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ANALYSIS OF SEISMIC RESPONSE OF PASSIVE TANK OF A NEW GENERATION NUCLEAR POWER PLANT

B. Jin[(1)], BR. Jiang[(2)], YW. Gao[(3)], L. Ye[(4)]

[(1)] *Associate Professor,*
Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration, Harbin 150080, China, jinbo@iem.net.cn
[(2)] *Postgraduate candidate,*
Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration, Harbin 150080, China,1181576210@qq.com
[(3)] *Postgraduate candidate,*
Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration, Harbin 150080, China, 984379231@qq.com
[(4)] *Postgraduate, Harbin Engineering University, Harbin 150001, China,1191417921@qq.com*

Abstract

In 2011, Japan Fukushima serious nuclear accident brought a deep influence on the world's nuclear power development, especially for China. Then the third generation nuclear power plant, applying passive safety system to prevent and mitigate the serious accidents, is getting more and more attention. In this paper, firstly the PCS (Passive Containment Cooling System) gravity drainage water tank of a nuclear power plant (AP1000) is introduced. AP1000 as the third generation of nuclear power technology has a unique concept in the field of passive safety design. Then the energy dissipation effect and the responses of different kinds of earthquake inputs to a tank are generally analyzed and compared, which includes different wave frequency, single and bidirectional input directions and so on. In the analysis process, an ABAQUS model is used to simulate the fluid structure interaction between water and tank wall by using the Coupled Euler Lagrange analysis technique (CEL) and the simplified added mass method. Meanwhile the effect of tanks with different volume of water storage on the containment building is also studied, and it shows that the sloshing of the water in the tank did not play a shock absorbing effect on the building, while the ground motion response of the building increased along with the volume of the water. Finally, some suggestions and discussions are presented.

Keywords: seismic response; gravity drainage water tank; ABAQUS; Coupled Euler Lagrange analysis; bidirectional input

1. Introduction

AP1000 is the third generation nuclear power technology, which is much simpler, safer and more economic, compared to the previous generations of nuclear power technology. And it is the main direction of the future development of nuclear power technology. The passive containment cooling system (as shown in Fig. 1) is one of the important design feature of the system. Its principle of action is that, the water in the water tank sprays to the steel containment by gravity spontaneously, to be heated and evaporated, and it is discharged from the plant through the natural convection channel at last, so as to reduce the temperature of the steel shell in the plant. The outer structure of the passive containment cooling system is composed of tubular reinforced concrete structure and water tank connected to each other. It is so called the containment building (as shown in Fig. 2) [1]. The containment building is one of an important part of the passive containment cooling system, and it is the last safety guarantee of nuclear reactor, whose normal operation and integrity has a vital impact on the safety of nuclear power plant.

In order to ensure the safety of the nuclear power plant, it is necessary to consider the response of the containment building under earthquake load which is likely to cause significant damage. However, under the action of an earthquake, the vibration of the liquid in the tank is different from that of the solid. Long before, the solution to the problem of liquid-solid coupling has caused great attention in engineering field. With the deepening of research, the related theory, simulation and experiment of liquid sloshing have reached a certain level. Referring the previous theories, liquid sloshing in tank can be divided into linear sloshing and nonlinear sloshing. In the analysis of the vibration response of a safety building, the liquid in the tank is in a state of nonlinear sloshing. However, the nonlinear sloshing of liquid in frequency is variable, and the damping of the liquid can not be linearly expressed. The liquid sloshing inside may also produce resonance, and the free surface of sloshing liquid also has the possibility of overflow. So it is very difficult to calculate the liquid nonlinear sloshing problem in theory [2][3]. Nevertheless, with more and more powerful computing capabilities and the development of finite element technology application, there is a new breakthrough in processing liquid nonlinear sloshing problems, which is named free surface wave simulation technology by finite element method. In this paper, we use Coupled Euler Lagrange analysis technique (CEL) by the finite element software of ABAQUS to carry out numerical simulation. It looks very good to deal with the liquid-solid coupling problem and has completed the simulation of free surface wave. This method is then compared with the traditional added mass method, the difference is distinguished.

