Seismic Response of Base-isolated CRLSS Considering Nonlinear Elasticity of Concrete

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Abstract

The purpose of this paper is to study the seismic response of a base-isolated, concrete rectangular liquid-storage structure (CRLSS) under small-amplitude sloshing. In this study, the three-dimensional FEM of the base isolated CRLSS is established by using ADINA. The concrete material is assumed to be nonlinear and elastic, and the criterion for the small amplitude sloshing is defined to determine the seismic response of a base-isolated CRLSS under different conditions. The results show that when small-amplitude sloshing occurs and the nonlinear elasticity of the concrete material is considered, the displacement of wallboard, the height of liquid sloshing and the equivalent stress are increased with the increase in the earthquake intensity when comparing the same liquid height and different intensities of a bidirectional earthquake. The liquid height is found to affect the seismic response of the base-isolated CRLSS. The lower the liquid height is, the larger the equivalent stress is, and the greater the displacement of the wallboard and the amplitude of the liquid sloshing are.

Keywords: concrete; rectangular liquid-storage structure; nonlinear elasticity; liquid-solid interaction; seismic response

1. Introduction

Because liquid-storage structures are usually closely related to people's life and production, they are often placed in crowded urban areas. Because these structures are often located in populated areas, once this type of structure is damaged (due to, e.g., earthquake, terrorist attack, accidental impact), there may be high risks of potentially serious secondary disasters (e.g., fire, environment pollution, and explosions). Therefore, the research has been conducted on the seismic response of these liquid storage structures.

A new added mass approach was put forward by Balendra (1982), in which the internal liquid of the storage structure was represented by the added mass. Ju and Zeng (1983) studied this problem through the velocity potential function of fluid movement and obtained an analytical solution to the problem based on the assumption of a small-amplitude sloshing of the liquid. Andrianarison and Ohayon (2006) performed a theoretical study of the effect of gravity waves on a liquid storage structure. Li et al. (2002) analyzed the problem of the fluid-solid coupling dynamic response on a cylindrical liquid storage structure. Liu et al. (2005) analyzed the seismic response and seismic capacity of a rectangular liquid storage tank. Souli and Zolesio (2001) combined the least square method with a study on the sloshing effect of the internal liquid on a three-dimensional liquid storage structure subjected to external excitation. Yue et al. (2001) systematically studied the nonlinear characteristic of the liquid sloshing response of a liquid storage structure in a three-dimensional space by use of the Arbitrary Lagrangian Eulerian (ALE). Using the displacement potential flow equation of a finite element and considering the fluid-solid coupling effect, Zhang et al. (2011) studied the dynamic response of a liquid storage structure. Ayman A. Seleemah and Mohamed El-Sharkawy (2011) investigated the seismic response of elevated liquid storage tanks isolated by elastomeric or sliding bearings. Shi et al. (2012) studied the dynamic buckling performance of fluid-solid coupling about a large liquid-storage tank. Tao (2013) solved the unsteady fluid-structure interaction (FSI) problems with large structural displacement by partitioned solution approaches. Hashemi et al. (2013) put forward the analysis method of dynamic response of a three-dimensional rectangular liquid storage structure with elastic wallboard and studied the relationship between the structure parameters and the dynamic response. Yazici (2014) studied the effect of isolation parameters on the dynamic response of a liquid storage structure using the state-space method and concluded that
isolation measures can effectively reduce the shear of the foundation but that attention must be paid to the increase in the sloshing height caused by the isolation. Zhang et al. (2014) performed the shaking table experiment on a steel storage tank with multiple friction pendulum bearings. Moeindarbari et al. (2014) conducted the probabilistic analysis of a seismically isolated elevated liquid storage tank using multi-phase friction bearing. Malhotra et al. (2014) concluded that only 28% of the liquid movement would produce seismic force and that the remaining 72% of the liquid would slosh near the free surface and would not significantly influence the seismic force. Cheng et al. (2009; 2011; 2014; 2015) studied the liquid-solid coupling vibration characteristics of a rectangular liquid storage structure in theory.

