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Research Article

The Mechanical Response Analysis of Large Horizontal LNG Storage tank

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Abstract: As a clean and efficient energy, LNG (Liquefied Natural Gas) is using on a big scale. For storage LNG, the design of the horizontal LNG storage tank is developing to large size and complicated functions. Under the earthquake, the destruction of storage tank will lead to explode, leak and make serious losses. Based on this present situation, for 463m^3 large horizontal LNG storage tank, this paper established finite element models that one has no water and one has 50% water, and analyzed model analysis and seismic response. Researching on the influence of water sloshing on structure, the results shows, the structural free vibration period is larger without water, and when storing water, the water sloshing reduces the structural free vibration period efficiently. The seismic response analysis shows, horizontal tank structure's response under the earthquake is not only related to the dynamic performance of the structure itself, but also related to the characteristics of seismic wave.
Keywords: large horizontal tank, finite element model, model analysis, seismic response.

INTRODUCTION

Due to using LNG is safe and convenient, and easy to storage and transport, the requirement of LNG is increasing rapidly, so for storing LNG, the requirement for tank is increasing to and developing to large size. According to the structural type, tank can be divided into vertical and horizontal. For large volume of low temperature storage tank, the designers usually choose the horizontal. In 1914, the U.S.A published the first patent of LNG and built a small LNG industry.

Japan is the largest LNG importer country and its import volume accounts for 40% of the world. And Japan is one country with building lots of large storage tanks in the world [1]. South Korea has begun to import of LNG in 1986, and its LNG industry has been rapid development. At present, South Korea has built 36 LNG tanks and 12 tanks is under construction [2, 3]. Compared with other countries, China's LNG industry has just started. The LNG receiving stations that are planning and building by China are more than 40 [4].

The study of Chinese designers for LNG horizontal tank is only calculation and analysis under static force without performance analysis under earthquake. It is estimated that the energy when a 160000m^3 LNG storage tank was full of liquid is 76 bigger than that in Hiroshima atomic bomb [5]. Because of this present situation, time-procedure analysis was carried out on the large horizontal LNG storage tank on the basis of the static analysis in this paper, as to provide theoretical basis for engineering application.

The establishment of finite element model

Large horizontal LNG storage tank is made up of inside container, shell, shell insulation, road line, saddle, etc.

Because the actual large horizontal LNG storage tank has lots of part, and its structure is large and complex, the modeling and analysis calculation of ADINA is complex, what we should first do before doing simulation is that make reasonable simplification in the horizontal LNG storage tank [6, 7].

1）For facilitating calculation, the inside container and the shell will be calculate as a whole in this paper, the allowable stress is 180N/mm^2. 2) These small parts will be ignoring that has low stress and make less influence on structural strength. 3) The whole model will be simplified to symmetric structure. 4) The actual weld parts and the surrounding condition are complex, so it will be not consider some problems that welds bring to horizontal model.

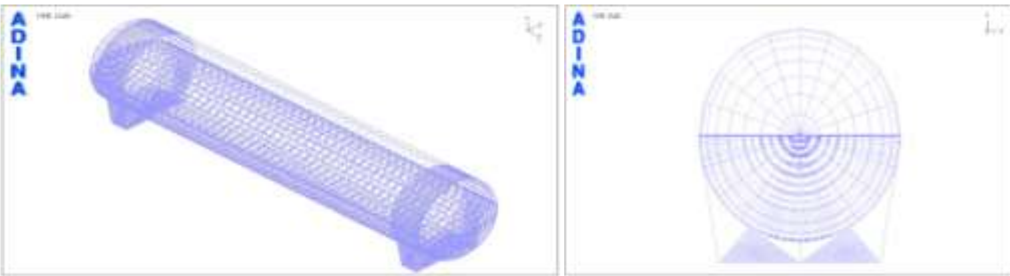
Tank capacity is 463m^3, cylinder diameter 5 m, cylinder length is 22 m, and this is no change along the length. The shell cover's thickness is 26mm and depth is 1.2 m. Specific related dimensions as shown in table 1.

