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THE SEISMIC RESPONSE ANALYSIS OF AP1000 NUCLEAR ISLAND SHIELD BUILDING CONSIDERING FSI

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Abstract

The cardinal component of the AP1000 nuclear island passive containment cooling system which is the much more different from other normal ones is the huge gravity water tank. This paper focus on the seismic response of AP1000 nuclear island shield building by creating a 3-D finite element model while takes the FSI into account. Then five different water levels have been studied, the water ratio of the water tank are 0%, 30%, 60%, 80% and 100% respectively. The natural vibration characteristics of the structure can be researched by the analysis of the refined-finite element model. The seismic motion record which is commonly used for the seismic analysis of the nuclear island is inputted as the earthquake loading. The displacement response, first principal stress response and response spectra of the important floors for the five water levels are analyzed to analyze the influence of the FSI to the seismic response of the shield building. The PGA of the input ground motion record is 0.3g, 0.6g and 0.9g to research the nonlinear seismic response of the AP1000 nuclear island shield building.

Keywords: AP1000 Nuclear Island, Shield Building, Fluid-Structure Interaction (FSI), Dynamic Characteristics, Seismic Response

1. Introduction

AP1000 nuclear island is a standard design developed by Westinghouse, which is an advanced nuclear island utilizes passive safety features. The design of the AP1000 nuclear island has been certified by the US Nuclear Regulatory Commission based on their review of seismic analyses at hard rock sites [1]. The AP1000 nuclear island has a containment as same as other normal nuclear islands, however it has a shield building as a second protective barrier which is much more different from others: the shield building is made of reinforced concrete with a steel containment vessel inside. The AP1000 nuclear island passive containment cooling system, which is another unique component, is composed of huge gravity water tank and air intakes. The passive containment cooling system just relies on the gravity, natural circulation and compressed gases to ensure the steel containment could be cooled down. The huge gravity water tank is located on the roof of the shield building and the air intakes are located at the top of the cylindrical portion of the shield building. The AP1000 nuclear island has been constructed in China named as Sanmen Nuclear Island.

The cardinal component of the AP1000 nuclear island passive containment cooling system is the huge gravity water tank. As the huge mass of the water tank is approximately 3000 tons, the sloshing phenomenon of the water may bring nonnegligible effects on the dynamic characteristics and seismic response of the shield building. And the Fluid-Structure Interaction (FSI) between shield building and the water in the water tank has attracted great interests of many researchers. Jean and Daniel [2] investigated the dynamic response of a naval propulsion ground prototype nuclear reactor with FSI modeling, and the FSI is considered by the following effects: added mass effects, coupling effects, added stiffness effects. By comparing the results of three effects, it showed that added mass and coupling effects proved to be of great importance, whereas added stiffness effects showed negligible influence on the reactor global dynamic behavior. Frano and Forasassi [3] investigated the influence of the internal structures and the FSI on the dynamic response of the nuclear island containment. He found that the internal structures had a dramatic effect on the stress distribution and deflection of the containment, while the sloshing of the water made the natural frequency of the structure reduce significantly. Zhao et al. [4-7] discussed the effect of the shape and elevation of air intakes, the water level of the water tank on the dynamic characteristics and seismic responses of the AP1000 nuclear island considering FSI to find the optimal design of air intakes. Lu et al. [8] studied the effect on acceleration response and Von Mises stress distribution when taking FSI into account under the earthquake loading. The results shown that the maximum Von Mises stress appeared at the intersection of the roof and the water tank of the shield building.

However, it is noticed that the previous researches focused on the FSI effects on the seismic response subjected to the Safe Shutdown Earthquake (SSE) intensity. Very few researchers pay attentions to the vibration mode and the influence of greater earthquake which intensity is more than the SSE intensity, and whether the shield building yields or not under larger earthquake loading when taking the FSI into consideration is not covered.

2. Finite Element Model of the AP1000 Nuclear Island Shield Building

2.1 Introduction of the AP1000 Nuclear Island Shield Building

The AP1000 nuclear island shield building is a huge reinforced-concrete structure which located outside of the steel containment vessel and the cylindrical portion, the roof, air intakes, huge gravity water tank, air diffuser and air baffle make up the shield building. The cylindrical portion located bottom which provides support to the huge gravity water tank on the roof. There are 16 rectangular air intakes locating at the upper corner of the cylindrical portion and four equipment holes with different size locating at the medium part of the cylindrical portion. The AP1000 nuclear island shield building structure is shown in Fig. 1 and the geometrical parameters are shown in Table 1.

