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Impact of aftershocks on a post-mainshock damaged containment structure considering duration

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ABSTRACT

During earthquake events, a mainshock may trigger a number of following aftershocks in a short time, which can cause additional damage to structures. This paper investigates the influence of aftershocks with different durations on the additional accumulative damage of containment structures considering the post-mainshock damage states. For this purpose, 15 as-recorded mainshock-aftershock records with a broad range of aftershock durations, which are scaled and adjusted to match the target spectrum using wavelet transformation, are considered in this study. The three-dimensional structural model which can capture the strength and stiffness degradation during seismic sequences is established. A normalized 'damage ratio' measuring tensile and compressive damage is proposed to quantify the accumulative damage from seismic sequences. The results indicate that aftershocks with longer durations can cause more severe accumulative damage and have a significant effect on the damage pattern. Therefore, to evaluate the safety margin of containment structures accurately, the aftershock and its characteristics of duration should be taken into account when selecting ground motion records for seismic safety assessment of a Nuclear Power Plant.

1. Introduction

In the 1980s, there were major advances in geoscience and seismolog, and researchers realized that nuclear power plants may be subjected to beyond-design earthquakes. Therefore, the original design basis was challenged. For example, a shaking intensity of PGA = 0.2 g was adopted for the design of second-generation nuclear power plants, while that for the third-generation ones (e.g., the AP1000) was improved to PGA = 0.3 g. To ensure the absolute safety of a nuclear power plant, it is necessary to study its performance and seismic capacity considering other possible beyond-design situations. As the last defense of nuclear power plants, the containment vessels play a critical role in ensuring the safety of nuclear power systems. Thus, it is of great importance to perform reliability analyses for containment vessels by examining their seismic capacities under beyond-design loadings. This will also provide useful insights into the design methods and seismic safety assessment of nuclear power plants.

When earthquake occurs, it is common to observe aftershocks following a mainshock. The M8.0 Wenchuan earthquake on May 12, 2008 triggered 104 aftershocks having magnitude greater than 4.0 in 72 h. The Chile earthquake was measured at M8.8 on February 27, 2010. After the mainshock, 90 strong aftershocks were recorded within 24 h. The Great Tohoku earthquake in Japan on March 11, 2011 was a deadly earthquake and triggered approximate 588 aftershocks with moment magnitudes 5.0 or greater. Numerous aftershocks, with the largest magnitude being 8.2, were recorded after the April 11, 2012 Indonesia earthquake. Aftershocks may further aggravate the structural damage caused by the mainshock and result in more loss of property and life, especially for structures already seriously damaged.

During the Fukushima earthquake, the nuclear power plants were subjected to multiple ground motions, and the containment was damaged by the mainshock as well as secondary disaster induced by the earthquake. In this circumstance, the damaged containment vessel suffered the following aftershocks, which were more likely to cause greater cumulative damage. Unfortunately, past studies generally took no account of aftershocks when performing dynamic analyses for nuclear structures, which obviously underestimated the impact of aftershocks. Thus, from a public safety perspective, it is urgent to assess the

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seismic performance of containment vessels during mainshock-aftershock sequences, and to consider various factors that may cause damage to nip in the bud.

After the Fukushima earthquake, the effectiveness of safe shutdown for the nuclear power plant was thrown into doubt. Due to nuclear decay, there can be 1% of power (about 30,000 kW) emitted from the reactor for a long period of time after a safe shutdown state. A reactor coolant system (including auxiliary water supply system, residual heat removal system and emergency diesel generator) is thus used for the cooling of the reactor. If the reactor coolant system fails to work due to earthquakes or human errors, there can be serious secondary disasters such as explosions. During the Fukushima earthquake event, the Fukushima Daiichi nuclear power plant automatically shut down after the earthquake struck it on March 11th at 14:46. However, at 15:37, all six power supply lines broke down and the electric power of the station was cut off, which eventually led to an explosion. For mainshock-damaged nuclear containment structures, there may not be time for repair before the occurrence of the subsequent aftershocks. For instance, on March 11, 2011, 64 aftershocks (with the magnitude ranging from 4.1 to 7.1) hit Fukushima following the mainshock. On April 11, an earthquake with magnitude of 7.1 occurred in Fukushima. One minute later, a homogenous aftershock with magnitude of 6.0 occurred. It can be seen that safe shutdown cannot guarantee the safety of nuclear power plants, considering the risk of aftershocks.

So far the containment design has experienced three stages among which the second generation plus (e.g., CPR1000) and the third generation (e.g., AP1000) adopt the pre-stressed concrete containment vessels. However, part of the second generation were designed with reinforced concrete containment vessels and are still in service. In general, concrete containment vessels have much lower seismic capacity compared to pre-stressed ones. A shaking intensity of PGA = 0.2 g is adopted for the design of the nuclear power plants equipped with reinforced concrete containment, and it is not clear that these containment structures can withstand beyond-design ground motions. If reinforced concrete containment vessels are hit by earthauakes like Fukushima (note that the Fukushima Daiichi nuclear power plant is designed with pre-stressed concrete containment vessels), the results may be catastrophic. Besides, due to the limitations of cognitive level and survey techniques, some risk factors were not included in the design process of older nuclear power plants. As requested by International Atomic Energy Agency (IAEA), seismic safety assessment for in-service nuclear power plants should be carried out when new earthquake information are acquired, especially for those older nuclear facilities. