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Elastic-plastic behavior of AP1000 nuclear island structure under mainshock-aftershock sequences

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ABSTRACT

This paper studies dynamic responses of AP1000 nuclear island structure in strong earthquake sequences. A numerical model to simulate nuclear structural behaviors in earthquake is validated by comparison with data from a previous study on a nonlinear dynamic analysis of a reinforced concrete shield building. The validated numerical model is then used to carry out a series of parametric analyses with 112 computational cases so as to determine influence of strong aftershocks on structural elastic-plastic behavior considering input of three-dimensional ground motions. The results indicate that the influence of aftershocks on structural horizontal/vertical dynamic responses is very small in design basis earthquake sequences. However, the influence must be considered seriously in beyond-design basis earthquake sequences as values of RMVs (Ratio of Mean Value) deviating IPRs (Input Peak Ratio) obviously, which means structural dynamic responses are greatly changed in strong aftershocks. Damage aggravating effect induced by strong aftershocks can cause severe damage of structural members and it is found the greater the magnitude of aftershocks, the severer the aggravation effect. Although earthquake input energy is mostly dissipated by damping energy, plastic damage energy plays considerable role in strong aftershocks as it shares beyond 8 percent of the total input energy, which is 10 times more compared to design basis earthquake sequences.

1. Introduction

Nuclear energy has been an important energy resource in China and also in most other countries of the world due to its outstanding characteristics of cleaning, stability and efficiency. For example, in China, the target of nuclear power engineering in the 13th Five-Year Plan will be up to 58 million kilowatts for installed capacity and 30 million kilowatts for capacity under construction, which means that about 8 nuclear power units will have to start construction each year. However, although many advantages exist for nuclear energy, people should remember some painful experience caused by nuclear power engineering, such as the Three-Mile Island nuclear accident of USA in 1979, the Chernobyl nuclear accident of the Former Soviet Union in 1986, nuclear accident induced by Kashiwazaki Kariwa earthquake of Japan in 2007 and the nuclear accident induced by the East Japan earthquake in 2011 (Waddington et al., 2017). What's more, strong and huge earthquakes happen frequently in recent years, which may also cause great potential dangers to the security of the nuclear island structure (Foulger et al., 2018; Yamin et al., 2017; Cancellara and Angelis, 2017).

Romualdas et al. (2008) studied the dynamic characteristics and responses of the Ignalina nuclear power plant located in earthquake excitation based on three-dimensional finite analysis. Nakamura et al. (Nakamura et al., 2008) built 3D FEM model of nuclear power plant considering the nonlinearity of building materials as well as the nonlinearity of the basemat uplift. Based on the numerical model, the behavior of the building's elements were investigated and it was found that the effects of the vertical ground motion on the horizontal response are slight. Lo Frano and Forasassi (2011) evaluated the safety and durability of nuclear power plant under "beyond design basis" events. The influence of different containment wall thickness and reinforced/prestressed concrete features was also studied. Ferrario and Zio (2014) studied the safety and recovery of unclear power plant using a system-of systems method, Hierarchical modeling and Monte Carlo simulation, under excitation of earthquakes. Chellapandi et al. (2008) determined the critical buckling loads at any instant during the seismic event through an integrated analysis of the reactor assembly vessels of a typical pool type fast breeder reactor. Carlos and Ji (2017) presented a systematic review on the seismic protection

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technology for nuclear power plants. More literatures (Bolisetti et al., 2018; Modarres et al., 2017; Blaauboer and Slaper, 1998; Richard et al., 2018; Schroer and Modarres, 2013) also did abundant and very valuable studies on seismic behaviors of nuclear power plants in both conventional and unconventional ground motions, which promote greatly the development of security design of nuclear structures.