In conclusion, although CRLSS have been extensively studied in the existing literature, the nonlinear effect of concrete has not been considered. Therefore, in this paper, the nonlinear elastic property of concrete is considered. An integrated model of liquid-solid coupling dynamic analysis of CRLSS is established by studying the seismic effect on liquid sloshing height, wallboard displacement and equivalent stress of CRLSS. The variation laws of wave height, wallboard displacement and stress with different liquid levels are also analyzed.

2. Governing Equation

2.1 Boundary Condition of Free Liquid

Considering the small sloshing of a free surface, the boundary condition is

$$\frac{1}{g} \frac{\partial^2 p}{\partial t^2} + \frac{\partial p}{\partial z} = 0$$

where $z$ is the vertical direction, $g$ is the acceleration of gravity, $t$ is time, and $p$ is the liquid pressure.

2.2 Boundary Condition of Liquid–wallboard Interface

On the interface between the liquid and wallboard, there is no liquid flowing in the direction of the vertical wallboard, and the boundary condition is

$$\frac{\partial p}{\partial n} = -\rho a_n$$

where $n$ is the normal direction of the wallboard and $a_n$ is the acceleration acting on the liquid in the $n$ direction.

2.3 Discrete Equation of Liquid Domain

Using the Galerkin method, the finite element discrete equation of fluid domain can be expressed as

$$G\ddot{P} + C_f \dot{P} + K_f P = F$$

where

$$G_j = \frac{1}{g} \int_{A_j} N_i N_j dA;$$

$$H_j = \int_{\Omega} \left( \frac{\partial N_i}{\partial x} \frac{\partial N_j}{\partial x} + \frac{\partial N_i}{\partial y} \frac{\partial N_j}{\partial y} + \frac{\partial N_i}{\partial z} \frac{\partial N_j}{\partial z} \right) \psi dV;$$

$$F = F_j - \rho Q^j \left( \ddot{U} + \ddot{U}_s \right);$$

$$F_j = \int_{A_j} \frac{\partial p}{\partial n} dA.$$
where $a$ and $b$ can be calculated by the Rayleigh damping $a$ can be obtained by the sloshing frequency of a free surface, and $b$ can be obtained by the natural frequency of the structure wallboard.

3. Constitutive Relation of Concrete

In practical engineering, the growth rate of the concrete stress is significantly less than that of the strain in the load application process. Thus, in practical engineering, the nonlinear elastic modulus of concrete materials is usually used, and the relationship between the stress and strain can be expressed as

$$\sigma = E(\varepsilon)\varepsilon$$

(6)

where $\sigma$ and $\varepsilon$ are the stress and strain of the concrete, respectively, and $E$ is the elastic modulus and is a function of stress, but is not a constant.

To obtain the solution conveniently, in this paper, the concrete constitutive model put forward by Sargin et al. is applied (Lv et al., 1999):

$$\sigma = k_1f_c \varepsilon - (F_2 - 1) \varepsilon^2$$

(7)

where $k_1$ is the effect coefficient of lateral restraint on strength, $f_c$ is the ultimate compressive strength of the prism, $\varepsilon_0$ is the strain corresponding to the ultimate compressive strength of the prism, and $F_1$ and $F_2$ are the strength parameters.

4. Determination of Small-amplitude Sloshing

In general, liquid sloshing is considered small-amplitude sloshing when the sloshing amplitude is no more than 1% of the liquid depth. Assuming that the sloshing of the liquid is linear under small-amplitude sloshing, basic theory can be used for the analysis. The liquid sloshing of CRLSS is a phenomenon that involves the mutual conversion between the liquid kinetic energy and the gravitational potential energy.

Considering the Bernoulli equation $p + \frac{\rho U^2}{2} + \rho g \eta = C$, the condition $|U|^2 < g \eta$ is satisfied. Namely, the liquid sloshing is linear, neglecting the nonlinear square term (Liu and Huang, 1993), the response frequency of liquid sloshing is $\omega$, and the movement rate $|U|$ is approximately equal to $|\omega \eta|$ in magnitude; thus,

$$|\eta| \leq \frac{2\varepsilon_0}{\omega_0^2}$$

(8)

where $\frac{2\varepsilon_0}{\omega_0^2}$ is defined as the critical amplitude $\eta_c$.