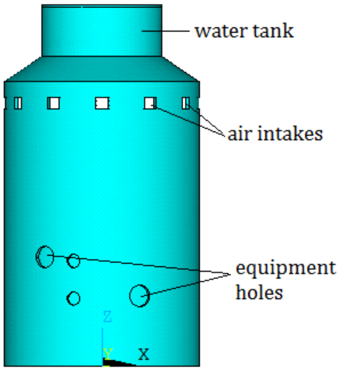


Fig. 1 – The AP1000 nuclear island shield building

Table 1 – Geometrical parameters of the shield building

outside diameter of the cylindrical portion	22.1m
inside diameter of the cylindrical portion	21.18m
height of the cylindrical portion	26.6m
outside diameter of the upper roof	5.6m
inside diameter of the upper roof	4.88m
height of the roof	11.31m
height of the huge gravity water tank	10.7m

2.2 Finite Element Model

Numerical simulation is an effective method to study the dynamic response, and it is an efficient way to study the FSI of a huge structure which is difficult to experimental studies. In this paper, the finite element analysis software ANSYS is used to build a numerical model of the huge structures. Based on the ANSYS software the finite element model of the AP1000 nuclear island shield building is established considering the FSI. The theory of FSI can be referred in a former study [4].

Fig. 2 shows the finite element model of the AP1000 nuclear island shield building including the huge water tank, air intakes and equipment holes. Solid 65 element in ANSYS is used to mesh the shield building except the water in the huge water tank, while Fluid 30 element is used to simulate the water for FSI analysis. The element size also affects the accuracy of the simulation analysis result. The smeller element size meshing the more accuracy results will be got, however, the computational costs will increase with the element size decreasing. Therefore, the parts which may cause stress concentration performance, such as equipment holes and air intakes, are meshed with an element size of 500 mm. The bottom of the shield building suffering large stress is meshed with the size of 800 mm, and the rest parts are meshed with an element size of 1000 mm. This model above can save computational costs and guarantee the accuracy of the results. The material properties of this model are shown in the Table 2.

When earthquake happens, the water in the huge water tank will spray to the steel containment vessel to cool the containment, and then the water level become lower during the earthquake happening. In order to simulate the continuous decrease of water, five different water levels corresponding to the 100%, 80%, 60%, 30% and 0% of operational water volume are researched to study the dynamic characteristics and seismic response of water level decreasing when the earthquake happens. Fig. 3 shows the five different water levels of the huge water tank.

Table 2 – Material properties of the model

Material	Density (Kg/m^3)	Elastic module (Gpa)	Poisson ratio
Concrete	2500	32.5	0.2
Steel	7800	200	0.27
Water	1000	-	-

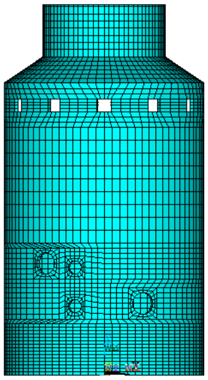
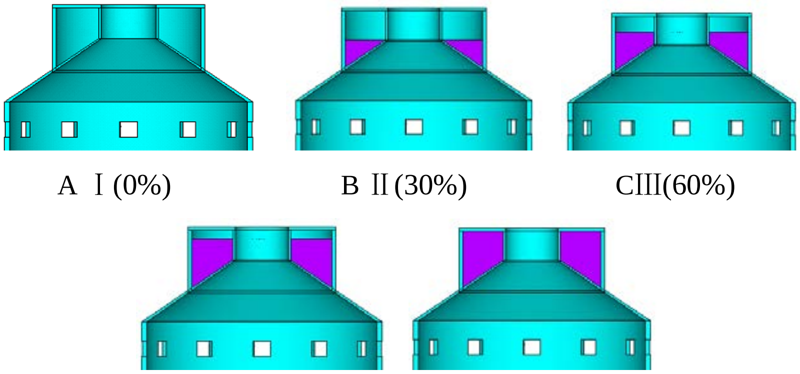


