DYNAMIC RESPONSE OF RECTANGULAR RC LIQUID STORAGE STRUCTURES CONSIDERING LIQUID-STRUCTURE INTERACTION

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ABSTRACT: This paper presents a dynamic simulation for rectangular reinforced concrete (RC) liquid storage tank structure taking liquid-structure interaction into account. A finite element approach is employed for the simulation of rectangular RC liquid storage tank making use of software ADINA, and the actions of reinforcement is considered using the element Rebar provided in the software, which is embedded in concrete materials in the finite element analysis. The effects of the surface gravity waves of the liquid, the stiffness of the wall panels of the tank and the shapes of the tanks on the dynamic response are discussed respectively considering liquid-structure interaction. The dynamic responses of the tank are also investigated for the cases of the action of the unidirectional, bidirectional and three-directional coupled seismic excitations, respectively. The study results indicate that the effect of the surface gravity waves on the dynamic response of the tank storage structures is not negligible for the dynamic analysis with liquid-structure interaction, while the dynamic pressure of the liquids is sensitive to the change of the stiffness of the wall panels of the tank, and the effect of the surface gravity waves on the dynamic response of the shallow liquid storage structures is much more significant than that of the deep ones. For the purpose of engineering designs, the effect of the stiffness of the wall panels on the dynamic response of the tank structures can be negligible, and the analysis by the action of unidirectional seismic action is sufficiently accurate.

KEYWORDS: liquid-structure interaction; rectangular liquid storage structures; reinforced concrete tank; ADINA; dynamic response

1. INTRODUCTION

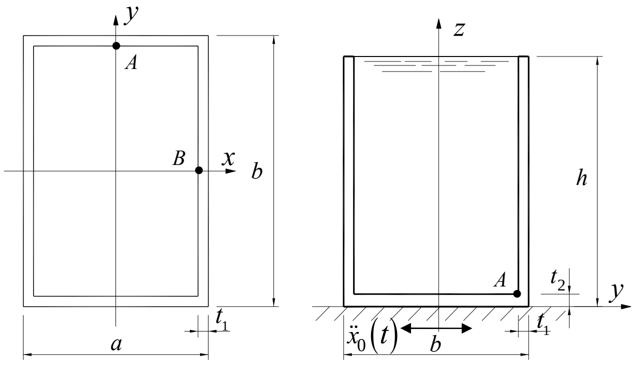
Liquid storage tanks are widely used in departments such as water treatment and petrochemical industry and play an important role in national economy. With several different materials and shapes being available for liquid storage tanks, reinforced concrete (RC) rectangular tanks attract more and more attention because of such advantages as construction convenience, cost effectiveness and adaptability to various terrains.

The dynamic response of liquid storage structures is different from other types of structures due to the influence of the liquid. Earthquake induced damages of liquid storage structures would lead to great losses. Secondary damages, e.g., environment pollution or fire, would also come into being if the chemical solution leaks. Therefore, the study aiming at the earthquake resistant ability of liquid storage structures aroused the attention of many researchers. Ju and Zeng (1983) investigated the dynamic pressure of liquid and the equation of motion of the liquid storage structures by the action of the ground movement for the case of micro rocking vibration with full liquid loaded; Li (2002) *et al*. accomplished a finite element analysis of the cylindrical liquid storage tanks considering liquid-structure interaction; Liu(2005) *et al*. presented an aseismatic analysis of the rectangular liquid storage tanks using finite element analysis method; Liu (2006) *et al*. studied the gravity waves of the rectangular elastic shell structure-liquid coupled system. However, most of the above studies neglected the effect of the gravity waves of the liquid surface, which is not suitable to the situation where the rocking amplitude is significant, and some other study performed the analysis by reducing the spatial problem into planar one. In this paper, the effects of the surface gravity waves of the liquid, the stiffness of the wall panels of the tank and the shapes of the tanks on the dynamic response are discussed respectively considering liquid-structure interaction. The dynamic responses of the tank are also investigated for the cases of the action of the unidirectional, bidirectional and three-directional coupled seismic excitations, respectively. A finite element simulation is carried out for reinforced concrete rectangular liquid storage structures using a popular finite element software ADINA.

