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Practical modeling of fluid in ABWR spent fuel pool for seismic analysis using 3D FEM model

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ABSTRACT

Seismic analysis is important for ensuring the integrity of structures in nuclear power plants. This study investigates the practical modeling method of the fluid in a spent fuel pool (SFP) of an advanced boiling water reactor (ABWR) nuclear power plant for seismic analysis using a three-dimensional finite element method (3D FEM) model of a reactor building (RB) in the plant. Three kinds of 3D FEM models of the RB were developed in this study: combined effect, impulsive, and no-fluid models. The combined effect model included both convective and impulsive effects of the fluid, whereas the impulsive model included only the impulsive effects. The no-fluid model did not include fluid. To investigate the fluid effects, the relative error ratios for maximum acceleration, von Mises stresses, and pressure fluctuations obtained from seismic analyses using these models were calculated. The relative error ratios for the impulsive model with respect to the combined effect model were less than 5%, excluding maximum pressure fluctuations; those for the no-fluid model with respect to the impulsive model were mostly less than 5%. These results indicate that the convective effects were significantly small, excluding pressure fluctuations, and the impulsive effects were also small. On the basis of these results, a practical modeling method of the fluid in an ABWR SFP is proposed and summarized in a modeling flowchart. The flowchart enables practical modeling of the fluid for seismic analysis using an ABWR RB 3D FEM model.

1. Introduction

Seismic analysis is critical in ensuring the integrity of structures in nuclear power plants. Three-dimensional finite element method (3D FEM) models have been used to conduct the seismic analyses of large structures in nuclear power plants due to advances in computer performance. For example, Tuñón-Sanjur et al. (2007) developed 3D FEM models of a nuclear island in an advanced passive 1000 (AP1000) nuclear power plant, and Tabatabaie et al. (2010) used a 3D FEM model of a nuclear island in a U.S. European pressurized water reactor (EPR) to conduct seismic analyses.

The authors have started to study the application of 3D FEM models to conduct the seismic analysis of reactor buildings (RBs) with large internal structures in boiling water reactor (BWR) nuclear power plants and identified several concerns in need of resolution, such as damping modeling and the modeling of a large volume of fluid contained in RBs. Some of the authors have studied a damping modeling method, which is important for obtaining accurate seismic analysis results, using element Rayleigh damping (Onitsuka et al., 2017a).

Fluid modeling is also important for obtaining the accurate seismic analysis results of structures containing fluid. Lu et al. (2015) used ANSYS (2009) fluid elements (Fluid30 and 80) for the seismic analysis of a shield building, which contains fluid in the upper position, in an AP1000 nuclear power plant. Other studies have used more precise fluid modeling methods; Zhao et al. (2014, 2016) applied an arbitrary Lagrangian–Eulerian method to a fluid–structure interaction problem in a shield building of an AP1000 nuclear power plant, and Xu et al. (2016) used a 3D FEM model with fluid modeled by smoothed particle hydrodynamics for the seismic analysis of a shield building in an AP1000 nuclear power plant. However, these precise fluid modeling methods require considerable computational time, even with current computers, as pointed out by Rydell et al. (2013). Thus, we should study practical modeling methods, such as modeling fluid as mass, on the basis of the effects of fluids on the seismic responses of structures.

The RBs in BWR nuclear power plants house large amounts of fluid in certain components: a suppression pool (SP), a spent fuel pool (SFP), and a reactor pressure vessel (RPV). To decrease the computational time required for seismic analysis involving fluid–structure interaction, a previous investigation (Onitsuka et al., 2017b) sought a practical modeling method for the fluid in an SP by evaluating the effects of the

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fluid on the seismic responses of the structures around the SP. The present study also focuses on fluid modeling, particularly a practical modeling method for the fluid in an SFP of advanced BWR (ABWR) RB 3D FEM models. To the best of the present authors' knowledge, no studies have developed a practical method of modeling such fluid, though some research (e.g., International Atomic Energy Agency, 2013) has evaluated the amount of water spilled from an SFP due to earthquakes.

Here, the effects of the fluid in an ABWR SFP on the seismic responses of the structures around it are evaluated through seismic analyses using ABWR RB 3D FEM models. The virtual mass method of MSC Nastran (MSC.Software Corporation, 2004) was used to model the fluid in the SFP. This method has been widely used for fluid modeling. Hashimoto et al. (2013), for example, used the method to model the fluid in a suppression chamber of a BWR nuclear power plant. In the authors' previous study (Onitsuka et al., 2017b), the method was applied to model the fluid in an SP.

The results of the seismic analyses indicate that the effects of the fluid in an ABWR SFP on the seismic responses of structures around it are small. A practical modeling method for the fluid is proposed on the basis of these findings and summarized in a modeling flowchart. With this modeling flowchart, the fluid can be modeled practically for seismic analysis using an ABWR RB 3D FEM model.

2. Structural description of ABWR RB and modeling overview

Figure 1(1) shows a schematic diagram of an ABWR RB. The RB is mainly built of reinforced concrete. The dimensions are approximately 60 × 60 m in area and 60 m high, with external walls approximately 1.5 m and a weight of approximately 260,000 t. The RB is a massive structure (large weight and stiffness), and the SFP is housed in an upper position.