Fig. 2 – Model of AP1000 nuclear island shield building



A Ⅰ(0%)

B Ⅱ(30%)

CⅢ(60%)

D Ⅳ(80%)

E Ⅴ(100%)

Fig. 3 – Five different water levels

3. Dynamic Characteristics Analysis of the AP1000 Nuclear Island Shield Building

The natural frequencies and mode shapes are important characteristics of a structure. A modal analysis of the shield building with five different water levels was studied, and the first six natural frequencies and natural vibration mode shapes were compared. Table 3 and Fig 4 show the first six natural frequencies of shield building with five different water levels from modal analysis. The results of the modal analysis of the shield building show that the first six natural vibration mode shapes for the different five water levels are similar, the modal shapes of shield building, cylindrical portion and the roof are represented in Fig. 5 (Because of the similarity between the mode shapes of five water levels, only the first six mode shapes of the empty shield building are showed in this paper)

Table 4 – First six order natural frequencies of the shield building for five different water levels

Water ratio(%)	**Mode**					
	1	**2**	**3**	**4**	**5**	**6**
0%	3.365	3.717	4.408	4.429	5.244	5.252
30%	3.28	3.287	4.406	4.428	5.200	5.208
60%	3.174	3.181	4.406	4.428	5.179	5.187
80%	3.078	3.086	4.406	4.428	5.172	5.179
100%	2.984	2.981	4.407	4.428	5.150	5.156

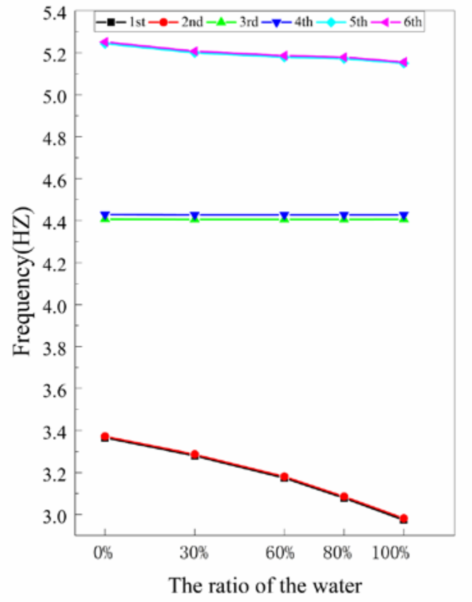
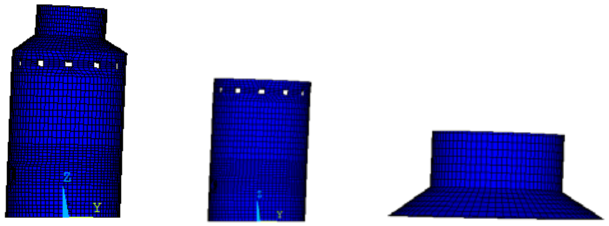
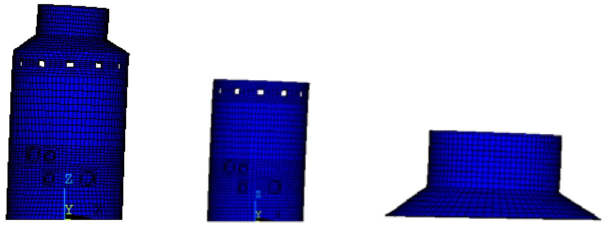


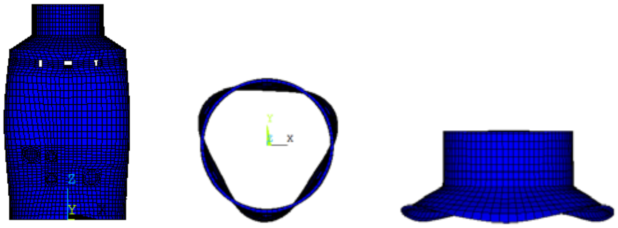
Fig. 4 – First six natural frequencies of the shield building for different water levels



