Progress in Nuclear Energy 74 (2014) 44–52

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Review

Dynamic analysis of AP1000 shield building for various elevations and shapes of air intakes considering FSI effects subjected to seismic loading

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A R T I C L E I N F O

Article history:
Received 13 November 2013
Received in revised form
4 February 2014
Accepted 7 February 2014

Keywords:
AP1000 shield building
Gravity drain water tank
Air intake
Fluid-structure interaction
Acceleration time history
Seismic loading

A B S T R A C T

The shield building of AP1000 was designed to protect the steel containment vessel of nuclear power plants. When an accident releases mass energy to containment, natural circulation of air outside containment cools steel containment vessel by air intake and water drains by gravity to enhance cooling with evaporation. However, the air intake in the original design located around the upper corner of shield building may not be the optimal position of shield building. In the previous study, the influence of various elevations and shapes of air intake on natural frequency considering fluid-structure effects under different water levels has been performed. In the present study, three elevations and two shapes (rectangle and circle) of air intakes with 71.3, 64.75 and 58.21 m are established and expressed as location I, II and III, respectively. The influences of various elevations and shapes of air intake on the structural response and stress distribution of shield building considering fluid-structure effects under seismic loading are also performed to identify the optimal design for stress analysis to improve the passive cooling system for AP1000 and CAP1400 (in China) in the future. The results of structural analyses indicated that the von Mises stress of both rectangular and circular air intakes at the lower location were greater than that of the higher location, and the stress for circular air intake was less than that of rectangular air intake under seismic loading. In addition, the simulation result also indicated that an optimal elevation of air intake should be implemented around the location II of shield building with circular shape, and the original design of air intake located around the upper corner of shield building may not be the optimal arrangement.

1. Introduction

AP1000 is one of the most popular units among the generation III + nuclear power plant (NPP) in the world. It employs a series of passive safety systems which rely only on redundant/fail-safe values, gravity, natural circulation and compressed gas to ensure its safety features rather than active components such as diesel generators and pumps (Lee et al., 2013; Zhao and Chen, 2014). As a generation III + reactor, AP1000 has been received Final Approval by U.S. NRC (Zhao and Chen, 2014). The geometry of the shield building in this analysis is shown in Fig. 1.

Recently, around the nuclear energy safety, plenty of studies (Lee et al., 2013; Pandey et al., 2006; Tuñón-Sanjur et al., 2007) (Lo Frano and Forasassi, 2009, 2012; Zhao and Chen, 2013a, 2013b, 2014; Zhao et al., 2012) have been done to investigate the structural safety and dynamic response of NPP. However, there has been little research that investigates the influence of air intake and water tank on the structural response and safety of the shield building. As the volume and quality of water tank above the shield building are approximately 3000 m^3 and 3000 ton. The presence of water in water tank and the location of air intakes might have an important influence on the dynamic behavior of the shield building and can affect the safety of the shield building under seismic loading from an earthquake (Zhao and Chen, 2014). Therefore, it is necessary to investigate the influence of the water tank and air intake on dynamic characteristic of the shield building and CV.

In the original design of AP1000, 16 rectangular air intakes are located around the upper corner of the shield building, which may not be the optimal position of the structure. Although many works have been done to study the AP1000, they were mainly focus on the thermal behavior of reactor and safety of loop system. However, studies are rather scarce on the influence of location and shape of

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http://dx.doi.org/10.1016/j.pnucene.2014.02.012

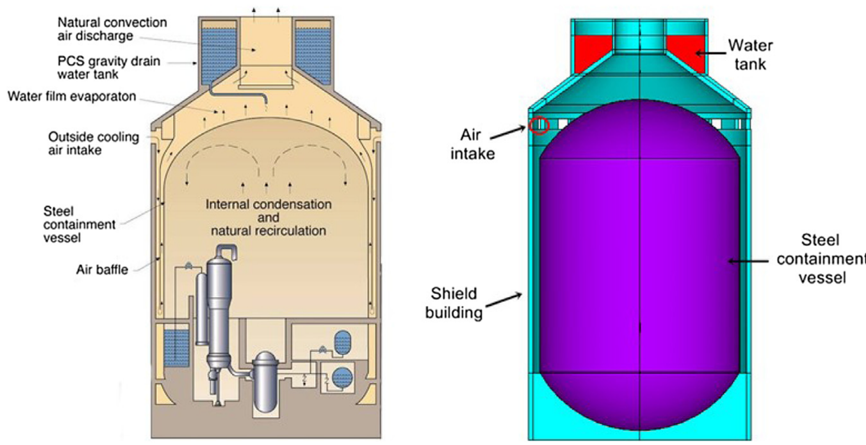

Fig. 1. The schematic passive containment cooling system of AP1000.