2. FINITE ELEMENT MODEL CONSIDER- ING LIQUID-STRUCTURE INTERACTION

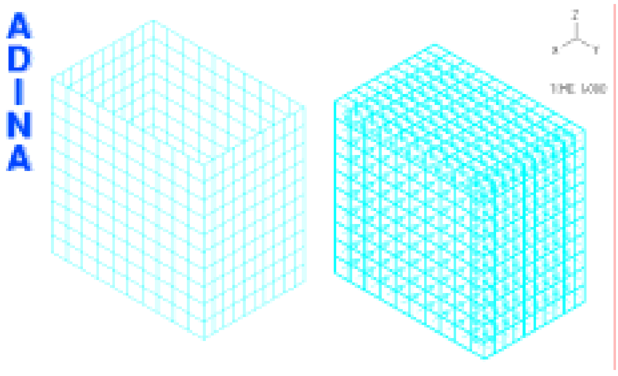
2.1 Calculation Diagram

Assuming the planar side length of rectangular liquid-storage structure to be a and b. The height is assumed to be h, and the thickness of the wall panel and bottom plate are t_1 and t_2, respectively. The horizontal seismic actions is $\ddot{x}_0(t)$. The calculation diagram is shown in figure 1. For the convenience of analysis, the dimension of the structure is set to be $a=4$m, $b=6$m, $h=6$m, $t_1=0.25$m, and $t_2=0.3$m. The gravity density of reinforced concrete is 25KN/m³. The tank is supposed to be fully filled with liquid, and the density of the liquid is 10KN/m³. Using the fluid-structure interaction (FSI) solution function which is provided by the software ADINA to establish the three dimensional model of the liquid storage structure. The basic load condition is earthquake wave El Centro (1940, NS) and Lanzhou wave in Y direction, and the seismic intensity is moderate, and the amplitude is 2.0m/s². Considering the influence of the surface gravity waves upon the liquids, the dynamic responses of the system have been discussed by the action of the seismic actions.



(a) plane figure (b) section figure

Figure 1 Calculation diagram of rectangular liquid storage structure



(a) mesh of structure (b) mesh of liquid

Figure 2 Mmesh partition

2.2 Vibration equation of the structure

When the liquid storage structure is reduced to be a cantilever shearing beam, the vibration differential equation of the structure under the action of inertia force and liquid dynamic pressure caused by ground motion $\ddot{x}_0(t)$ is

$$\frac{GF}{K_0}\frac{\partial^2 u}{\partial z^2}=\frac{\rho_c A}{g}\left[\frac{\partial^2 u}{\partial t^2}+2\varepsilon\frac{\partial u}{\partial t}+\ddot{x}_0(t)\right]-S^0(z,t) \tag{1}$$

Where G is the shearing elastic modulus of the material, A is the area of the cross section, g is the acceleration of gravity, K_0 is a coefficient which is related to the shape of the cross section, ρ_c is the volume weight of the reinforced concrete, $u(z,t)$ is the displacement along the vibration direction, ε is the damping coefficient of the structure, $\ddot{x}_0(t)$ is the ground acceleration of the earthquake, and $S^0(z,t)$ is the unit dynamic pressure of the liquid which exerted onto the wall panels.

2.3 Determination of the Elastic Constants

Reinforced concrete is considered as an orthotropic material (Wilson, 2006), the properties of the material are defined by the elastic modulus E, the shearing modulus G and the Poisson ratio μ along three directions. In some other finite element analysis of reinforced concrete structures (Song, *et al.*, 2005), reinforced concrete have been considered as composite material with Rebar and concrete, and the calculation model with separated element, composite element and uniform element have been proposed respectively. However, the above-mentioned models are hardly feasible to apply in simulation of actual liquid storage structures because of the complex construction and tremendous calculation cost. Considering the reinforcement in the liquid storage structures are placed at equal spacing in two layers and two directions, the effect of the concrete and reinforcement can be considered synthetically as an average composite material to determine its elastic properties. In this example, the grade of concrete is C30, reinforcement is HRB335, and the reinforcement ratio in x direction and y direction are all 0.8%. According to the averaging method proposed by the authors (Cheng and Du, 2006), the elastic constants can be derived as