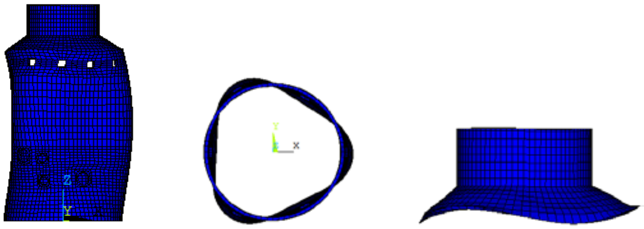
(a) The first order modal shape



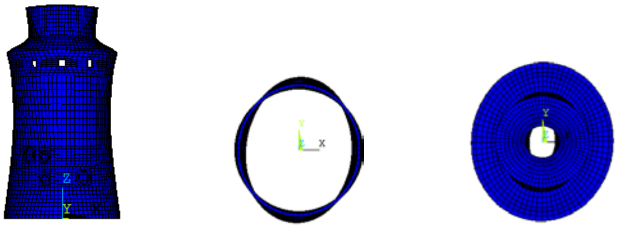
(b) The second order modal shape



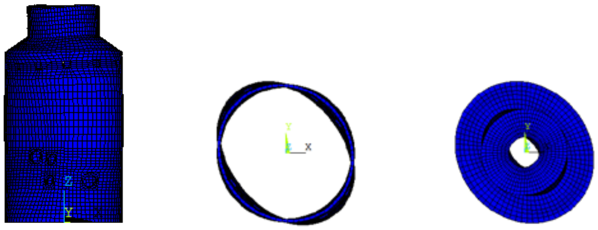
(c) The third order modal shape



(d) The fouth order modal shape



(e) The fifth order modal shape



(f) The sixth order modal shape

Fig. 5 – First six modal shapes of the shield building, the cylindrical portion and the roof

As shown in Table 4, the first and second natural frequencies of each water level are approximately equal. The third and fourth natural frequencies appear the same phenomenon, so as the fifth and sixth natural frequencies. Because of the four different size equipment holes which located on the shield building unsymmetrically, the shield building is not a completely symmetrical structure. That is the reason why the first and second order natural frequencies are approximately but not equal. Fig 4 shows the changes of the natural frequency for various water levels. It shows that the first six natural frequencies are decreasing with the water levels increasing except the third and fourth natural frequencies. However, the changed rates are not the same. For the first two natural frequencies, when the ratio of the water is less than 60%, the rate of the natural frequencies decreasing with the level increasing is less than when the ratio of the water greater than 60%. The third and fourth natural frequencies are almost unchanged with the water level increasing. The fifth and sixth natural frequencies are decreasing with the water increasing which as same as the first two natural frequencies, while the rate of change is much less than the rate of the first natural frequencies. Comparing the influences of the water levels to the natural frequencies of the shield building, the effect to the first two natural frequencies are greatest.

According to the mode shapes of the shield building, the first two mode shapes are lateral translation movements of the shield building with the water sloshing. However, the third and fourth mode shapes are circumferential multi-wave vibration of the cylindrical portion without the roof vibration that the water does not contribute for the third and fourth mode shapes. That is the reason why the third and fourth natural frequencies do not change with the water level changes. The fifth and sixth mode shapes are circumferential multi-wave vibration of the cylindrical portion and roof respectively. It can be observed from the Fig. 5 that the circumferential vibration of the cylindrical portion has larger amplitude than the roof vibration. Comparing the first six mode shapes of the shield building, the sloshing of the water with the shield building lateral translation movements makes larger contribution to the shield building natural vibration. That is the reason why the first two natural frequencies are relative strongly influenced by the change of the water level.

4. Seismic Response of the AP1000 Nuclear Island Shield Building

This paper studied the effects of water sloshing and oscillation to the seismic response of shield building considering FSI. A Kobe ground acceleration record, as shown in Fig. 6, is selected as the input earthquake loadings. The input earthquake ground motion is normalized to have PGA of 0.3g to analyze the seismic response of shield building under Safe Shutdown Earthquake intensity. Then in order study the non-linear seismic response of the shield building, the PGA of the input ground motion are scaled to 0.6g and 0.9g respectively. Newmark numerical method is used for the dynamic time history analysis of the shield building under the earthquake loading. Rayleigh damping method is used in this paper for the damping calculation of the shield building structure. According to the UK AP1000 Safety, Security, and Environmental Report [9], the damping coefficient of the shield building is assumed as 7%.

