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Dynamic response of generation III+ integral nuclear island structure considering fluid structure interaction effects

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ABSTRACT

AP1000 has two key components of water storage tank and air intakes for cooling down the temperature of containment vessel when an accident happened. The fluid–structure effects of different water levels and locations of air intakes may affect the dynamical response and stress distribution of integral structure of nuclear island. In the present study, three elevations of air intake with height of 62.23, 57.23 and 52.23 m and four cases of water levels with 0%, 40%, 60% and 80% water are designed to investigate the effect of dynamic response and structural damage for integral structure of nuclear island. The numerical results indicate that the dynamical response and the stress at lower location of air intake are less than the upper location. The case of water level 3 with air intake C is the optimal scheme for AP1000 nuclear island. In addition, some consolidated measures should be taken for the corner of air intake, and the original design of air intake around the upper corner of shield building may not be the optimal arrangement.

1. Introduction

AP1000 is an advanced general III+ nuclear reactor designed by Westinghouse Electric Company and has been certified by the US NRC based on their review of seismic analyses at hard rock sites. It is an improved pressurized water reactor (PWR) designed with a series of passive safety features, which relies on natural forces of gravity, natural circulation and compressed gases to prevent the core or containment from overheating. AP1000 has advanced passive components of water storage tank and air intakes to cool down the temperature of containment vessel (Zhao et al., 2015). The water tank has sufficient capacity for three days of operation and the water flows from the top, outside, domed surface of the steel containment shell and down the side walls allowing heat to be transferred and removed from the containment by evaporation. Outside air is pulled in through air intakes near the top of the shield building and pulls down, around the baffle and then flows upwards out of the shield building to remove heat from inside the containment.

In the past, for the safety of nuclear energy, many works have been done to investigate the dynamical response and structural safety, those works mainly pay attention to the overall structure safety based on the original design of nuclear power plant (NPP) (Abbas et al., 1996; Chen et al., 2014; Forni et al., 2009; Frano and Forasassi, 2011; Huang et al., 2011a,b; Iqbal et al., 2012; Lee et al., 2013; Lo Frano and Forasassi, 2010, 2012; Lo Frano et al., 2010; Zhao and Chen, 2014; Zhao et al., 2014a; Zhao and Chen, 2013; Zhao et al., 2012). Fluid-structure interaction (FSI) may also affect the dynamical performance of the partially filled tanks. As the fast advance of computer technology, there are several numerical studies on different aspects of liquid sloshing and FSI effects being reported in last decades (Akyildiz and Ünal, 2005; Amiri and Sabbagh-Yazdi, 2012; Hernández-Barrios et al., 2007; Maleki and Ziyaeifar, 2008; Nicolici and Bilegan, 2013; Sezen et al., 2008; Souli and Zolesio, 2001; Zhao et al., 2017; Zhao et al., 2014b). However, little research investigates the influence of water tank or air intake on the structural response and safety of the nuclear island of AP1000. Furthermore, the volume and mass of water tank above the shield building are approximately 3000 m^3 and 3000 ton, thus, the water tank and location of air intakes may affect the dynamic behavior of the nuclear island and have an important influence on the safety of structure under severe earthquakes. Consequently, the effect of water levels of water tank and locations of air intakes on structural response should be taken into account and investigated.

In the current design of AP1000, the air intakes are located around the upper corner of shield building. This may not be optimal for passive containment vessel cooling (Lee et al., 2013).