$$E_x = E_y = E_c\left[1+\left(\frac{E_s}{E_c}-1\right)\times\rho_{sx}\right]=1.0453E_c = 3.136\times10^{10}\ \mathrm{N/m^2}$$

$$E_z = \frac{1+\sqrt{\rho}\,(\alpha-1)}{1+\sqrt{\rho}\left(1-\sqrt{\rho}\right)(\alpha-1)}E_c = 1.0310E_c = 3.093\times10^{10}\ \mathrm{N/m^2}$$

$$G_{xy} = G_{yx} = \frac{1-\sqrt{\rho}\left(1-\frac{G_s}{G_c}\right)}{1+\sqrt{\rho}\left(1-\sqrt{\rho}\right)\left(1-\frac{G_s}{G_c}\right)}G_c = 1.03G_c = 1.236\times10^{10}\ \mathrm{N/m^2}$$

$$\mu_{xy}=\mu_{yx}=\mu_c+\rho_y\left(\mu_s-\mu_c\right)=0.2008$$

Where E is the elastic modulus of the material, μ is the Poisson ratio, ρ is the reinforcement ratio of the structure, and $\alpha=E_s/E_c$ is the ratio of elastic modulus of reinforcement to elastic modulus of concrete. The liquid in the structure is considered as a potential-based fluid, and is assumed to be incompressible liquid because of the low flowing velocity.

2.4 Boundary Conditions and Mesh Partition

The bottom of the structure is fixed. If the influence of movement of the water surface is neglectful, i.e., the effect of the surface gravity waves of the liquid on the structure is not considered, the fluid potential is set to be zero; if the effect of the surface gravity waves of the liquid on the structure is considered, the free liquid surface condition (Free Surface), which is provided by ADINA, can be used. The structure and liquid can be thought as Shell element and 3D-Fluid element respectively.

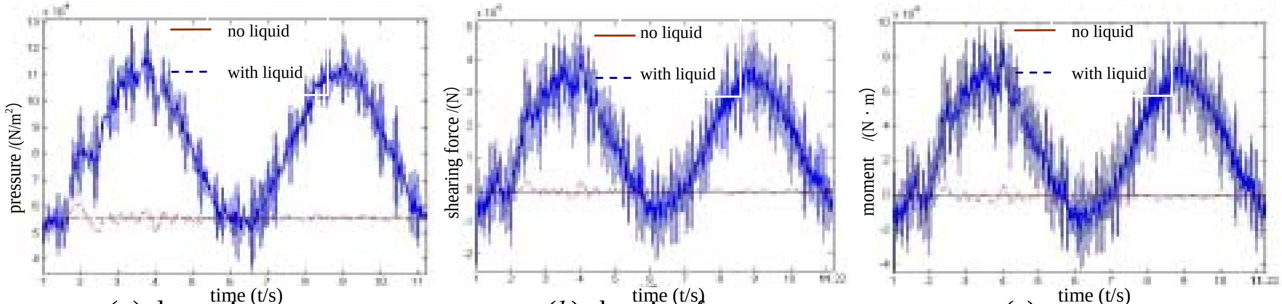
The solid region and liquid region are meshed respectively. Because the shape of the structure is regular, the length direction, width direction, and height direction are all divided equally into 10 portions. The liquid region is also divided into 10 portions in the length direction, width direction, and height direction, respectively, corresponding to the mesh of the structure. The result of the mesh is shown in figure 2.

3. CALCULATION RESULTS AND ANALYSIS

The main purpose of the aseismatic research for engineering structures is to study the change and the maximum of the dynamic internal force at the governing sections during an earthquake. Therefore, this paper will discussed the dynamic pressure of the liquid, the dynamic shearing force and moment at the bottom centre of the wall panel (point *A* and *B in* Figure 1) along the *x* and *y* direction by the action of the earthquake.