4.1 Displacement Response

In order to analyze the displacement response of the shield building, thirteen nodes, shown in Fig. 7, are selected along the vertical direction of the shield building. The elevation of the 13 nodes are A (10m), B (20m), C (30m), D (40m), E (50m), F (60m), G (64m), H (67m), I (70m), J (73m), K (76m), L (79m), M (81m) respectively. The X direction horizontal displacement response is investigated.

According to the dominant natural mode shape of the shield building, the displacement response of the top node (M), shown in Fig. 8, is analyzed under the SSE intensity (0.3g). The time history curve of the displacement response (M) shows that the maximum displacements of the top node for five water levels appear at different times and show a delay behavior with the water level increase. The maximum displacement response of the top node with different water levels are also shown in Fig 9 under input ground motion with PGA of 0.3g, 0.6g and 0.9g. It can be observed that the maximum displacement responses of the top node increase with the water level increase in different changing rates. The changing rates were increasing with the water lever increasing which shows a great agreement with the changing rates of the first two natural frequencies of the shield building. It also shows agreement with the first and second mode shapes of the shield building which are mainly lateral translation movements. However, the maximum displacements of the top node still do not show nonlinear behavior because of the three parallel lines in Fig. 9 even at 0.9g. The largest difference of the maximum displacement of the top node (M) among the five water levels is 30%. The maximum displacements of the 13 nodes for different water levels under the SSE intensity are shown in the Fig. 10. As for the cylindrical portion of the shield building, the influence of the FSI on the maximum displacement increases with the elevation of the nodes increase. The impact of the FSI on the water tank on the roof increases with the water level increase. Comparing the influence of the water levels on maximum displacement of the three portion of the shield building, the influence of water level on the water tank is much more obvious than any other portions of the shield building.

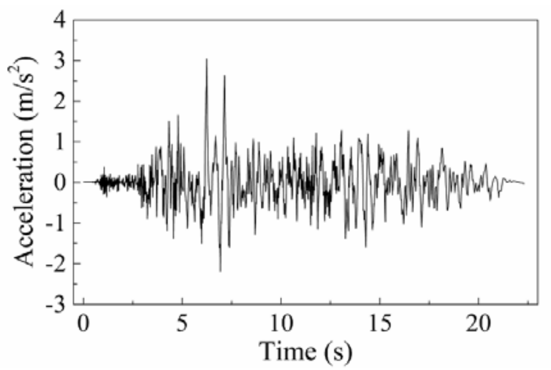


Fig. 6 – Kobe acceleration record

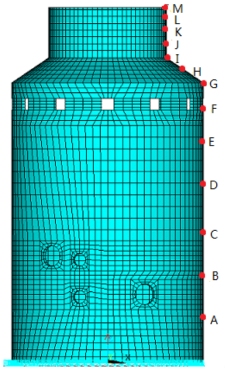


Fig. 7 – Selected 13 nodes of the shield building

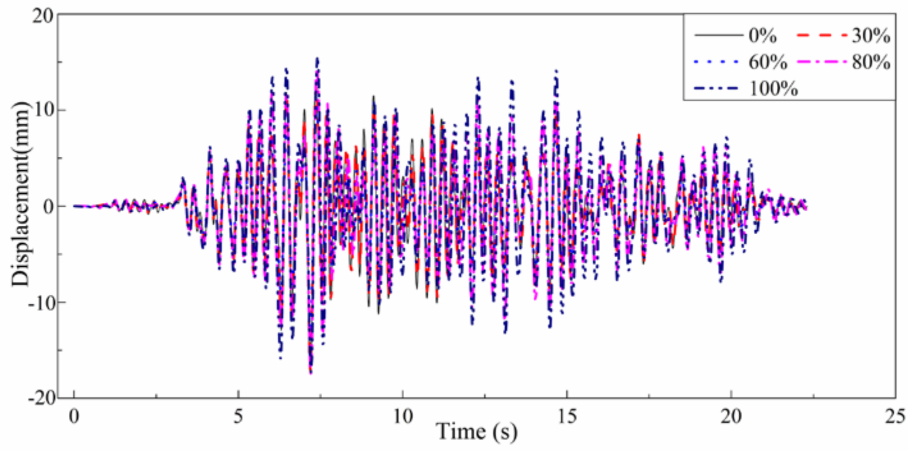


Fig. 8 – Displacement time history response of the top node (M)