However, as is known, many more aftershocks happen frequently after the mainshock and strong aftershocks may also occur. For example, there are more than 2300 aftershocks occurred in Wenchuan earthquake of China and 64 aftershocks occurred in East Japan earthquake (Foulger et al., 2018). Obviously, performance of a damaged structure in mainshock will deteriorate further or even collapse in aftershocks, especially in strong aftershocks, because the time between the main and after shocks is so short that we cannot do anything to repair the damaged structure timely. Thus, more and more experts and also designers start to focus on the influence of aftershocks on structural performance. Unfortunately, very limited information can be found in both current design specifications and research results, especially in the field of nuclear power plants. Yu et al. (2017) assessed quantitatively the secondary damage caused by aftershocks on a damaged structure in mainshock using method of incremental damage spectra. Results showed that some earthquake sequences (mainshock and aftershocks) can cause significant incremental damages to the damaged structure and the ones with medium-to large natural periods can generate larger incremental damages under earthquake sequences. Zhang et al. (2010) studied dynamic responses of a bridge using the Chi-Chi earthquake sequences and found that the bridge girder will fall down from supports in mainshock, and may fall off the piers in aftershocks. He also indicated that it's necessary to analyze the seismic performance of bridges under earthquake sequences so as to guarantee seismic safety. Study on ductility demand spectra in near-fault and far-fault earthquakes was conducted by Hatzigeorgiou (2010) and expressions of the ductility demands were proposed based on more than 120 millions dynamic inelastic analyses. Conclusions showed that it is certainly insufficient to consider only the "design earthquake" due to the effect of earthquake sequences, namely the ductility demands and structural damage are underestimated for traditional hypothesis. Ground motions of multiple sequences that produce the maximum damage in a structure were modeled by Abbas and Izuru (2010) and found that critical repeated earthquake sequences produce larger structural damage compared to single critical earthquakes.

As for the behavior study of the nuclear structures in earthquake sequences, it will be a bit difficult for us to find enough research literatures. This is really a challenging and worth exploring topic as both other scholars (Zeng et al., 2016; Jha et al., 2017) and authors (Wang et al., 2017) found in previous works that: the nuclear structure will enter a working state of plastic damage subjected to beyond-design basis earthquakes, and the dynamic responses will be magnified greatly relative to the excitation of design basis earthquakes. There will be obviously a huge challenge to the security of a nuclear structure if strong aftershocks generate. Hence, this paper will focus on the elastic-plastic dynamic responses of AP1000 nuclear structure (nuclear shield building and steel containment vessel) subjected to strong earthquake sequences. The influence of different magnitudes of aftershocks on a damaged structure induced by mainshocks is also mainly discussed from the angle of elastic-plastic characteristics and energy dissipation. Analysis of the damage mechanical properties of the concrete shield building and steel vessel is also carried out in detail in the strong earthquake sequences.

2. Overview of AP1000 nuclear power plant

AP1000 nuclear power plant, as the safest & most advanced nuclear power plant and the one certified by the United States Nuclear Regulatory Commission in the world nowadays, is designed by the Westinghouse Electric Corporation. The AP1000 nuclear power plant consists of steel containment vessel, shield building, auxiliary building, waste building, ancillary building and so on, as shown in Fig. 1. The most important parts of the AP1000 nuclear power plant for seismic design are the concrete shield building and steel containment vessel, which have the highest seismic rating. In this study, the concrete shield building and steel containment vessel are defined as nuclear island structure (as shown in Fig. 2) and the dynamic performance of the nuclear island structure subjected to strong earthquake sequences is focused on. The primary piping in the vessel are not considered in computational model in order to simplify the calculation.

The shield building has the diameter of 44.2 m, the height of 83.37 m and the thickness of 912 mm for the concrete plate. The containment vessel has the height of 65.634 m, the diameter

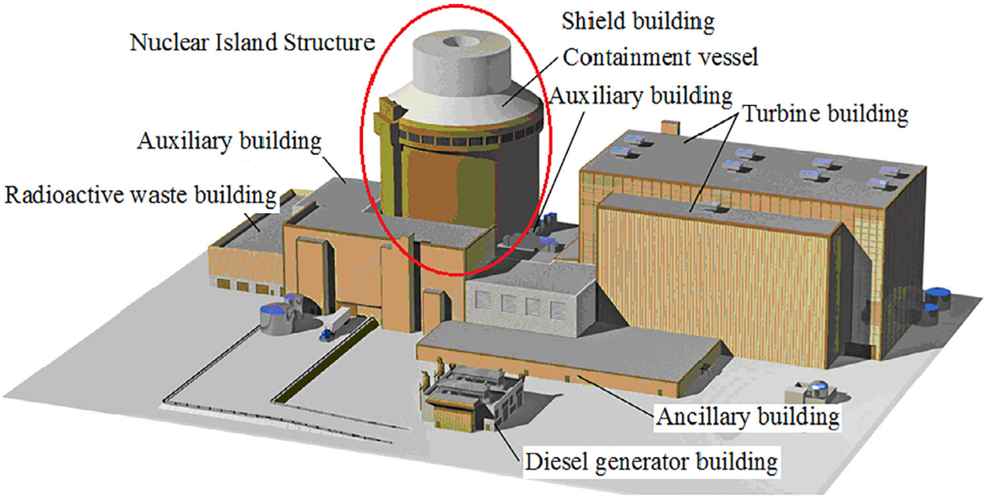

Fig. 1. AP1000 nuclear power plant.