3.1 Influence of Liquid on Dynamic Response of Liquid Storage Structure

For illustrating the influence of the liquid on the dynamic response of the structure, the calculation results of the liquid storage structure full of liquid and without liquid are shown in figure 3. It can be seen from the figures that the time history curves of the dynamic responses for the aneroid liquid storage structure are similar to the common structures, that is the shapes of the curves are correspond to the shape of the seismic waves. On the other hand, the value of the time history curves for the liquid storage structure full of liquid is much more than it for the aneroid liquid storage structure and, what's more, the shapes of these time history curves are significant different than that for the common structure. The value of the response between adjacent points changed irregularly; however, the value as a whole is similar to the curve of trigonometric function.

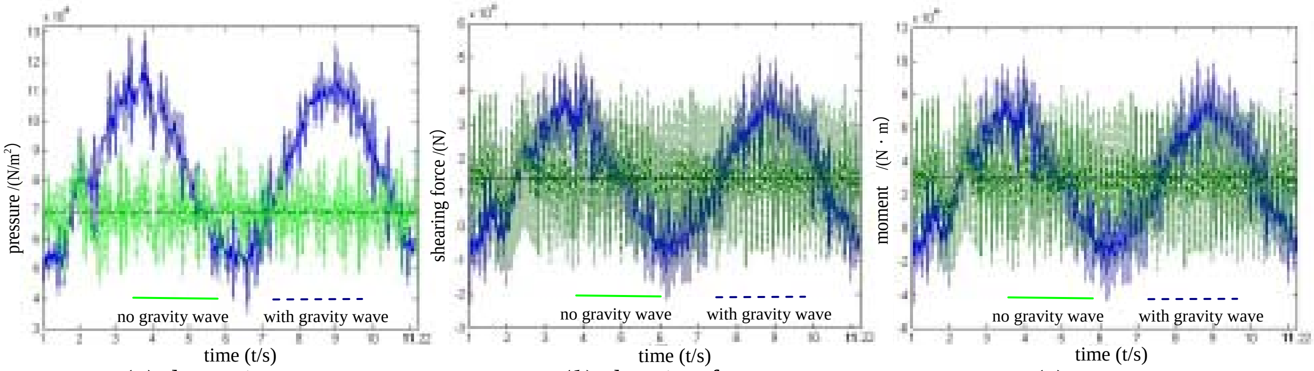


(*a*) dynamic pressure (*b*) shearing force (*c*) moment

Figure 3 the time history curves of point *A* by the action of El Centro wave with liquid or not

3.2 Influence of Liquid Surface Gravity Waves on the Dynamic Response

The calculation model is established for the cases of considering the liquid surface gravity waves, or without surface gravity waves. The results are shown in figure 4. One can observe from the figures that the value of the dynamic pressure of the liquid without the gravity waves is much less than that with the gravity waves. Furthermore, the shapes of the time history curves of the two cases are obviously different. Under the dynamic pressure of the liquid, the characteristics of the time history curves for shearing force and moment are uniform. Therefore, the effect of the surface gravity waves on the dynamic response is significant.



(a) dynamic pressure (b) shearing force (c) moment

Figure 4 the time history curves of point A by the action of El Centro wave considering gravity wave or not