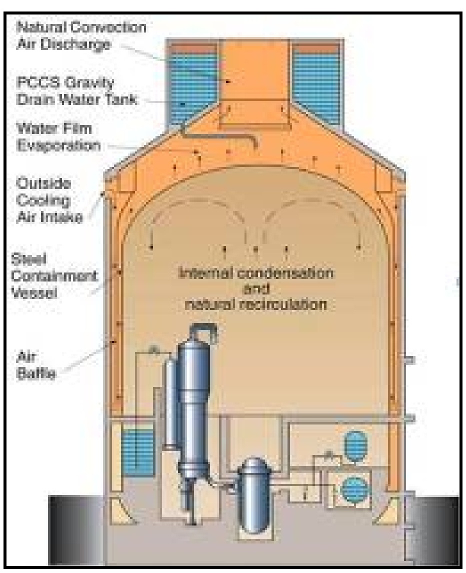

Fig.1 Passive containment cooling system

Fig.2 Containment building

2 Methods and principles of analysis

2.1 Liquid-solid coupling

The problem of liquid-solid coupling dynamics is a branch of mechanics to study the interaction between liquid and solid. In the simulation of the water tank of a containment building, the water tank will deform or move under the load of the moving liquid, and at the same time the deformation or movement of the water tank in turn will affect the movement of the liquid inside, and further change the liquid loading on the tank. This is a kind of liquid-solid coupling phenomenon. The liquid-solid coupling problem can be defined by the coupling equation. The definition domain of the equation is liquid domain and solid domain. The variables of the equation are the ones describing the phenomena of the liquid and the others describing the phenomena of the solid. But it is generally not possible to solve liquid domain or solid domain separately, and can not explicitly eliminate variables describing phenomena of solid and liquid. These are the characteristics of liquid-solid coupling.

In the last few years, the liquid-solid coupling theory has been introduced into the scientific research and developed fast, as in the following three aspects: The first one is that the linear problem of liquid-solid coupling has been gradually developed to the nonlinear problem. In the second aspect, the problem of deformation and intension has been gradually developed to the problem of buckling of solid structure. The third aspect is about the integration model of liquid-solid coupling, whose specific form of computation has been developed from the single solid finite element format and the single fluid difference format to a merging liquid-solid coupling mutual fusion form. Through the research and development of the liquid-solid coupling problem, it has been able to fully consider with the material nonlinearity and the geometric nonlinearity, which not only can be used in the solid, but also has made outstanding achievements in the liquid. Nowadays, the fluid model has begun to consider its viscosity and its cavitation, and then the phenomena of splashing, cavitation, shaking, and so on are simulated [4][5][6].

2.2 Additional mass method and Coupled Euler Lagrange analysis technique (CEL) of finite element programs

When we deal with the liquid-solid coupling problem of liquid storage container, additional mass method is usually used to simplify the model. The method of simplifying a rigid storage tank to the mass elastic system proposed by Housner has the significance of simple model and practical engineering, and has been recognized by the engineering community. This method divides the hydraulic pressure into two parts: one part is the impulse pressure generated by the inertia force of liquid that is synchronized with the container, and the other part is the convection pressure generated by the free sloshing of liquid in the container. Housner simplified the liquid part to different mass units and spring the units (as shown in Fig. 3) [7][8]. However, when the additional mass method is used to calculate the seismic response of liquid storage container, the calculation of seismic shear force and bending moment is often lower than actual result, so it can not be fully applied to the calculation of the water tank of containment building. With the development of finite element programs, the calculation of the liquid storage container has a new breakthrough. Before the finite element software ABAQUS (V6.8), the adaptive grid method by Arbitrary Lagrangian-Eulerian (ALE) is used to simulate the liquid-solid coupling effect, and then the ABAQUS provides a new technique, that is the coupled Eulerian-Lagrangian (CEL). This method uses the Lagrange grid to simulate solid, and uses Eulerian mesh to simulate liquid, whose results can be very close to the actual, and it is more valuable in numerical simulation and practical application [9].