The material of cylinder and shell over was Q345. Considering the material nonlinear; this paper used the bilinear strengthening model. The liquid in the tank was LNG. Saddle material was 16Mn.

Table 1: Geometric parameters of tank

Parts	Parameters of tank	Size（mm）
Shell cover	Depth H_i	1200
	Thickness T_f	26
Cylinder	Length L	22000
	Diameter D_i	5000
	Thickness t	24

Finite element model was established according to the size of the structure and materials. The tank stored LNG, assuming liquid was potential fluid. The boundary between liquid and solid was set for the liquid-solid coupling; its basic theory was consisted of fluid mechanics and solid mechanics [8]. Defined boundary conditions according to the actual constraints of storage tank, one saddle was set to full constraints, and the other saddle on the other side was set to the vertical, horizontal and three rotational constraints. After meshing, the finite element model of horizontal tank was shown in figure 1.



（a）horizontal tank grid model （b）the side view of horizontal tank model

Fig-1: 50% liquid of LNG horizontal storage tank finite element model

The dynamic characteristics analysis

In actual test shows that in the model analysis, the damping has little impact on the natural frequency and vibration mode of structure, so we don't consider the effect of damping. Modal analysis solving process without damping is as follows.

$$([K]-\omega_i^2[M])\{\mu_i\}=\{0\} \qquad (1)$$

Which, $[K]$——Stiffness matrix, $[M]$——Mass matrix, $\{\mu_i\}$——The first order modal modal vector, ω_i ——The first order natural frequency of the modal.

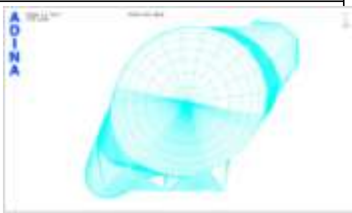
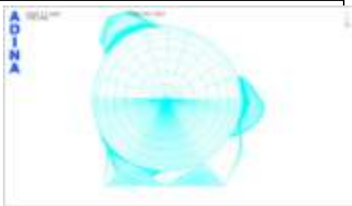
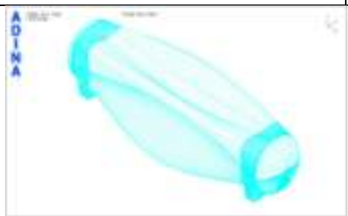
In ADINA, modal extraction methods have determinant-search method; the Subspace Iteration method and the Lanczos Iteration method. In this paper, the finite element model is belong to large symmetric eigen value problem. Considering the liquid level of liquid sloshing in the liquid storage tanks, we need to extract the low frequency vibration of liquid and the vibration of outer tank's high frequency, thus using the Lanczos Iteration method [9].

Modal analysis of storage tank without liquid

Analyzing large horizontal LNG storage tank model, table 2 shows the mode of vibrations and the side view of the large horizontal LNG storage tank wall in empty tank (we only shows pictures that have a significant vibration shape.)

It can be seen form table 2 that different natural frequencies had the different modes in horizontal LNG storage tank model. In this example, the first inherent vibration mode that was inspired was 2 waves vibration of storage tank in direction of ring, the third order natural vibration mode was the 3 waves vibration of storage tank in the ring direction, after that the wave vibration in ring direction was not obvious. The wave's number of eighth order natural vibration mode was similar to that in the third order natural vibration mode, and the nine and ten order natural vibration mode were the 4 waves vibration of storage tank in the ring direction.