air intake considering the fluid-structure interaction effects of water tank on the safety of the shield building for AP1000. Therefore, in order to satisfy the harmony of system and dynamical design of the shield building and consider the correlation of the arrangement and dynamical characteristics of air intakes, it is necessary to study the influences of different elevations and shapes of air intakes on the dynamic response of the shield building considering fluid-structure interaction effects, and find out the optimal location of air intake.

In the previous study, the influences of air intake elevations, shapes and water tank on natural frequency of shield building considering fluid-structure interaction (FSI) have been investigated. The results of finite element analysis clearly indicated that the natural frequency increases as the water level decrease, and elevation of air intake also influenced the frequency for various shapes of air intakes (Zhao and Chen, 2014). The main purpose of the this study is to perform a dynamic analysis that focus on the influence of various air intake elevations, shape of air intake and their influence on the dynamic response and stress distribution of shield building under seismic loads considering fluid-structure interaction effects. The obtained results may provide a theory foundation for optimal parametric design of the AP1000 and CAP1400 (in China) in the future.

2. Basis theories in dynamic analysis of shield building

2.1. Fluid-structure interaction

The fluid-structure interaction can be expressed by coupling the governing equation of the structure and fluid at the interface. The interface force caused by the fluid pressure at the interface is transferred to the structure. The structural equation of motion can be written as (Choi et al., 2013; Zhao and Chen, 2014):

$$[M]\{\ddot{u}\} + [K]\{u\} = \{F^p\} \tag{1}$$

where $[M]$, $[K]$ are mass and stiffness matrices for the structure and $\{\ddot{u}\}$, $\{u\}$ are vectors of acceleration and displacement for the structure. The fluid pressure load vector $\{F^p\}$ at the interface A is obtained by integrating the pressure over the area of the submerged surface as follow:

$$\{F^p\} = \int_A \{N_u\}P\{n\}\mathrm{d}A \tag{2}$$

where $\{N_u\}$ is the element shape function for approximating from displacement component vectors $\{u\}$, P is the spatial variation of the pressure and $\{n\}$ is the unit vector normal to the fluid-structure interface. In FEM, P with approximating shape function is given by:

$$P = \{N_p\}^T\{P_e\} \tag{3}$$

where$\{N_P\}^T$ represents the element shape function for approximating from pressure vector $\{P_e\}$. Substituting Eq. (3) into Eq. (2), we obtained fluid pressure load vector as follows:

$$\{F^p\} = \int_A \{N_u\}\{N_p\}^T\{P_e\}\{n\}\mathrm{d}A \tag{4}$$

Then the fluid pressure load $\{F^p\}$ can be expressed as a matrix form:

$$\{F^p\} = [B]\{P_e\} \tag{5}$$

where $[B] = \int_A \{N_u\}\{N_p\}^T\{n\}\mathrm{d}A$. By introducing Eq. (5) into Eq. (1), the equation of motion for structural dynamics is obtained as follows (Choi et al., 2013):

$$[M]\{\ddot{u}\} + [K]\{u\} - [B]\{P_e\} = 0 \tag{6}$$

In addition, a matrix equation for the pressure field in the fluid is needed. Accordingly, the fluid is assumed as incompressible and inviscid in order to perform the numerical analysis. Following above assumption, the acoustic wave equation can be represented as follows (Choi et al., 2013):

$$\frac{1}{c}\frac{\partial^2 P}{\partial t^2} - \nabla^2 P = 0 \tag{7}$$

where c is the sound speed of fluid$c = \sqrt{k/\rho_0}$, and k, ρ_0, P and t are the mean bulk modulus, mean fluid density, acoustic pressure, and time, respectively. The wave equation is discretized by using Galerkin method (Zienkiewicz and Newton, 1969):

$$[Q]\left\{\ddot{P}_e\right\} + [H]\{P_e\} - \int_A \{N_p\}\{n\}\frac{\partial p}{\partial n}\mathrm{d}A = 0 \tag{8}$$

where the matrices $[Q]$ and $[H]$ are