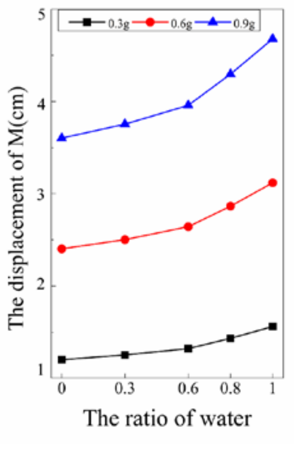


Fig. 9 – The maximum of the top node (M)

(0.3g, 0.6g, 0.9g)

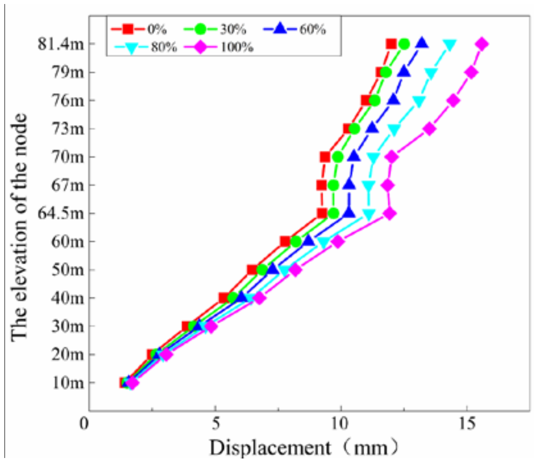


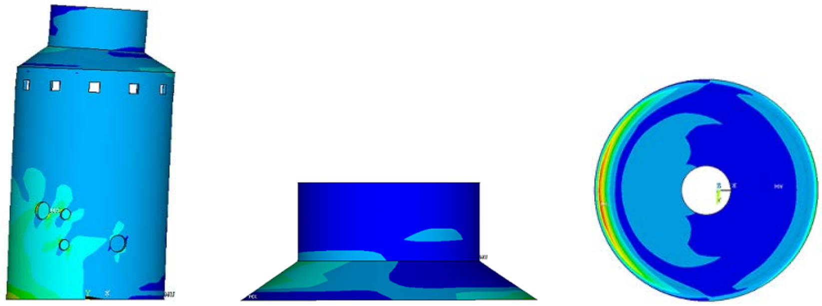
Fig. 10 – The maximum displacement of

the 13 nodes (0.3g)

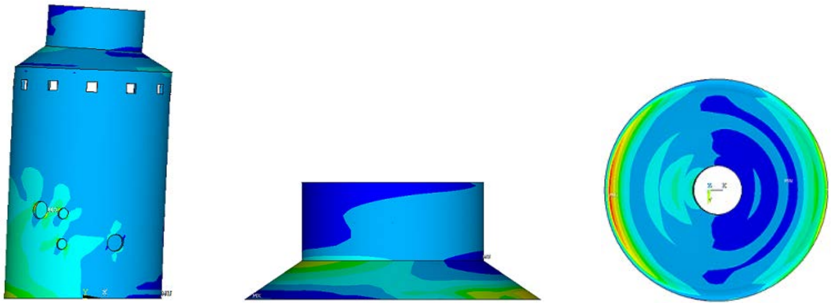
4.2 First Principal Stress Response

The first principal stress distribution for five water levels when the displacement of the top node reaches the maximum value are obtained. The first principal stress distribution of the roof is obtained with front view and top view. They are all shown in the Fig. 11. The maximum first principal stress of the shield building with different water levels are shown in Fig. 12 under input ground motion with PGA of 0.3g, 0.6g and 0.9g.

