Modal Analysis and Verification of Super Large FRP Combined Tank System Considering Reservoir Sloshing

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Abstract. The modal analysis and verification of super large FRP combined storage tank structure without floating roof are carried out. First, the finite element model of the structure system of the super large FRP composite storage tank without floating roof is established by ADINA. Then, the modal analysis of the structure system of the super large FRP composite storage tank without floating roof is carried out. Finally, the theoretical analysis of the sloshing frequency of the liquid storage is compared with the finite element results. The results show that the larger water storage height is, the larger the sloshing frequency is, on the contrary the larger the storage tank radius is, the smaller the sloshing frequency is. The theoretical analysis of the sloshing frequency of the super large FRP storage tank system is in good agreement with the results of the finite element calculation, and the correctness of the finite element model and the analysis method of the super large FRP composite storage tank structure system is verified. The calculation formula of the basic frequency of the storage sloshing of the super large FRP combined tank system is given.

1. Introduction

With the rapid development of the global economy, oil has become increasingly important as a strategic energy reserve. Devices storing petroleum or processing products are essential oilfield equipment, while vertical circular tanks are widely used in major oil fields, chemical plants, and offshore platforms because of their large volume and ease of storage. With the increasing production and processing volume of oil, the volume requirements for temporary storage equipment are also increasing. Therefore, innovative research on ultra-large storage tanks has attracted more and more attention [1].

In 1995, J B LeBleu and B Hummel[2] in the United States proposed a storage tank to consider the FRP lining. This thick film liner is tightly bonded to the secondary tank wall of the tank, which not only prevents internal corrosion but also reduces the possibility of leakage. In 2004, A Bogdanovic[3] of the University of Manitoba, Canada, developed the application of FRP reinforced concrete in storage tanks based on the leakage of large agricultural storage tanks. In 2008, Cai Siyuan[4] of Zhejiang University of Technology carried out the application and force performance analysis of FRP in space structure. The results show that the GFRP composite material has a greater superiority. This paper proposes a super large fiber reinforced plastic (FRP) combined tank structure system. The combined tank structure includes tank top, tank wall and tank bottom. The tank top adopts FRP
reticulated shell structure; the tank wall is composed of inner and outer FRP plates and sandwich RPC. The inner and outer FRP plates are reliably connected by the transverse connecting members, and the ultra-large storage tanks not only have a large volume but also a large tank wall rigidity. Used ADINA finite element software[5], the modal analysis of the super large FRP combined storage tank with the inner diameter of the tank is 100m[6], and compared with the simplified theoretical formula of the vibration frequency of the combined tank, verifying the correctness of the finite element modeling method; further developing the influence of different water storage height and different liquid storage radius on the vibration self-vibration frequency of the storage tank of the super-large FRP tank, and the vibration mode of the storage tank sloshing and the variation rule with different parameters are obtained.

2. Finite element model of super large FRP combined storage tank structure system

2.1 Structural System Simplified Mechanical Model

The super large FRP combined tank structure system tank adopts a fully symmetrical cylindrical vertical tank structure. The basic parameters of the tank are: volume is 160,000m³, inner diameter D is 100m, height H is 21.7m, the liquid storage height Hw is 20.18m, and the inner layer of the tank wall and the outer layer is FRP board, and the double wall thickness tf is taken as 0.1m. The intermediate layer of the tank wall and the bottom plate are made of reactive powder concrete (RPC100) with excellent performance. The wall thickness of the tank wall tc is taken as 2m, the bottom plate tb is taken as 5m, and the outer diameter of the storage tank is 104.4m. The simplified mechanical model of the super large FRP combined storage tank is shown in figure 1. The main parameters of the FRP composite tank structural materials are shown in table 1.

![Figure 1. Simplified mechanical model of super large FRP combined storage tank structure system.](image)

| Material        | Density ρ(kgm⁻³) | Elastic modulus E (Nm²) | Poisson's ratio | Bulk modulus (Nm²) |
|-----------------|------------------|-------------------------|----------------|--------------------|
| RPC100          | 2500             | 4×10¹⁰                  | 0.2            | ---                |
| FRP board       | 1800             | 1.5×10¹⁰                | 0.2            | ---                |
| Water           | 1000             | ---                     | ---            | 2×10⁸              |

2.2 Establishment of finite element model for super large FRP combined storage tank structure system

The boundary conditions of the model are determined according to the actual constraints of the tank. The lower surface of the concrete floor is defined as a full constraint, that is, three translational degrees of freedom and three rotational degrees freedom, and a gravitational acceleration of 9.8 m/s² is applied to the tank. The wall of the super large FRP combined storage tank is divided into 20 parts in the height direction, 40 parts in the circumferential direction, divided into one part in the thickness
direction, and the middle concrete is divided into 4 parts. The tank wall higher than the liquid part is divided into 2 along the Z axis. The bottom plate is divided into 5 parts in the height direction, 40 parts in the circumferential direction, and 30 parts in the radial direction. The finite element model of the FRP combined tank without floating roof is shown in figure 2.

3. Modal analysis of super large FRP combined tank structural system

The ADINA provides three methods for calculating modal analysis: Determinant-Search, Subspace Iteration and Lanczos Iteration. This paper uses the third algorithm. To account for the sloshing of the tank liquid, we set the surface of the liquid as a free surface, ensuring that the surface of the liquid can freely sway in the Z direction. The first third-order beam mode of an oversized tank considering liquid sloshing is shown in figure 3-5.