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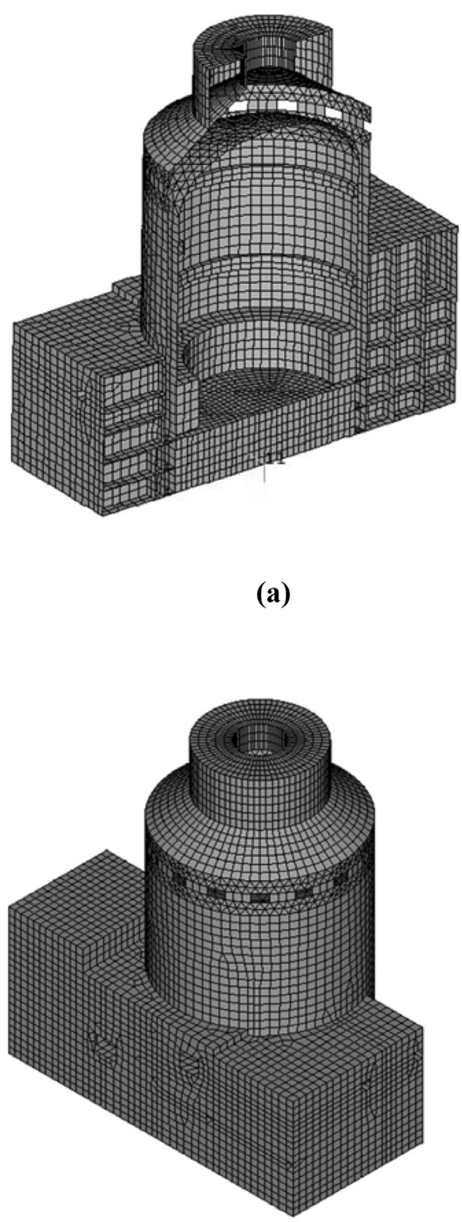
Although numerous works have been done to study the AP1000 nuclear structure, literature on influence of location and shape of air intake considering FSI effects of various water levels on the dynamical response and safety of nuclear structure is difficult to find. In some references, the influence of location, shape of air intake and water height of water tank on dynamic characteristic and stress distribution of only shield building structure have been studied, while the influences of auxiliary building and other equipment were neglected. The results indicated that the natural frequency increased as the water level decreased, and elevation of air intake also influenced the frequency (Zhao and Chen, 2014; Zhao et al., 2014a; Zhao et al., 2015). As the arrangement and complicated shape of overall structure of AP1000, a more detailed analysis model of AP1000 nuclear structure considering the influences of auxiliary building and internal components should be built and studied to obtain the optimal scheme of air intake and water level.



(a)

(b)

Fig. 1. Model of AP1000.

The present study focuses on the dynamic response and stress distribution of overall nuclear structure affected by water level or air intake under earthquakes considering FSI effects. All of the compositions of material, including structures and fluids, were assumed to have homogeneous and constant thermodynamic properties. Pursuing superior heat transfer may cause a conflict with the structural strength, particularly under the threat of an earthquake. Therefore, this study identified the optimal parametric design for stress analysis to improve cooling by using appropriate passive air intakes and water levels.

2. Mathematical model and assumptions

The dynamic responses of structures in contact with fluid are different from those without fluid. The seismic response of structure as the presence of fluid is important for design structure which is contact with or immersed in fluid (Zhao et al., 2015).

The equation of motion of structure can be written as

$$\mathbf{M}\{\ddot{u}\} + \mathbf{C}\{\dot{u}\} + \mathbf{K}\{u\} = \mathbf{F} = -\mathbf{M}\ddot{u}_g(t) \quad (1)$$

where **M** is the mass matrix, **C** is the damping matrix, **K** is the stiffness matrix, $\{u\}$is displacement vector, and the **F** is the load vector caused by earthquake acceleration. In general, the structural response of overall structure of nuclear island can be calculated by Newmark's numerical method in the time domain analysis. The structural viscous damping is represented by Rayleigh damping, and the damping matrix **C** in a system can be defined as

$$\mathbf{C} = \alpha\mathbf{M} + \beta\mathbf{K} \quad (2)$$

$$\alpha = \frac{2\xi\omega_1\omega_2}{\omega_1 + \omega_2} \quad (3)$$

$$\beta = \frac{2\xi}{\omega_1 + \omega_2} \quad (4)$$

where α and β are the mass and stiffness proportional Rayleigh damping coefficient, respectively. ξ, ω_1 and ω_2 are damping ratio, the first and second undamped natural frequency of the structure.

Table 1
Geometry of AP 1000 NI.

Parameter	Value	Unit
Width of nuclear island	26.67	m
Length of nuclear island	77.42	m
Height of nuclear island	81.98	m
Radius of shield building	22.1	m
Radius of water tank	13.565	m
Radius of CV	19.8	m
Wall thickness	0.92	m
Thickness of CV	0.041	m
Height of water tank	11.8	m
Height of auxiliary building	39.42	m

Table 2
Materials of AP 1000 NI.

Material	CV and reinforcement	Concrete	Water
Density (kg/m^3)	7800	2300	1000
Poisson's ratio	0.3	0.2	–
Young' modulus (MPa)	2.06×10^5	3.35×10^4	–
Sonic velocity (m/s)	–	–	1449
Boundary admittance	–	–	0