Finite Element Analysis and Dynamic Characteristics of Anchored Rectangular Liquid-Storage Tank

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Abstract. In order to obtain the natural frequencies and vibration modes of the rectangular storage tanks under liquid-filled state, open anchorage rectangular storage tank models of 1000 m³ are established and the dynamic characteristics analysis is carried out. Considering the influence of wall thickness (t), liquid storage level (h) and other factors on the natural frequencies and vibration modes of the models under static state, the finite element analysis models of rectangular tanks with different parameters are established, and different natural vibration frequencies are compared and analyzed. The results show that the natural vibration frequencies of the structure increase with the increasing of the thickness of the tank wall and the bottom plate. The liquid storage level is negatively correlated with the tank-liquid coupling vibration frequency. The natural vibration frequencies of the tank decrease with the increasing of the liquid storage level.

1. Introduction

The storage tank is an important equipment for storage and transportation in the petrochemical industry. In recent years, the proportion of China’s imported oil consumption in the total oil consumption has gradually increased, and the transportation and storage of oil has also been paid more attention [1-5]. The construction of large-scale liquid storage tanks in my country began in the mid-1990s. As a high-hazard natural disaster, earthquakes may cause serious damage to the structure of the liquid storage tank [6]. The current research on liquid storage tanks mainly uses finite element and test methods to carry out static analysis and dynamic analysis under seismic loads on liquid storage tanks, focusing on the analysis of modal and seismic response. Cheng et al. assumed that the liquid is incompressible, established a finite element model, and analyzed the seismic response of a rectangular reinforced concrete liquid storage tank with a rubber isolation layer [7]. The dynamic response of open anchored storage tanks under horizontal and vertical earthquakes is analyzed, and the impact of elastic tank wall and base anchoring conditions on impulse response, convection response, and sloshing wave height are discussed. Contrast with the development of finite element software and numerical simulation, numerical analysis methods based on finite element are widely used in the study of fluid-solid coupling problems in liquid storage tanks [8]. N.W. Edwards used the finite element method for the first time to numerically simulate the seismic response of liquid storage tanks [9]. L.Y. Gu used ANSYS finite element software to study the dynamic response of anchored liquid storage tank and non-anchored liquid...
storage tank under horizontal seismic wave excitation and carried out comparative analysis [10].

In this paper, the three-dimensional finite element models of the 1000m³ rectangular storage tanks are established by ANSYS [11-12], and the regular pattern of influence on the natural frequency of the rectangular tank with thickness of tank wall and bottom plate as well as liquid level is discussed, and the change regularity of the natural vibration frequency of the rectangular tank with different variables is further studied [13].

2. Liquid-storage tank specimens design

The open anchorage tanks with a volume of 1000 m³ are selected as the study object, and the type of tank is rectangular cross-sectional anchorage tank. The material of the tank wall and the bottom plate is Q235-B carbon steel, and the elastic modulus and the Poisson's ratio are 1.98×10⁵ MPa and 0.3, respectively. The density of steel is 7850 kg/m³. The specific design sizes of the tanks are shown in table 1. In order to analyze the influence of tank wall thickness(t) and liquid level(h) on the modal analysis of storage tanks and compare the natural frequencies of rectangular storage tanks and square storage tanks with different foundation sizes (a×b), 12 three-dimensional specimens of storage tanks with different variables are designed. The volume of all storage tank models is 1000 m³ and the height is 10m, and the natural frequencies of storage tanks with different variables are compared and analyzed.

### Table 1. The main parameters of 1000 m³ tank specimens

| Specimens | a×b (m²) | t (mm) | h (m) | v (%) |
|-----------|----------|--------|-------|-------|
| T-1       | 8×12.5   | 5      | 8     | 80    |
| T-2       | 8×12.5   | 6      | 8     | 80    |
| T-3       | 8×12.5   | 7      | 8     | 80    |
| T-4       | 8×12.5   | 8      | 8     | 80    |
| T-5       | 8×12.5   | 9      | 8     | 80    |
| T-6       | 8×12.5   | 9      | 7     | 70    |
| T-7       | 8×12.5   | 9      | 6     | 60    |
| T-8       | 8×12.5   | 9      | 5     | 50    |
| T-9       | 8×12.5   | 9      | 4     | 40    |
| T-10      | 10×10    | 5      | 8     | 80    |
| T-11      | 8×12.5   | 5      | 0     | 0     |
| T-12      | 10×10    | 5      | 0     | 0     |

3. Finite element model

The finite element models of the tanks are established by ANSYS. The SHELL63 element contains bending and membrane effect, ignoring the transverse shear model. Because of the shell with a small thickness of models required in this paper, the SHELL63 element is used to simulate the tank wall and the bottom plate, and the thickness of the tank wall and the bottom plate keep equal. Referring to the standard, 5mm, 7mm and 9mm are selected respectively as the thickness parameters of the tank wall and the bottom plate. For establishing three-dimensional tank models, the anchorage connection between the tank and the foundation is simulated by restricting the six degrees of freedom of the bottom plate. The FLUID30 is selected as the fluid element, and the fluid-solid interface is defined by the FSIN command between the fluid and the tank. The global element size is set to 0.5, and then the mesh is divided. Unsympathetic method is adopted as the model extraction method, and both modal order and the extended modal order are set to 30. The finite element model after meshing is shown in Figure 1.
Figure 1. Finite element model of tank