If the sloshing amplitude is less than the critical amplitude, namely, $|\eta| < |\eta_c|$, the small-amplitude hypothesis can be used. However, if the sloshing amplitude exceeds the critical amplitude, namely, $|\eta| > |\eta_c|$, the nonlinear term $\frac{1}{2}|U|^2$ of the Bernoulli equation must be considered. For liquid, the critical amplitude is decided by the sloshing frequency, and the influence of the external excitation on the response frequency of the liquid storage is small when the sloshing is linear and the amplitude is small. Therefore, the response frequency can be replaced by the natural frequency of the corresponding modal, which is

$$\eta_0 = \frac{2\varepsilon_0}{\omega_0^2}$$

(9)

Therefore, as long as the natural frequency of the liquid sloshing is calculated, the limit wave height under small amplitude sloshing and large-amplitude sloshing can be obtained. The natural frequency can be obtained directly by the dispersion equation of ideal potential fluid, which is

$$\omega_0^2 = \frac{n\pi g}{2b} \tanh \left( \frac{n\pi d}{2b} \right)$$

(10)

where $n$ is the $n$th order modality, $d$ is the liquid depth, and $b$ is the wallboard width of the liquid storage structure.

5. Calculation Model and Calculation Parameter

5.1 Calculation Model

An isolated CRLSS that is positioned over land and does not have a top plate is the model selected for analysis in this paper. The length, width and height of the structure are all 6 m, the thicknesses of the wallboard and soleplate are both 0.3 m, the height of the liquid in the structure is 4 m, and the isolation layer thickness of the rubber pad is 0.2 m.

A 3D-solid unit is adopted as the structure unit, and the fluid is assumed to be the potential flow unit. Considering the effect of gravity waves, the fluid surface is defined as a free liquid surface. By dividing the structure, the fluid and the rubber isolation body into uniform grids, the grid density is set at 0.15 m, and the 8-node format is selected to divide the element.

Substituting the relevant data into Eq. (8), we can obtain $\frac{\omega_0^2}{2}=0.1998$ rad/s. Substituting it into Eq. (9), we can obtain $H=0.50$ m. Therefore, in this study, the dynamic response of the CRLSS is considered when the wave height of the liquid sloshing is less than 0.50 m.

5.2 Calculation Parameter

(1) Rubber isolation cushion

To describe the hyper-elastic constitutive model of rubber, the strain energy density function obtained by Mooney-Rivlin (Zheng et al., 2003; Huang et al., 2008) is used. The strain energy density function $W$, as described by the invariant of deformation tensor, is

$$W = \sum_{i,j=1}^{n} C_{ij}(I_i - 3) (I_j - 3)$$

(11)
where, $C_{ij}$ is the material constant, generally determined by experiments. $I$ is the deformation tensor invariant.

All rubber supports are established through the 3D-Solid unit. According to the material constants reported in the literature (Liu et al., 2011), the parameters of the Mooney-Rivlin rubber model are shown in Table 1.

Table 1. Parameters of Mooney-Rivlin Rubber Model

|   | C1   | C2   | C3 | C4 | C5 | C6 |
|---|------|------|----|----|----|----|
|   | 807300 | 168900 | 0  | 0  | 0  | 0  |

(2) Concrete
For concrete with a tensile strength of 30 MPa, $f_c$ is 14.3 MPa, $\varepsilon_0$ is 0.002, $k_1$ is 1, $F_1$ is 1.7388, and $F_2$ is 0.5.

(3) Fluid
Because the object of the study is small-amplitude sloshing, the liquid is considered a potential fluid, and the bulk modulus of the liquid is $2.3 \times 10^8$ Pa. The density of the liquid is 1000 kg/m$^3$.

6. Dynamic Responses
The liquid storage structure is analyzed by using the El Centro seismic wave. The seismic wave record of 30 s is taken, and the bi-directional horizontal seismic wave is input in the $x$ and $y$ directions. The change in the liquid sloshing displacement, wallboard displacement, and structure stress of the CRLSS with seismic fortification intensities of 7, 8 and 9 are considered.

