency of first liquid-shell mode

Depth of Clay (m)	Frequency (Hz)			
	$\varphi=28^\circ, C=20\text{KPa}$	$\varphi=40^\circ, C=20\text{KPa}$	$\varphi=28^\circ, C=80\text{KPa}$	$\varphi=40^\circ, C=80\text{KPa}$
1.0	1.6903	2.622	1.7635	2.6395
2.0	1.6746	2.5336	1.8124	2.5691
3.0	1.6459	2.3942	1.8395	2.4524
4.0	1.6139	2.2295	1.8533	2.3181
5.0	1.5856	2.0598	1.8599	2.1878

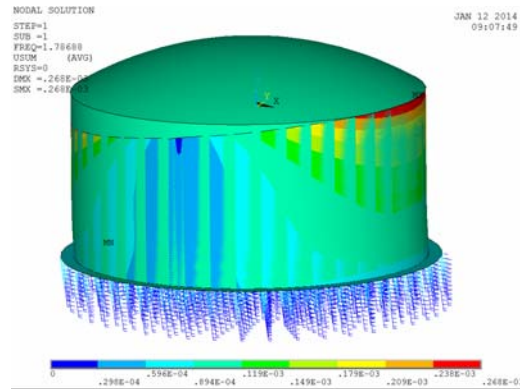


Figure 10: Mode shape of the first liquid-shell mode

As can be seen, the first liquid-shell mode of model 2 is impulsive mode for which the effective mass is 9.18×10^7 kg, 66% to total mass, shown in Fig 8. Moreover, the maximum frequency is 2.6395Hz which is 41% drop comparing with 4.516Hz of model 1. The results show that: after calculating the pile-soil interaction, the lateral bearing capacity of the tank structure above the ground becomes lower, and the period of impulsive mode is longer; besides, the seismic force on the LNG tank structure becomes smaller, which is conducive to resist earthquakes. Hence, the pile-soil interaction is sensitive for the vibration characteristic for the LNG tank structure, which if considered in seismic design of buildings will reduce the earthquake force of the structures.

6 CONCLUSIONS

- In this paper, a fine FE method was employed to study the fluid–structure interaction for liquid-filled LNG tanks, and the pile-soil interaction was also under consideration for the pile foundation of tank structure. The liquid inside the tank was modeled using FLUID80 elements, and the COMBIN39 elements and COMBIN14 elements were used as the spring-dashpot elements for calculating the pile-soil interaction.
- The results of the modal analysis considering the fluid–structure interaction for LNG tanks show that the free vibration modes of the LNG tank were classified as the sloshing, the circular multi-wave and the impulsive mode, respectively. Besides, the first sloshing mode and the impulsive mode were identified as the fundamental mode.
- When the LNG tank are leaky at half level of liquid, the sloshing mode frequency of structure decreased 17.6%, and the impulsive mode frequency of structure increased 56%.
- When the pile-soil interaction was taken into consideration in the modal analysis, the frequency of impulsive mode was almost half of that in the model which is of the hinged boundary condition. As a result, the great influence of pile-soil interaction can't be ignored for the vibration characteristic and aseismic design of the LNG tank structure.

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