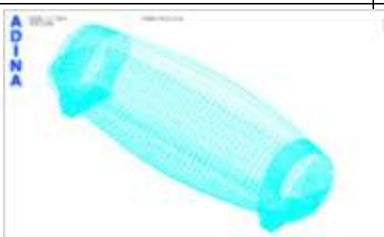
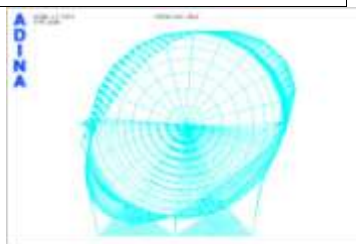
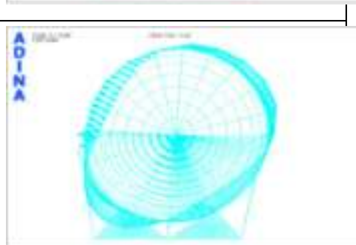
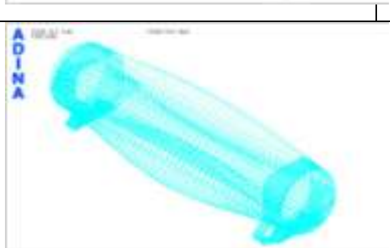
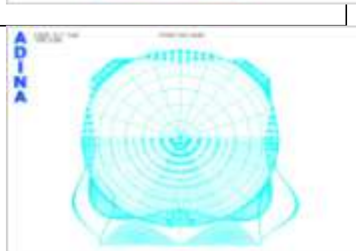
Table 2: mode of vibrations of large horizontal LNG storage tank without liquid

Order(n)	mode of vibration	side view
The first order vibration mode Frequency: 7.674 Hz		
The third order vibration mode Frequency: 9.285 Hz		
The ten order vibration mode Frequency: 15.92 Hz		

Modal analysis of storage tank with 50% liquid

Table 3 shows the mode of vibrations and the side view of the Large horizontal LNG storage tank wall with 50% liquid.

Table-3: mode of vibrations of large horizontal LNG storage tank with 50% liquid

Order(n)	mode of vibration	side view
The first order vibration mode Frequency: 2.09Hz		
The third order vibration mode Frequency: 2.332Hz		
The ten order vibration mode Frequency: 2.387Hz		

The mode of vibration in tank with 50% liquid was mainly shown in mode of vibration in liquid. Compared with the frequency of LNG tank without liquid, the sloshing frequency of tank with 50% liquid was lower than the tank without liquid, and the period of tank with liquid was long.

The table 2 and 3 results showed that when tank without liquid, the basic frequency of outside tank was 7.674Hz, when tank with 50% liquid, the basic frequency of outside tank was 2.09Hz.Through the frequency calculation to tanks with no liquid and 50% liquid, we can conclude that the frequency of empty tank was taller than that in tank with 50% liquid, and the period of empty tank was smaller. Its illustrate that liquid had much influence on Natural vibration characteristics of the storage tank system. When the tank had a half of liquid in itself, the overall flexibility was improved a lot, it was equal to increase the liquid constraints in the inside of that tank.

THE EARTHQUAKE RESPONSE ANALYSIS

Adopted the acceleration seismic ground motion method, we selected classic waves (including two natural waves and one artificial wave), made the earthquake excitation on the large LNG horizontal tank, and researched on seismic response of large LNG horizontal tank.

The adjustment of the peak acceleration formula is 2.

$$A'(t) = \frac{A'_{max}}{A_{max}} \times A(t) \qquad (2)$$

Which, $A'(t)$ ——seismic wave curve, A'_{max} —— the structure's maximum value of the seismic ground motion in frequent earthquake and rare earthquake under the fortification intensity. A_{max}、 $A(t)$ ——the original seismic wave curve and the maximum value.

In earthquake acceleration time history curve, the maximum acceleration peak values for calculating were unified adjustment to 70 cm/s^2 under 8 degree frequent earthquakes. In front of inputting the seismic ground motion, we should process 10s preloading under static load, then calculate earthquake in restart procedure.