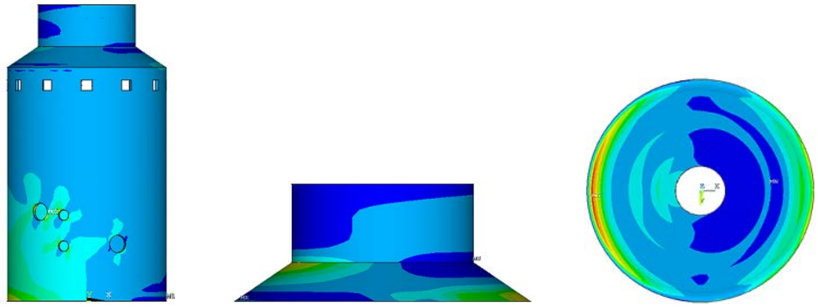
The maximum first principal stress of the shield building appears at the bottom of the shield building which shows a great agreement with the first mode shape of the shield building. The water level almost not impact the first principal stress distribution of the cylindrical portion of the shield building. The compressive region of the cylindrical portion at upper left extends with the water level increase. The compressive region of the roof extends with the increase of the water level. The maximum first principal stress of the roof arises at the intersection of the roof and the huge water tank where also occurs stress concentration phenomenon. It is observed that the first principal stress distribution is almost unaffected by the water level. However, the maximum first principal stress of the shield building increases with the water level increase obviously. In addition, the curves of the maximum first principal stress of the shield building for different water levels under the ground motions with PGA of 0.3g, 0.6g and 0.9g are parallel which again shows the shield building still on linear elastic state under the 0.9g ground motion.



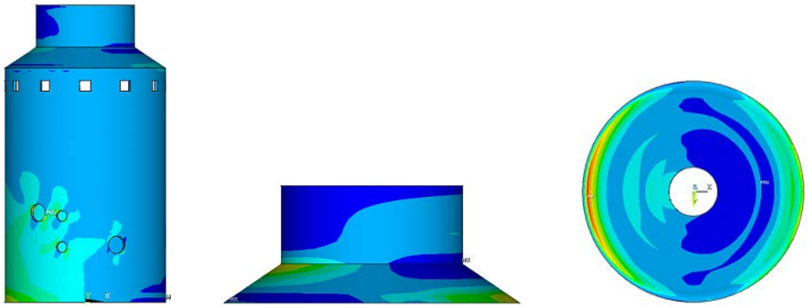
(a) Ⅰ(0%)



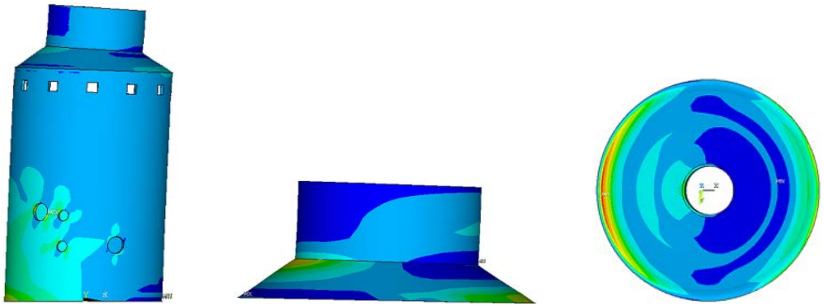
(b) Ⅱ(30%)



(c) Ⅲ(60%)



(d) Ⅳ(80%)



(e) Ⅴ(100%)

Fig. 11 – Maximum principal stress distribution of the shield building (frond and top view)