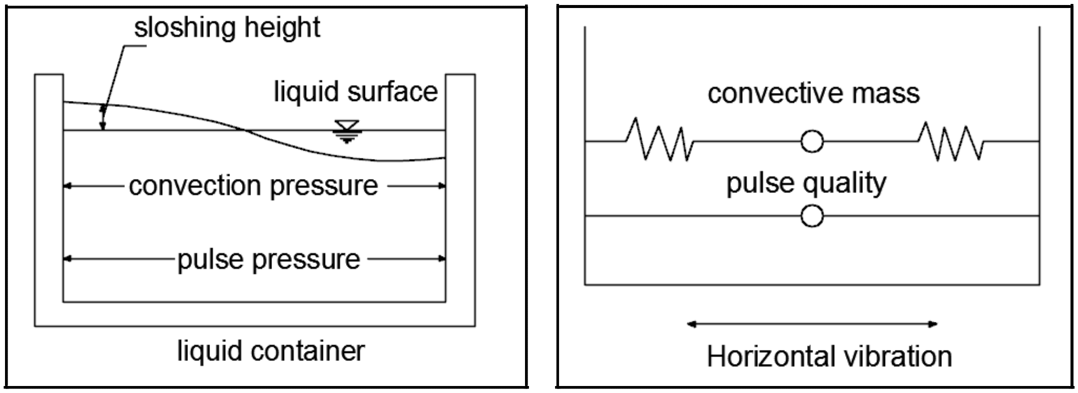

Fig. 3 Simplified model of Housner's additional mass method

3 The calculation model and material parameters

The basic information of the containment building is required in the model. The outer diameter of the cylindrical shell is 44.20m, The wall thickness is 0.984m. Ignoring the influence of the connection mode between the gravity tank and the shell, they are regarded as a whole. The water tank is a circular cylinder shaped structure with a bottom inclined ring, whose material is reinforced concrete. The thickness of the outer wall is 0.61m, and the thickness of the inner wall is 0.46m. The thickness of roof is 0.38m, and the volume of the tank is 2864.0m^3 (as shown in Fig. 4).

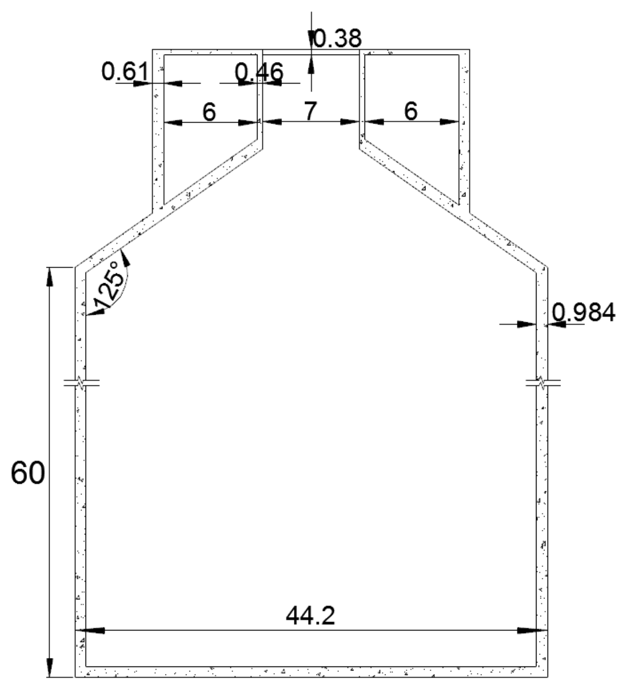

Fig. 4 The skeleton of the containment building (unit: m)

In this article, the influence of the water tank on the whole safety shell under earthquake is mainly studied. In order to smooth the modeling and not affect the simulation results, some of the details in the design of the plant are ignored, and an ideal model is established. For example, the opening of the security shell, the connection mode of the water tank and the concrete containment, and the effect of some non-structural attachments on the wall are ignored. Ideally, the ground is regarded as a rigid foundation, and the connection mode between the bottom of the building and the foundation is assumed to be a simple rigid connection.

The calculation analysis is limited at the elastic stage of material, and this assumption was checked for accuracy in the final results. And the Abaqus model need not be verified. When defining the constitutive model of reinforced concrete, we adopt a composite one. That is the reinforced concrete was defined as a material, and in a specific operation the appropriate weights is we needed to set to make it much closer to reality. In addition, the water in the tank is assumed to be incompressible ideal fluid. The necessary data required for the modeling are shown as in Table 1 and Table 2.

Table 1 Concrete parameters

ρ (kg/m^3)	E_c (N/m^2)	V	αl (/K)	K W/(m·K)	f_{tk} (N/m^2)	f_t (N/m^2)	f_{ck} (N/m^2)	f_c (N/m^2)
2500	3.25e10	0.2	1e-5	1.74	2.86e6	1.71e6	26.8e6	19.1e6

Note:
ρ -- Density
E_c -- Elastic modulus
αl -- Coefficient of linear expansion.
f_{tk} -- Standard value of axial tensile strength
f_{ck} -- Standard value of axial compressive strength
f_t -- Design value of axial tensile strength
f_c -- Design value of axial compressive strength
K -- Thermal conductivity
V -- Poisson ratio

Table 2 Liquid parameters

Density ρ (kg/m^3)	Coefficient of viscosity η (Ns/m^2)	Sound velocity in medium C_0 (m/s)	Us-Up curve's slope S	Gruneisen ratio Γ_0
983.204	0.00113	1500	0	0

ABAQUS is used to model the containment building with 1/4 volume, 2/4 volume and 3/4 volume of the water tank inside respectively. Among them liquid is simulated by two methods: additional mass method and CEL analysis technique. The first one uses solid element to simulate water, and ignores convection, only considering the effect of pulse. The CEL method is used to establish the Euler model of water, and then it is still needed to define the boundary constraints of Euler bodies, in order to prohibit the outflow of the Euler body through the tank wall. The unit type used in the containment building and the water tank is C3D8R unit type and the one used in the liquid is EC3D8R unit type. The type of release stiffness is set by the control of sandglass. Model grid is shown as in Fig. 5.