6.1 Seismic Response of Same Liquid Height
(1) Wallboard displacement
Under small-amplitude sloshing, when the numerical simulation is carried out on the isolated CRLSS, considering the nonlinear elasticity of concrete, and the waves of frequent seismic fortification intensities 7, 8 and 9 are input in the $x$ direction and $y$ directions, the wallboard displacement of the CRLSS is shown in Fig.1., and the peak displacement of the wallboard under the seismic effect is shown in Table 2.

From Fig.1., it can be clearly seen that when considering the nonlinear elastic characteristic of concrete, the peak displacement of the isolated CRLSS appears at the edge of the top of the wallboard when seismic fortification intensities are 7, 8 or 9. It can also be seen that the peak displacement of the wallboard is different when different seismic intensities are applied and that the peak displacement of the wallboard of the CRLSS increases continuously with the increase in seismic intensity.

(2) Liquid sloshing height
When the frequent seismic fortification intensities are 7, 8 or 9, the horizontal seismic wave is input in the $x$ and $y$ directions to the CRLSS. Considering the nonlinear elasticity of concrete, the change in liquid sloshing height of the isolated CRLSS is shown in Fig.2., and the peak height of the liquid sloshing wave is shown in Table 3.

From Fig.2. and Table 3., when the nonlinear elasticity of concrete is considered in the effect of frequent bidirectional seismic waves, the peak liquid shaking height of the isolated CRLSS is different with different seismic intensities, and the liquid sloshing amplitude increases continuously with the increase of seismic intensity.

(3) Equivalent stress
When the frequent seismic fortification intensities are 7, 8 or 9, the bi-directional horizontal seismic wave is input to the CRLSS, considering the nonlinear elasticity of concrete; the change in the equivalent stress of the isolated CRLSS is shown in Fig.3. The equivalent stress peak of the CRLSS is shown in Table 4.
From Fig. 3. and Table 4., the equivalent stress peak of frequent seismic fortification intensities for 7, 8 or 9 appear in the middle of the bottom of the wallboard, and the equivalent stress increases continuously with the increase in seismic intensity.

6.2 Seismic Response with Different Liquid Heights

To study the seismic response of the liquid-solid interaction of the nonlinear isolated CRLSS with different liquid heights, the liquid heights selected are 4 m, 3 m and 2 m, and a rare earthquake wave, the El-Centro wave, with a seismic fortification intensity of 7 in the y-direction is added.

When the liquid appears to have small-amplitude sloshing, considering the nonlinear elasticity of concrete, under the unidirectional earthquake of a rare El-Centro wave of seismic fortification intensity of 7 and with different liquid levels, the wallboard displacement, liquid shaking and equivalent stress of the isolated CRLSS are obtained as shown in Figs.5., 6. and 7. Then, based on Figs.4., 5. and 6., the peak values of the seismic responses of the different liquid levels are shown in Table 5.

| Seismic fortification intensity | 7   | 8   | 9   |
|-------------------------------|-----|-----|-----|
| Peak shaking                  | 0.001439 | 0.002023 | 0.01278 |

| Seismic fortification intensity | 7   | 8   | 9   |
|--------------------------------|-----|-----|-----|
| Peak equivalent stress (Pa)    | 2966941 | 4431690 | 23190000 |
Fig. 4. Wallboard Displacement

(a) 4 m  
(b) 3 m  
(c) 2 m

Fig. 5. Liquid Shaking Height

(a) 4 m  
(b) 3 m  
(c) 2 m
7. Conclusions

(1) Due to the influence of frequency-domain and time-domain and the characteristics of the seismic waves under different earthquake intensities, the seismic response of the isolated CRLSS is different.

(2) When frequent bi-directional seismic action of different intensities are applied to the same liquid height, the wallboard displacement and amplitude of liquid shaking are. In contrast, the higher the liquid level is and the greater the volume of liquid is, the smaller the liquid shaking amplitude, equivalent stress and wallboard displacement are for the isolated CRLSS.

(3) Different liquid levels influence the seismic response of the isolated CRLSS. The lower the liquid level is, the greater the change of equivalent stress, wallboard displacement and amplitude of liquid shaking. On the contrary, the higher the liquid level is and the greater the volume of liquid is, the smaller the liquid shaking amplitude, stress and wallboard displacement of the isolated CRLSS are.

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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