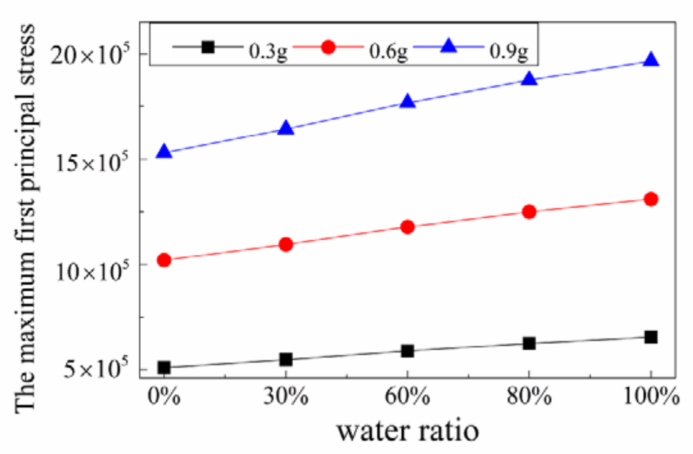
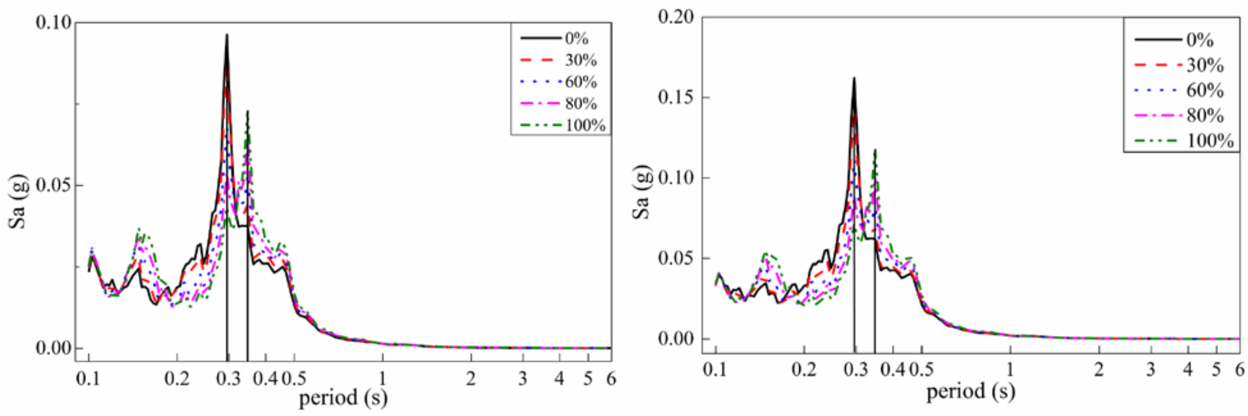


Fig. 12 – Maximum principal stress of the shield building (0.3g, 0.6g, 0.9g)

4.3 Response Spectrum of Important Floor

AP1000 nuclear island has two important floors [10], one is the maintenance floor and another is the operation floor. The elevations of the two important floors are at 31.4m and 46.6m respectively. The equipment and reactors on the floors may suffer large dynamic forces when the structure subjects to the seismic loadings. The response spectra of the important floors are main bases for the seismic design of the equipment and reactors. The floor response spectra for maintenance and operation floor are shown in Fig. 13 separately. The maximum value of the floor response spectra appears at the period of 0.3s when the water ratios of the water tank are 0%, 30% and 60%. Therefore, if the natural period of the equipment is almost 0.3s, the equipment will appear resonance phenomenon under the seismic loading, which may increase the dynamic response of the equipment. When the water contents are 80% and 100%, the natural period, when resonance phenomenon develops, is about 0.35s. In conclusion, the maintenance and operation floors should avoid placing equipment with natural period of 0.3s to 0.35s to prevent the possible occurrence of the resonance phenomenon.



(a) Maintenance floor response spectrum (b) Operation floor response spectrum

Fig. 13 – Floor response spectra

5. Conclusion

This paper investigated the dynamic characteristics and seismic response of the AP1000 nuclear island shield building considering the FSI for five different water levels. A three-dimensional finite element model considering the FSI is developed. By comparing the results in terms of the first six natural frequencies and mode shapes, displacement response, the first principal stress response and the response spectra of the important floors for different water levels (0%, 30%, 60%, 80%, 100%), the influence of FSI on the dynamic characteristics and seismic response are studied.

The first six natural frequencies of the shield building increase with the decrease of the water level. The first two natural frequencies are influenced by the change of water levels much obviously than any other four natural frequencies. However, the third and fourth natural frequencies are little affected by the increase of the water level. The first two mode shapes of the shield building are primarily lateral translation movements. Moreover, the first six mode shapes for different water levels are similar, indicates that the mode shapes are not much affected by the water levels.

A Kobe ground motion is picked as the input earthquake loading with PGA of 0.3g, 0.6g and 0.9g. The maximum displacement of the top node increases with the water level increase. The maximum first principal stress of the shield building appears at the bottom of the structure. The maximum first principal stress of the shield building increases with the increase of the water level. The water level hardly influences the first principal stress distribution of the shield building. However, the first principal stress distribution of the water tank are affected by the water level apparently. Equipment with natural period of 0.3s to 0.35s is advised not to be placed on the maintenance and operation floors to avoid the resonance phenomenon.

6. Acknowledgements

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