The analysis of the displacement

Table-4: The maximum value of the horizontal tank's peak displacement under different earthquake waves

direction	seismic wave	Space of time(s)	Lasting time(s)	peak displacement(m)	Time that peak displacement occurred(s)
X axis	EL wave	0.02	10	1.319E-3	12.26
	Taft wave	0.02	10	1.317E-3	14.24
	artificial wave	0.02	10	1.236 E-3	19.26

The horizontal tank's maximal displacement appeared in the middle of tank. Because under the action of earthquake, the upper tank shaking and the middle part don't have constrains, these generate larger relative displacement. Through finite element software, we found that node 22590 which self-weight was the biggest had 9E-4 m initial negative X direction displacement. EL wave displacement peak appeared on the largest seismic ground motion. And Taft wave displacement peak appeared in 14.24 s, compared with the seismic waveform, we found that in 14.24s, the vibration was very strong, close to the maximum value. The maximum relative displacement was 4.3E-4 m in X direction, its was far less than the displacement value that design requirements. From table 4, we easily found that even in different earthquake types, under the same intensity, the peak displacement was very close; the error was within 1%.

The analysis of the acceleration

In El-centro wave, Taft wave and artificial wave, the maximum acceleration value of the horizontal tank peak acceleration time history curve as shown in table 5.

Table-5: the maximum value of the horizontal tank's peak acceleration under different earthquake waves

direction	seismic wave	Space of time(s)	Lasting time(s)	peak acceleration (m/s2)	Time that peak acceleration occurred(s)
X axis	EL wave	0.02	10	-0.859	12.26
	Taft wave	0.02	10	0.694	14.24
	Artificial wave	0.02	10	1.257	15.00

In the initial stages of earthquake wave, under the different kinds of seismic waves, the acceleration of a horizontal tank had the same change trend, after that shown a different state of vibration? In Horizontal tank, the absolute maximum acceleration value of X direction was in -0.69m/s^2-1.26m/s^2. Peak acceleration appeared on the node 22626, where saddle joint tank. On the X direction, due to the effect of the saddle, the maximum acceleration appeared in the stress concentration. Generally, maximum acceleration peak value appeared near the maximum acceleration of earthquake. But the maximum acceleration of Taft wave appeared in 14.24s, the time was same with the maximal displacement appeared and the appearing location was very close.

The analysis of equivalent stress

In El-centro wave, Taft wave and artificial wave, the maximum equivalent stress nephogram of the horizontal storage tanks was respectively shown in figure-2, 3 and 4