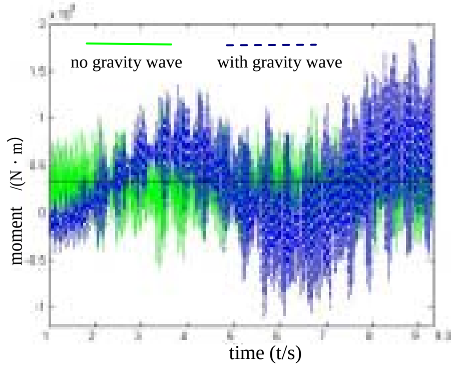


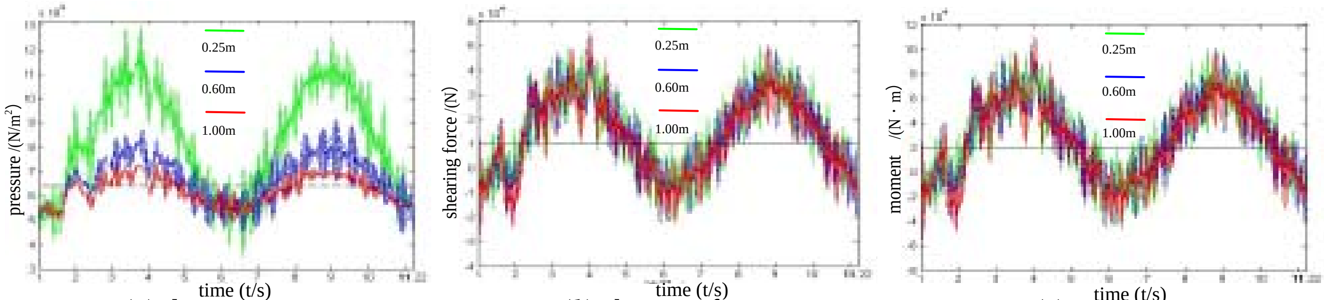
Figure 5 the time history curves of the moment in point A by the action of Lanzhou wave

The characteristics of the response by the action of Lanzhou wave are similar to that by the action of El Centro wave. The time history curve of the moment in point A by the action of Lanzhou wave is shown in figure 5

3.3 Influence of Relative Thickness Wall Panels on the Dynamic Response

The wall panels of the liquid storage structure are calculated using one-way or two-way plates according to the side length of each panel, and the thickness of the panel are correspondingly chosen to be 1/10~1/20 of the tank's height or 1/20~1/30 of the structural height (design handbook, 1985). To study the effect of the stiffness of the wall panels on the dynamic response, the dynamic characteristics of the same model have been calculated considering the liquid surface gravity wave, with a different thickness of wall panel being 0.25m, 0.60m, and 1.00m, respectively. The results are shown in figure 6.

One may observe from the calculation results that the dynamic pressure of the liquid is a sensible physical quantity. Following the increase of the thickness of wall panel, the time history curve of the dynamic pressure of liquid has similar shape but the value of the curve declines obviously. Therefore, the more elastic the wall panel is, the stronger the liquid-structure interaction will be. The vibration of the structure is resulted from the inertia force and the dynamic pressure of the liquid which are all caused by the ground acceleration. When the thickness of the wall panel increases, the inertia will force increase, but the dynamic pressure of the liquid declines. As a result, the time history curves of the dynamic response (moment and shearing force) by the action of the two effects approaches closer in the shapes and in the values. The amplitudes of the shearing force and moment with a thickness of the wall panel being 0.6 meter are only 3.73 and 3.74 percent higher than that when the wall panel thickness is 0.25 meter. Therefore, for the engineering application, the effect of the relative thickness of the wall panel on the dynamic response of the structure can be negligible.



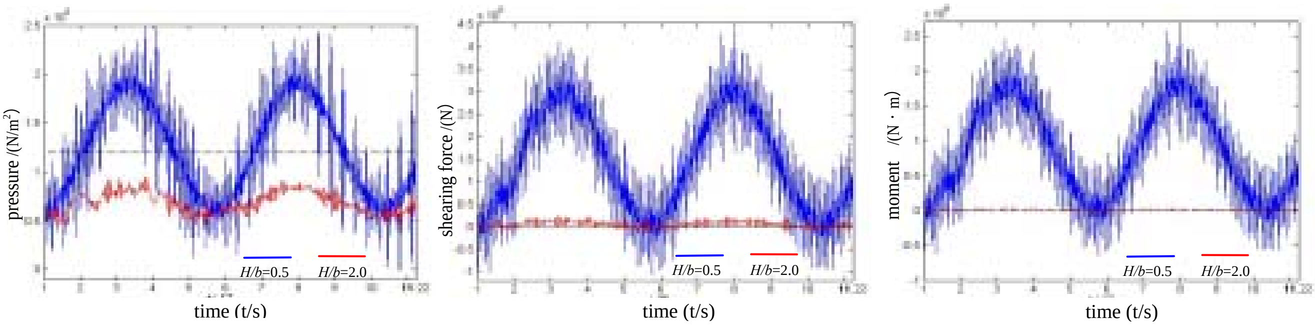
(*a*) dynamic pressure (*b*) shearing force (*c*) moment

Figure 6 the time history curves of point *A* by the action of El Centro wave with different wall panel thickness

3.4 Influence of the Dimension of the Structure on the Dynamic Response

With the liquid surface gravity wave considered, the dynamic response of the shallow liquid storage tank (*H*/*b*=0.5) and the deep one (*H*/*b*=2.0) are calculated respectively (where *H* is the height of the structure and *b* is length of the longer side). The results are shown in figure 7.