4. Dynamic Characteristics analysis

4.1. Comparative analysis of rectangular tank and square tank

When the tank volume and wall thickness are constant, the natural frequencies of rectangular tanks and square tanks under the empty condition and 80% liquid storage height are compared, as seen in Table 2. It can be seen from Table 2 that the natural vibration frequency of the square tank is greater than that of the rectangular tank under empty condition and 80% liquid storage height, and the natural vibration frequency of the structure under empty tanks is much greater than that under liquid-filled state. It is proved that the stability of rectangular tank is better than that of square tank.

| Order | Specimens | 1  | 2  | 3  | 4  | 5  | 6  |
|-------|-----------|----|----|----|----|----|----|
| T-1   | 0.035     | 0.059 | 0.081 | 0.083 | 0.106 | 0.108 |
| T-10  | 0.043     | 0.044 | 0.117 | 0.118 | 0.128 | 0.133 |
| T-11  | 0.134     | 0.157 | 0.269 | 0.334 | 0.368 | 0.376 |
| T-12  | 0.154     | 0.212 | 0.212 | 0.289 | 0.400 | 0.435 |

4.2. Natural frequency and vibration mode

The reciprocating motion of the mechanical and structural system near its equilibrium position is called vibration. The number of independent coordinates describing the system model is usually called the degree of freedom of the system. The inherent vibration of the tank-liquid coupling system is a multi-degree of freedom and undamped vibration. For the free vibration of the finite-degree-of-freedom system, damping generated by the structure is not considered, and the free vibration equations of the tank-liquid coupling system are shown in Formula (1) and (2).

\[
[M] \cdot \{\ddot{q}\} + [K] \cdot \{q\} = \{0\} \\
[M] = [M_S] + [DM]
\]

Where, \([M]\) is the mass matrix of coupling system, \([M_S]\) is the mass matrix of shell, \([DM]\) is the additional mass matrix of liquid, \([K]\) is the stiffness matrix of system.

The modal analysis of the tank is carried out by ANSYS software, and the first six-order modes of the T-1 specimen are obtained, as shown in Figure 2. The deformation of the storage tank is mainly the out-of-plane buckling deformation, but the overall deformation is slight, which can ensure the overall stability of the storage tank.
4.3. Vibration characteristics analysis of liquid-filled tank

The modal analysis of ANSYS software is used to establish models with different parameters, and the first six-orders natural frequencies of the rectangular tank model under liquid filling state are extracted, as shown in Table 3.

Table 3. Natural vibration frequency of rectangular tanks

| Order | Specimens | 1   | 2   | 3   | 4   | 5   | 6   |
|-------|-----------|-----|-----|-----|-----|-----|-----|
| T-1   | 0.035     | 0.059| 0.081| 0.083| 0.106| 0.108|
| T-2   | 0.045     | 0.077| 0.106| 0.108| 0.137| 0.140|
| T-3   | 0.055     | 0.097| 0.098| 0.133| 0.136| 0.171|
| T-4   | 0.059     | 0.067| 0.118| 0.120| 0.162| 0.166|
| T-5   | 0.070     | 0.080| 0.140| 0.142| 0.193| 0.197|
| T-6   | 0.087     | 0.098| 0.163| 0.167| 0.220| 0.222|
| T-7   | 0.112     | 0.123| 0.196| 0.202| 0.259| 0.260|
| T-8   | 0.148     | 0.163| 0.246| 0.257| 0.317| 0.323|
| T-9   | 0.197     | 0.223| 0.331| 0.339| 0.365| 0.366|

4.4. Analysis of natural vibration frequency of liquid-filled tank

Comparing the natural frequency values of T-1, T-2, T-3, T-4 and T-5 finite element models, it can be seen from Figure 3 that when the tank volume and liquid storage height are constant, the natural frequency of liquid-filled tank increases with the increase of the thickness of the tank wall and the bottom plate. It can be considered that the natural frequency of the tank is affected by the stiffness. By comparing the natural frequency values of T-5, T-6, T-7, T-8, T-9 finite element models, it can be seen from Figure 4 that when the tank volume and the thickness of the tank wall are constant, with the increasing of the liquid level height of the storage tank, the natural frequency of the storage tank decreases gradually.
5. Conclusions
Based on the above finite element modeling method, this paper designs a total of 12 three-dimensional models of anchoring type storage tanks, and ANSYS is used to carry out modal analysis. According to the asymmetric method, the natural vibration frequency of the storage tank is extracted, and the natural vibration frequency and deformation characteristics of the storage tank under liquid-filled state are obtained. Finally, the natural frequency of the tank models with different parameters is analyzed, and the first-order vibration modes of the tanks under different parameters are compared. The conclusions can be drawn as follows:

(1) The natural frequency of the storage tank under the condition of empty tank is much larger than that under liquid-filled state. Compared with the square tank, the natural frequency of the rectangular tank is lower, that is, the stability of the rectangular tank is better under the conditions of the same volume and equal wall thickness.

(2) When the tank volume and storage height are constant, the natural vibration frequency of the liquid filled tank increases with the increase of the thickness of the tank wall and the bottom plate. It can be considered that the natural vibration frequency of the tank is affected by the stiffness. As the stiffness of the structure increases, the natural vibration frequency increases.

(3) The three-dimensional finite element models of the tanks with different liquid levels are simulated and analyzed. The height of liquid storage is negatively correlated with the tank-liquid coupling vibration frequency. The natural vibration frequency of the tank decreases with the increase of the liquid storage height.

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