The SFP has the form of a rectangular vessel with an area of 18 × 14 m and a depth of approximately 12 m (GE Nuclear Energy, 1997). The SFP's bottom slab forms the top slab of a reinforced concrete containment vessel (RCCV). The SFP also constitutes part of the RB. The SFP is composed of reinforced concrete walls and slabs with steel liner plates; the walls are 2 m thick, and the slabs are approximately 2 m thick. The SFP contains a large volume of water, and in this study fluid movements (sloshing) were assumed to occur during earthquakes, possibly affecting the seismic responses of the RB.

To evaluate the fluid effects, a 3D FEM model (Fig. 1(2)) was developed, composed of the RB and the following large internal structures: the SFP, a pedestal made of steel and concrete, the RCCV, a diaphragm floor mainly of reinforced concrete, an RPV of steel, a reactor shield wall of steel and concrete, and the SP. The details of this model are available in Section 4.1.1.

3. Virtual mass method

The MSC Nastran virtual mass method was used to model the fluid in the SFP. This method cannot capture complicated fluid phenomena, such as splashing and turbulence, because it models fluids with mass and spring elements. However, such phenomena were assumed to occur locally in the present study. The virtual mass method was thus applicable because the present study focused on the global seismic responses of the structures around the SFP and evaluated the fluid's effects on these responses.

In a previous study (Onitsuka et al., 2017b), the authors verified the virtual mass method in terms of natural frequencies, pressure fluctuations, and fluid motion (wave heights), which are important in fluid–structure interaction analyses. These items were obtained from vibration tests using a double cylindrical vessel and then compared to those from simulation analyses using the virtual mass method. In the current study, the virtual mass method was verified for a rectangular vessel because an ABWR SFP is a kind of rectangular vessel.

The verification here was conducted from the same viewpoint as that in the authors' previous study (Onitsuka et al., 2017b). While the previous verification was based only on the vibration tests, however, the one here also used analytical solutions. Specifically, to verify the virtual mass method in terms of natural frequencies and pressure fluctuations, the simulation results using the method were compared with the analytical solutions. In contrast, the verification in terms of wave height used vibration test results for a rectangular vessel because the wave heights could easily be measured with an ultrasonic displacement meter.

3.1. Overview of virtual mass method

Equation (1) is the equation of motion for fluid, with the damping term neglected for simplicity:

$$[M_v]\{\ddot{\mathbf{u}}\} + [K_g]\{\mathbf{u}\} = \{\mathbf{F}(t)\} \tag{1}$$

where $[M_v]$ is the mass matrix of the fluid, $[K_g]$ is the matrix of stiffness due to gravity, $\{\mathbf{u}\}$ is the displacement vector, and $\{\mathbf{F}(\mathrm{t})\}$ is the external force vector. The method to obtain the mass and stiffness matrices using the virtual mass method is outlined in the following.

The MSC Nastran manual (MSC.Software Corporation, 2004) describes the theoretical background of constructing the mass matrix in Eq. (1). To use the virtual mass method in MSC Nastran, structures containing fluids must be modeled by shell elements. Virtual mass elements must be applied to all shell elements at fluid–structure interfaces. The virtual mass method automatically determines the additional mass derived from fluid for nodes on the shell elements. In other words, the fluid mass matrix is combined with the mass matrix of the structure containing the fluid. The additional mass at each node represents the impulsive, or fixed-mass, effects of the fluid. Pressure fluctuations can be obtained from the virtual mass elements.

Fluid-free surfaces must also be modeled using shell elements (called free surface models) to represent the motion of those surfaces, or the convective effects of the fluids. According to the MSC Nastran manual, a free surface model must have thickness close to zero and be located just below the actual surface (Hashimoto et al., 2013).

The manual (MSC.Software Corporation, 2004) describes the

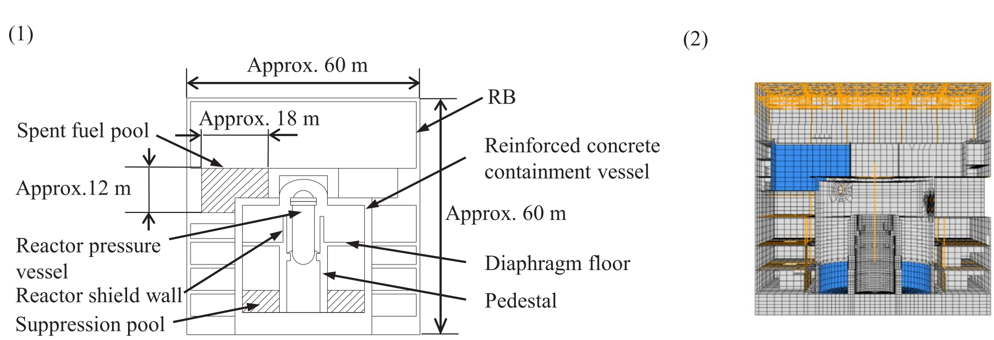

Fig. 1. Schematic diagram of reactor building (RB) in ABWR nuclear power plant and its 3D FEM model: (1) schematic diagram and (2) 3D FEM model.