It can be seen from the calculation results that the dynamic responses between the shallow liquid storage structure and the deep ones are very different. The variables such as dynamic pressure of the liquid, shearing force and moment of the shallow liquid storage structure are all much higher than the corresponding values of the deep ones. This phenomenon present again that the effect of the liquid surface gravity waves on the dynamic response is significant. Accompanying with the increase of the height of the tank, the influence of the surface gravity wave on the dynamic response is declined rapidly. So the dynamic response of the deep liquid storage structure is enormously reduced. For the liquid storage structures with same height, it can clearly be seen that the bigger the plane dimension is, the stronger the dynamic response by the action of earthquake will be.

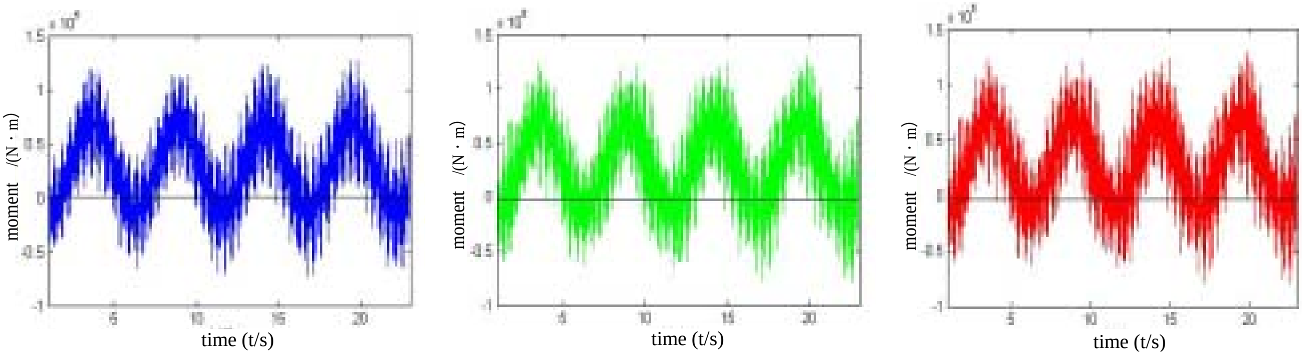


(*a*) dynamic pressure (*b*) shearing force (*c*) moment

Figure 7 the time history curves of point *A* by the action of El Centro wave with various ratio of height to width

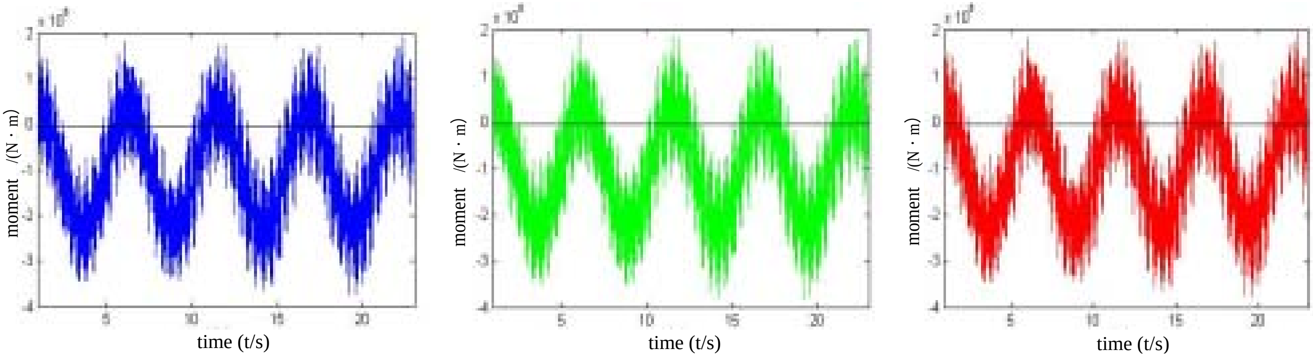
3.5 Dynamic Response by the Action of Coupled Multi-Directional Seismic Input