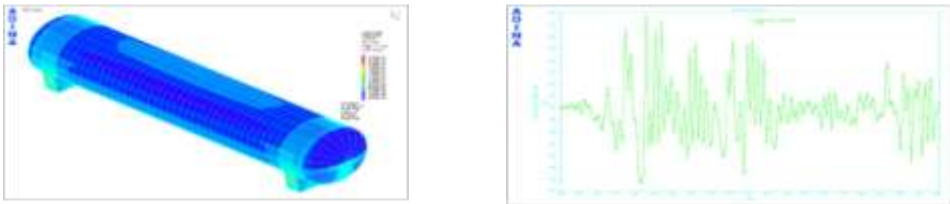


Fig. 2: The horizontal tank equivalent stress nephogram in El-centro wave

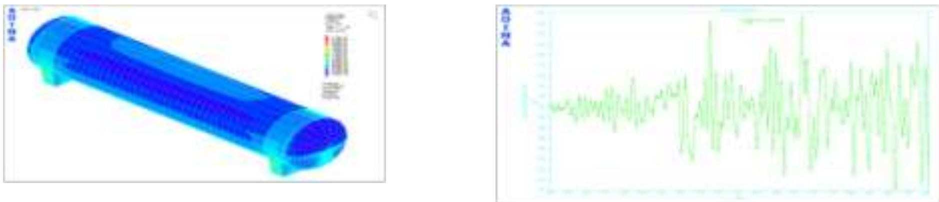


Fig.3: The horizontal tank equivalent stress nephogram in taft wave

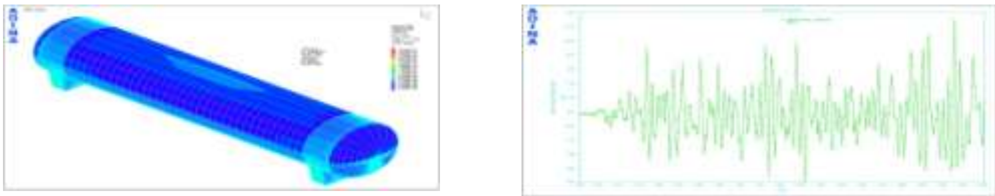


Fig. 4 the horizontal tank equivalent stress nephogram in artificial wave

From the equivalent stress nephogram fig. 2 to 4 under the seismic ground motion in the X direction, the distribution of equivalent stress were basically identical, and maximum value appeared in the junction and local parts of saddle. It is not being ignored that the X direction earthquake wave had an effect on the junction and local parts of saddle.

The maximum value of equivalent stress was 23.96 MPa in EL wave, the maximum was 23.95 MPa in Taft wave and the maximum was 24.03 MPa in artificial wave. ALL of the maximum values were large, we shouldn't ignore. Above all, it proved that the saddle form, especially the connection ways had significant effect on the horizontal tank under earthquake. The saddle of horizontal tank can be selected based on article [10], we can according to the nominal diameter of equipment to select standards of saddle.

The analysis of axial stress

The horizontal tank axial stress nephogram , respectively, as shown in figure 5 ,figure 6 and figure 7.

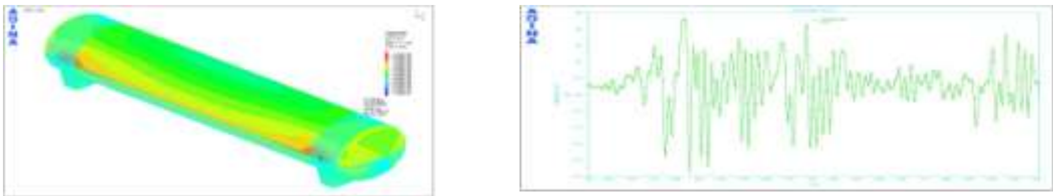


Fig. 5 the horizontal tank axial stress nephogram in EL-centro wave

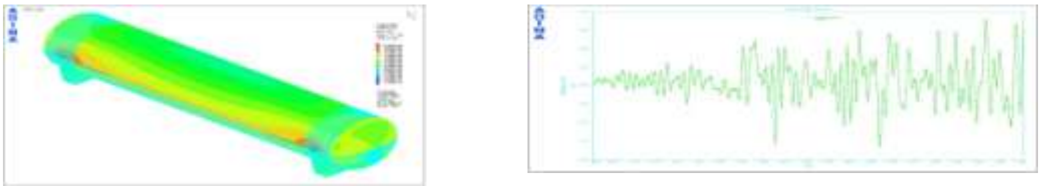


Fig. 6 the horizontal tank axial stress nephogram in Taft wave

Fig.7 the horizontal tank axial stress nephogram in artificial wave

From the axial stress nephogram figure 5 to 7, under the seismic ground motion in the X direction, the distribution of axial stress were basically identical, and the maximum negative stress appeared in the joint and local parts of saddle, the maximum normal stress appeared in the central part of tank above the peripheral saddle joint. This illustrated that under the horizontal X direction earthquake wave, the tank central axial where on the saddle had a great normal stress and negative stress appeared in the joint below the tank. The maximum value of axial stress was -11.25MPa in EL wave, the maximum was -11.38 MPa in Taft wave and the maximum was -9.33 MPa in artificial wave.

The analysis of shear stress

The horizontal tank shear stress nephogram, respectively, as shown in figure 8, figure 9 and figure 10.