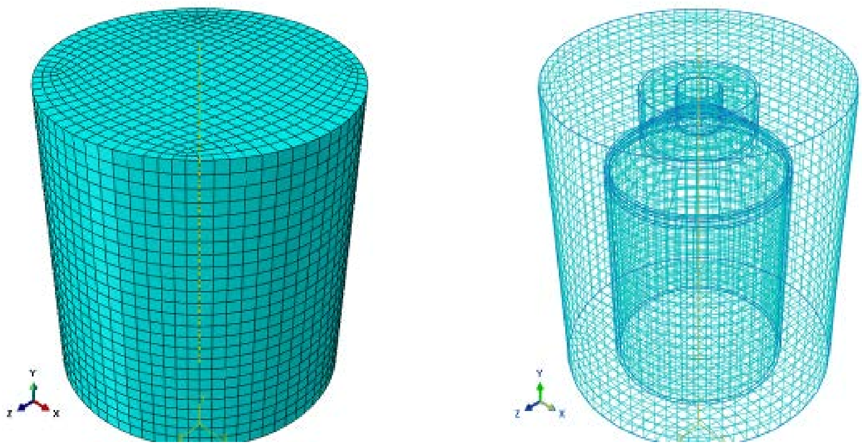

Fig. 5 Euler body and water tank’s model grid

4. Modal analysis

By means of defining the linear perturbation analysis in ABAQUS, the mode of the first 30 steps of the containment building without water is calculated. The results show that the same frequencies usually occur in horizontal two directions because of the structure’s regular symmetry. At the same time, the total model effective mass accounts for 95% of structure mass, indicates that the 30 order modes can fully reflect the dynamic characteristics of the structure. The first ten order modes are shown as in Table 3.

Table 3 First ten order modes of the containment building

Order	1	2	3	4	5	6	7	8	9	10
Frequency (Hz)	3.1486	3.1490	3.4229	3.5201	3.9591	4.2890	4.2920	4.5871	4.5873	5.4017
Periods	0.3176	0.3176	0.2921	0.2840	0.2526	0.2332	0.2330	0.2180	0.2180	0.1851

5. Response analysis with different volume of water storage under single direction seismic wave input

In order to complete the response analysis of the model under seismic excitation, seismic wave input is necessary. The purpose of this part is to study the seismic effects of the tank with different water storage on the containment building. Consequently EL-Centro wave is selected by the controlling variable method, and is input in the way of acceleration. The peak acceleration is 0.4g, and the ground motion duration is 12s according to experience.

5. 1 Seismic response of containment building with 1/4 volume of water tank

When the water tank has 1/4 of total volume of water, the height of the liquid level is about 52% of the total height of the tank. Additional mass method and CEL analysis technique are used to establish the model respectively. Then the stress nephogram and the displacement time history curve of the water tank vertex are drawn by ABAQUS (as shown in Fig. 6 and Fig. 7).