The actual earthquake is a complex three-dimensional vibration. It vibrates not only in horizontal direction(x and y) but also in vertical direction (z) at the same time. The dynamic response of the system by the action of the unidirectional, bidirectional and three-directional coupled seismic actions in Qianan wave (N-S, E-W, and vertical) shown in figure 1 are calculated respectively. The amplitude of the seismic wave are adjusted proportionately to be 2.0m/s^2, 1.47m/s^2, and 1.16m/s^2. Comparing the dynamic response by the action of bidirectional and three-directional coupled seismic actions with that by the action of the unidirectional seismic action, it can be found that the increase of the amplitudes by the action of the coupling conditions are tiny than unidirectional condition for the liquid storage structure. Because the symmetry of the quality and stiffness of the rectangular liquid storage structure, the increases of the amplitude are all less than 3 percent, and several variables are declined. Because the anti-seismic design aim at the amplitude of the internal force, the calculation using the unidirectional seismic action can meet the need of design. Furthermore, the maximum of the time history curves by the action of unidirectional, bidirectional and three-directional coupled seismic actions is not coincident, which reflects the coupling effect. If the interest of the researcher is the dynamic response at any time, they should pay attention to the coupling effect of the bidirectional and three-directional seismic actions. For the limitation of the space, only parts of the calculation results are shown in figure 8 to figure 9.



(a) unidirectional (b) bidirectional (c) three directional

Figure 8 the time history curves of the moment in point A by the action of Qianan wave



(a) unidirectional (b) bidirectional (c) three directional

Figure 9 the time history curves of the moment in point B by the action of Qianan wave

4. CONCLUSIONS

Through the analysis described above, the main conclusions can be derived as follows:
(1) The effect of the gravity waves on the dynamic response is not negligible. The values and the shapes of the time history curve between the two conditions with or without the gravity waves are obviously different.

(2) The more elastic wall panel is, the stronger the liquid-structure interaction will be. But for the engineering application, the influence of the stiffness of the wall panel on the dynamic response of the structure can be negligible.

(3) Because of the effect of the liquid surface gravity wave, the dynamic response of the shallow liquid storage structures is much higher than that of the deep ones. The anti-seismic design should attach more importance to the phenomenon that for the liquid storage structures with the same height, the bigger the plane dimension is, the stronger the dynamic response by the action of earthquake will be.

(4) Because the influence of bidirectional and three-directional coupled seismic actions on the dynamic response are trivial, the calculation by the action of the unidirectional seismic action can meet the need of the anti-seismic design of the liquid storage structure.

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REFERENCES:

Ju RC, and Zeng XC. (1983). Theory of Coupled Vibration of Elastic Structure and Liquid. Beijing: earthquake press,.

Li Yanming, Xiu Gang,etc. dynamic response analysis of liquid-filled tanks [J]. engineering mechanics,2002.8. 19(4):29-31.

Liu Yunhe, Wang Kecheng,etc. seismic analysis of liquid storage container[J]. earthquak engineering and engineering vibration,2005.2.25(1):149-154.

Liu Xijun,Zhang Suxia,etc. the analysis of gravity waves in a rectangular elastic fluid-shell coupled system [J]. china journal of theoretical and applied mechanics,2006.1.38(1):106-111.

Wilson, E.L., statical and dynamic analysis of structure-the physical methods stressed on earthquake engineering [M].china architecture and building press,2006.1:1-10.

Song Tianxia, Guo Jiansheng，etc. nonlinear conculational solid mechanics [M].Wuhan ∶Huazhong University of Science an Technology press,2005.11

Cheng Xuansheng,Du Yongfeng. Confirm of elasticity coefficient about orthotropic plates of reinforced concrete[J]. Sichuan building science,2006.32(5):30-33

Shanghai municipal engineering design and research institution,etc. design handbook of water and wastewater engineering. china architecture and building press,1984:536