4. Influence of liquid storage height on the mode of super large FRP combined storage tank

In order to compare the influence of water storage height on the sloshing mode of the storage tank of the super-large FRP tank, we list the first third-order vibration frequency under different water storage heights \((f_1, f_2, f_3)\) in table 2. Figure 6 shows the first third-order frequency curve of liquid sloshing storage tanks with different water storage heights.

| \(H_w\) (m) | \(f_1\) (Hz) | \(f_2\) (Hz) | \(f_3\) (Hz) |
|---|---|---|---|
| 2.018 | 0.0266 | 0.0442 | 0.0609 |
| 4.036 | 0.0368 | 0.0608 | 0.0832 |
| 6.054 | 0.0449 | 0.0735 | 0.0997 |
| 8.072 | 0.0515 | 0.0835 | 0.1118 |
| 10.090 | 0.0571 | 0.0915 | 0.1208 |
| 12.108 | 0.0620 | 0.0979 | 0.1274 |
It can be seen from table 2 and figure 6 that the higher the water storage height, the greater the storage sloshing frequency; the larger the water storage height, the more obvious the sloshing effect of the liquid storage. When the storage height is less than 50% of the total storage height, the storage sloshing frequency changes a lot; when the storage height is greater than 50%, the storage sloshing frequency does not change much, and the higher order frequency value the smaller difference.

5. Influence of liquid storage radius on the mode of super large FRP combined storage tank

In order to compare the influence of different tank radius on the sloshing mode of the large storage tank, we carried out the modal analysis under the conditions of tank radius of 37.2m, 42.2m, 47.2m and 52.2m, and the water storage height was 20.18m. Figure 7 shows the first third-order frequency curves of the liquid sloshing with different tank radius. Table 3 lists the first third-order frequency with different tank radius.

Table 3. Storage sloshing frequency of FRP combined storage tank system at different tank radius.

| R(m) | $f_1$ (Hz) | $f_2$ (Hz) | $f_3$ (Hz) |
|------|------------|------------|------------|
| 37.2 | 0.1015     | 0.1432     | 0.1720     |
| 42.2 | 0.0915     | 0.1318     | 0.1599     |
| 47.2 | 0.0832     | 0.1220     | 0.1495     |
| 52.2 | 0.0761     | 0.1134     | 0.1403     |

It can be seen from table 3 and figure 7 that when the tank radius is different, the sloshing vibration mode is basically the same, and the storage sloshing frequency decreases as the tank radius increases.

6. Theoretical analysis of storage sloshing frequency and comparison of finite element results

In the theoretical calculation of liquid sloshing frequency of liquid storage structure, it is considered that the storage tank is mainly composed of concrete material, the structure has large space rigidity, and the liquid storage structure is assumed to be an absolutely rigid body. At the same time, the liquid is an ideal liquid that is tack-free, spin-free and incompressible. Based on the above assumptions, the formula for calculating the natural vibration frequency of a liquid in a rigid cylindrical liquid storage structure is as follows:
$$\omega^2 = \sqrt{\frac{27}{8}} \frac{g}{R} \tanh\left(\sqrt{\frac{27}{8}} \frac{h}{R}\right)$$  \quad (1)

Where: $\omega$ is the natural vibration frequency (rad/s) of the liquid storage; $R$ is the storage tank radius (m); $h$ is the liquid storage height (m), and $g$ is the gravity acceleration (ms$^{-2}$).

Combined with the formula (1), the calculation formula of the basic frequency of the storage tank sloshing of the cylindrical storage tank is simplified, as shown in the formula (2).

$$f_s = \frac{\tanh(1.84\frac{h}{R})}{1.48\sqrt{R}} \quad (\text{Hz})$$  \quad (2)

Where: $f_s$ is the basic frequency of liquid storage sloshing; the physical meaning of other variables is the same as (1).

Calculating the first-order liquid storage sloshing frequency of different liquid storage heights according to formula (2), and comparing with the finite element results, we know that the first-order liquid storage sloshing frequency of the FRP combined tank structure system with different water storage heights and different radius is very close to the theoretical result, and the maximum error is less than 5%, which meets the engineering needs and verifies the correctness of the finite element model and analysis method of the tank structure system. The finite element model realistically simulates the actual state of the tank, and the tank model is reliable, laying the foundation for the analysis of seismic time-history response of subsequent storage tanks.

7. Conclusion

Based on ADINA, the first-order natural vibration frequency of the tank model is compared with the theoretical formulas under different tank heights and different tank radius conditions. At the same time, the first three modes of vibration of a large FRP combined tank system without floating roof and its variation law are given. The conclusion is: with the increase of water storage height, the storage sloshing frequency increases; the storage sloshing natural vibration frequency of the storage tank decreases with the increase of the storage tank radius; The influence of the sloshing vibration mode of the reservoir is not significant; the theoretical analysis of the sloshing frequency of the non-floating super large FRP combined tank system is in good agreement with the finite element calculation, and the correctness of the finite element model and analysis method of FRP combined tank structure system is verified; the calculation formula of the basic frequency of the storage sloshing of the super large FRP combined storage tank system is given.

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