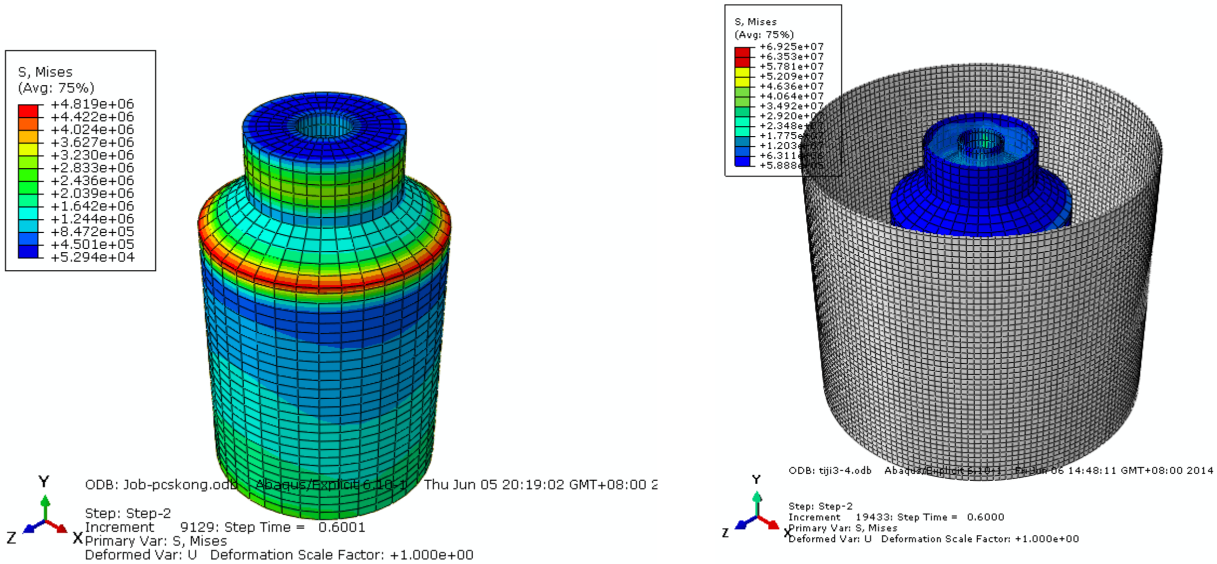

Fig. 6 Additional mass model's stress nephogram and the CEL model's stress nephogram of the containment building at a certain moment with 1/4 volume of water tank

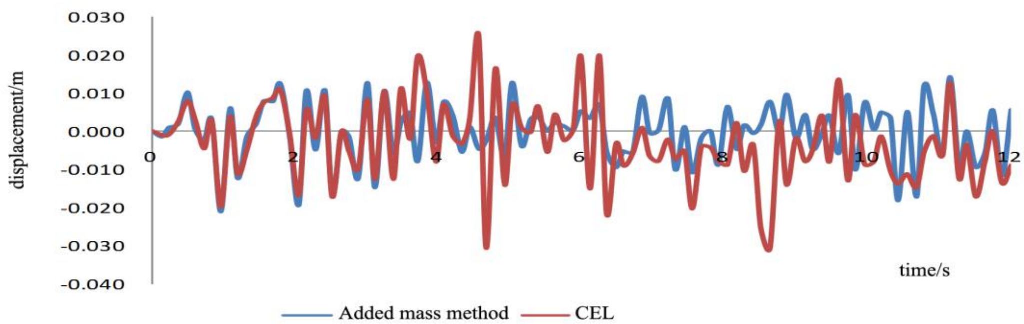

Fig. 7 Displacement time history curve of water tank vertex with 1/4 volume of water tank

Two views are drawn according to the stress nephogram above: (1) The maximum stress of the additional mass model is located in the shrinkage of the building, and the maximum value of Mises stress reaches 7.101MPa at 3s. (2) The maximum stress of the CEL liquid-solid coupling model is concentrated in the gravity drainage water tank, and the maximum value of Mises stress reaches 11.01MPa at 4.5s.

Meanwhile two views are drawn according to the time history curve above: (1) The peak displacement of the additional mass model reaches the maximum value of 0.021m at 0.96s. (2) Peak displacement of the CEL liquid-solid coupling model reaches the maximum value of 0.031m at 4.68s.

5. 2 Seismic response of containment building with 2/4 volume of water tank

When the water tank has 2/4 of total volume of water, the height of the liquid level is about 66% of the total height of the tank. Additional mass method and CEL analysis technique are used to establish the model respectively. Then the stress nephogram and the displacement time history curve of the water tank vertex are drawn by ABAQUS (as shown in Fig. 8 and Fig. 9).