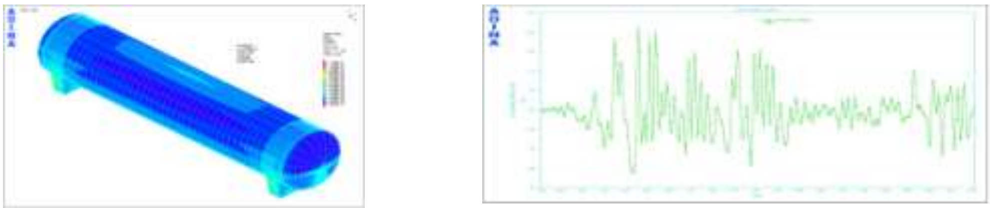


Fig. 8 the horizontal tank shear stress nephogram in EL-centro wave

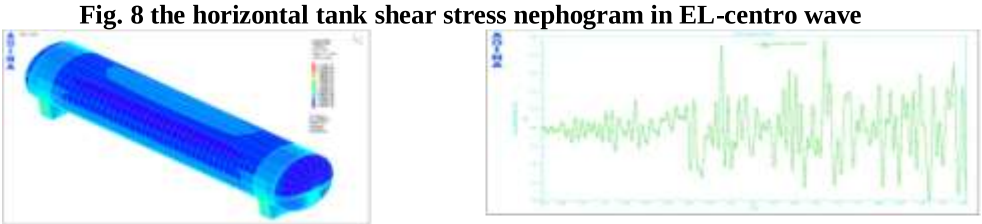


Fig. 9 the horizontal tank shear stress nephogram in Taft wave

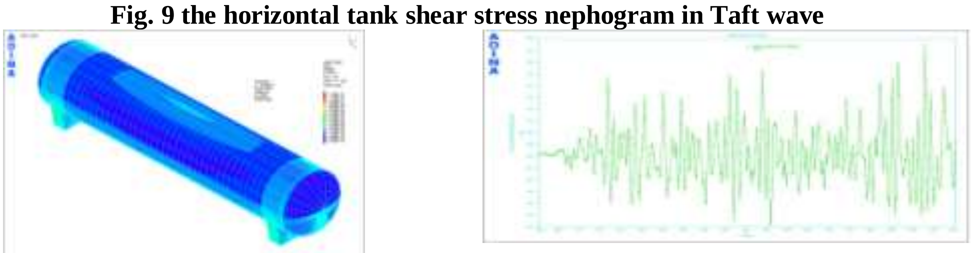


Fig. 10 the horizontal tank shear stress nephogram in artificial wave

From the axial stress nephogram figure 8 to 10, different seismic waves had the same effect on the maximum shear stress of structure. It illustrated that the seismic form had no obvious influence on the shear stress, only the earthquake size affected the maximum shear stress. Shear stress concentration position was basic same with equivalent stress distribution, there was an obvious stress concentration on the saddle and the bottom of joint. The maximum value of shear stress was 12.06MPa in EL wave, the maximum was 12.06 MPa in Taft wave and the maximum was 12.09 MPa in artificial wave.

CONCLUSIONS

At present, the research of LNG horizontal tank seismic is still in primary stage in China. This paper took 463 m^3 LNG horizontal tanks as the research object, and applied large finite element software to process the modeling analysis of tank. Adopt the potential flow theory and considered liquid-solid coupling effect, we researched the analysis of characteristic and seismic response by simulated calculation.

Main conclusions are as follows:

1. Analyzed the dynamic characteristics of the horizontal tank with no liquid and liquid, researched the influence that the water sloshing made on the structure, calculations shown that water sloshing greatly reduced the period of the tank structure.
2. Based on the modal analysis research, horizontal tank model were set up in 8 degree frequency earthquake, respectively got dynamic time history analysis under three different waves. The analysis shows that maximum displacements under the different earthquake were very small, all in a safe state. Acceleration was related with the earthquake type. The influence of equivalent stress shear stress influence was very close to that in shear stress, and both of them were not affected by the earthquake type. All of maximum values appeared at the bottom of the tank and saddle joint. The axial stress appeared maximum value in the central axial of tanks where saddle located, and negative maximum value appeared in the bottom half of the saddle, these were suitable for the structural characteristics.

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