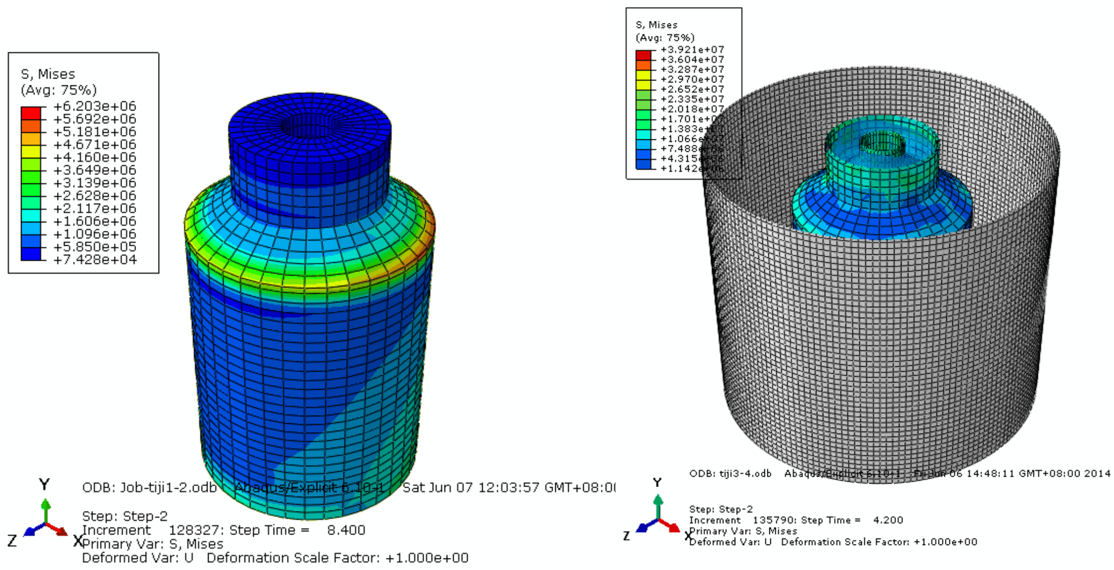

Fig. 8 Additional mass model's stress nephogram and the CEL model's stress nephogram of the containment building at a certain moment with 2/4 volume of water tank

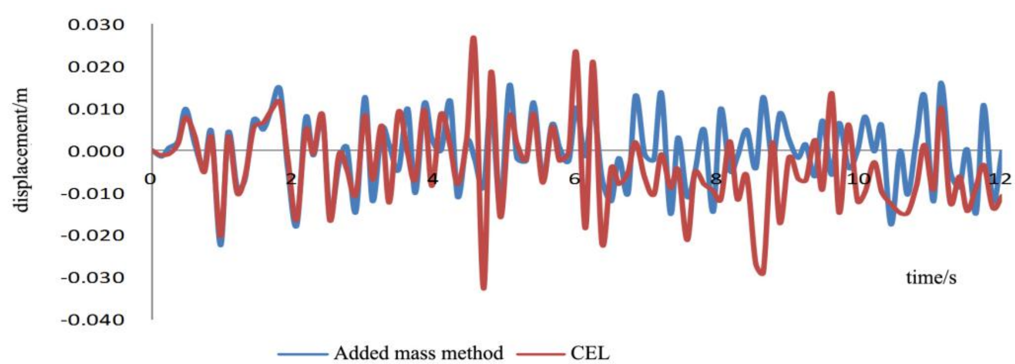

Fig. 9 Displacement time history curve of water tank vertex with 2/4 volume of water tank

Two views are drawn according to the stress nephogram above: (1) The maximum stress of the additional mass model is located in the shrinkage of the building, and the maximum value of Mises stress reaches 7.849MPa at 1.8s. (2) The maximum stress of the CEL liquid-solid coupling model is concentrated in the gravity drainage water tank, and the maximum value of Mises stress reaches 12.34MPa at 4.5s.

Meanwhile two views are drawn according to the time history curve above: (1) The peak displacement of the additional mass model reaches the maximum value of 0.022m at 0.96s. (2) Peak displacement of the CEL liquid-solid coupling model reaches the maximum value of 0.033m at 4.68s.

5. 3 Seismic response of containment building with 3/4 volume of water tank

When the water tank has 3/4 of total volume of water, the height of the liquid level is about 80% of the total height of the tank. Additional mass method and CEL analysis technique are used to establish the model respectively. Then the stress nephogram and the displacement time history curve of the water tank vertex are drawn by ABAQUS (as shown in Fig. 10 and Fig. 11).

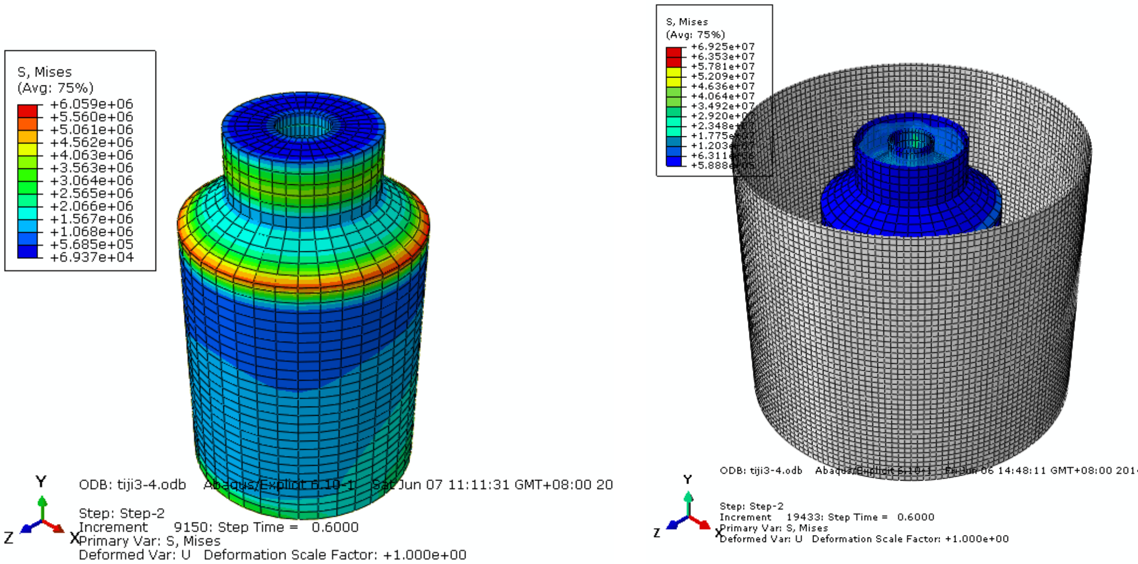

Fig. 10 Additional mass model's stress nephogram and the CEL model's stress nephogram of the containment building at a certain moment with 3/4 volume of water tank

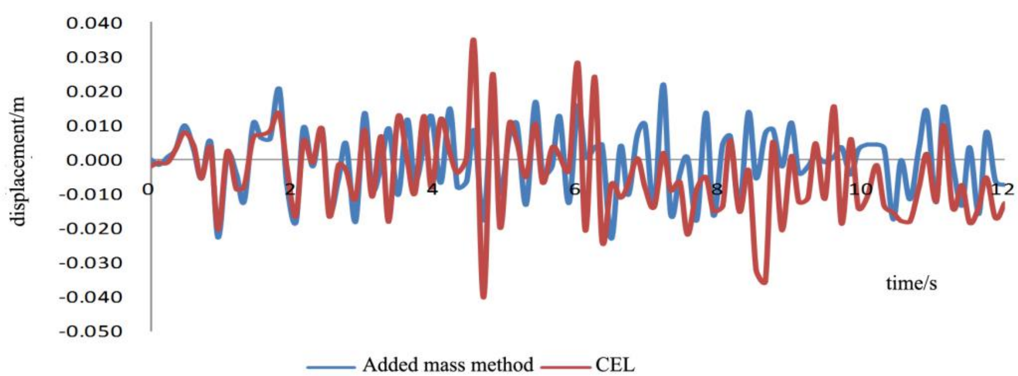

Fig. 11 Displacement time history curve of water tank vertex with 3/4 volume of water tank

Two views are drawn according to the stress nephogram above: (1) The maximum stress of the additional mass model is located in the shrinkage of the building, and the maximum value of Mises stress reaches 9.660MPa at 1.8s. (2) The maximum stress of the CEL liquid-solid coupling model is concentrated in the gravity drainage water tank, and the maximum value of Mises stress reaches 19.34MPa at 4.5s.

Meanwhile two views are drawn according to the time history curve above: (1) The peak displacement of the additional mass model reaches the maximum value of 0.023m at 0.96s. (2) Peak displacement of the CEL liquid-solid coupling model reaches the maximum value of 0.040m at 4.68s.

5.4 Comprehensive analysis and discussion

Under different volume of water storage, we found that the maximum stress of the additional mass model usually appears on the neck of the containment building, and the maximum stress of the CEL fluid-solid coupling model is concentrated on the gravity drainage water tank correspondingly. Under the same volume of water storage, compared with the additional mass model, the maximum stress of the later one occurs at late time, and its value is much larger. However the displacement time history of vertex for the two models have the same change, except for some much larger value of the vertex displacement of CEL liquid-solid coupling model. The main reason for those difference is that the additional mass model of water is built by solid element for water, which only considered the effect of pulse mass, but not of water on the convection, whereas the CEL liquid-solid coupling model can take into account the both effects very well, and also can reflect the convection of liquid, that is the maximum stress is the size of the liquid sloshing.

According to the stress nephogram and the time history curves of vertex, it is not hard to see that under ground motion, the influence of gravity water tank with different volume of water storage on the containment building is different. Under the same ground motion, no matter the added mass model or the CEL liquid-solid coupling model, the maximum stress in the stress cloud and the maximum displacement of vertex increase along with the volume of water storage. The sloshing of the water in the gravity tank did not play a shocking absorbing effect on the whole structure, while the ground motion response of the building increased along with the volume of the water.

6. Primary response analysis with different volume of water storage under bidirectional seismic wave input

In the previous sections, the response of containment building under single horizontal ground motion was analyzed, but vertical ground motion should also be considered in actual working conditions. Consequently, on the basis of the results of previous parts, the responses of containment building with different volume of water storage and different seismic wave inputs is studied with the CEL liquid-solid coupling model under vertical ground motions. In this section, the El-Centro earthquake wave, Ms8.0 Wenchuan earthquake wave recorded by 001BAH station and Ms7.0 Lushan earthquake wave recorded by 51BXD station are chosen as the input seismic waves, and the following combined simulation conditions are obtained: (1) Horizontal input: EL-Centro wave of 0.4g peak acceleration; vertical input: EL-Centro wave of 0.2g peak acceleration. (2) Horizontal input: Lushan earthquake wave of 0.4g peak acceleration; vertical input: Lushan earthquake wave of 0.2g peak acceleration. (3) Horizontal input: Wenchuan earthquake wave of 0.4g peak acceleration; vertical input: Wenchuan earthquake wave of 0.2g peak acceleration. The following results are obtained through the primary model calculation and analysis (as shown in Table 4).

Table 4 Maximum stress and maximum peak displacement under different seismic wave input conditions

Seismic wave	**Water volume**	**Position of maximum stress**	**Maximum stress value（MPa）**	**Maximum peak displacement（m）**
EL-Centro wave	1/4	building shrinkage	12.63	0.049
	2/4	building shrinkage	14.17	0.061
	3/4	building shrinkage	17.54	0.076
Lushan earthquake wave	1/4	building lower part	11.30	0.038
	2/4	building lower part	13.85	0.042
	3/4	building lower part	14.70	0.047
Wenchuan earthquake wave	1/4	building shrinkage	6.936	0.068
	2/4	water tank	9.696	0.071
	3/4	building shrinkage	13.66	0.079

From Table 4 we can get following results: (1) At the same ground motion input, the position of the maximum stress of the model with different water storage is not the same, where is concentrated in the water tank, the building shrinkage and the building lower part. The maximum stress value is also different, which increases along with the volume of water storage. (2) At the same ground motion input, the peak displacement increases along with the volume of water storage. (3) At the same volume of water storage, the bidirectional maximum displacement and stress is larger than the single direction's under the same El-Centro wave input. In summary, the numerical simulations of two models of different direction seismic wave input have little difference. It is further verified that the water in the gravity tank has no effect in energy dissipation. Moreover, the input of the vertical ground motion increases the response of the model.

This section is a just preliminary study on the response of the model under bidirectional ground motion input, and it is still need further research. For example, simulation of three-direction ground motion input, according to seismic design spectrum of a plant to determine the synthetic wave input, the unidirectional and bidirectional input of multiple sets of seismic waves input, etc.

7 Conclusion and prospection

7.1 Conclusion

(1) By ABAQUS to model and analyze the structure, it is found that the seismic response between the methods is different, and the response of the CEL liquid-solid coupling model is much larger, because the CEL liquid-solid coupling model can simulate both of the pulse and convection of the water, while the simplified model of the added mass is only account for the pulse effect.

(2) The magnitude of seismic response of the structure increased along with the volume of water storage in the tank, moreover the water in the water tank not only has no damping effect on the structure of the containment building, but also has the tendency to enlarge the seismic dynamic response, so the influence of the water must be taken into account in the design of containment building.

(3) For the response of the containment building, the results of bidirectional seismic wave input is larger than the ones of single direction's at the same volume of water storage.

7.2 Prospection

This paper is mainly the application of CEL technology in ABAQUS to simulate the seismic response of containment building in conditions of water storage, and some preliminary results have been drawn. Nevertheless there are still several problems need to be improved and studied in future as follows:

(1) During the analysis, we simplified the added mass method, without considering the influence of convection of the water, which is much easier to compare with simulated results of the CEL technology that had considered the influence of convection of water. While in the next step someone can use the additional mass model with the consideration of both convection and pulses of water to make theoretical derivation and then compare with the results of modeling and analysis.

(2) This time, only the unidirectional and bidirectional seismic inputs have been studied, more input directions should be considered and analyzed in the future.

(3) The influence of the proportion of the water storage mass in the total mass of the containment building should be considered to further study.

(4) For the passive water tank, the evaluation on its safety is valuable to conduct further research.

(5) In the next step, fine modeling and corresponding experiment should be considered and explored.

(6) The maximum displacements are more or less similar but the stress levels are quite different of the behavior of structures between El-Centro and Wenchuan earthquakes, whose ground motion characteristics and reasons need further analysis.

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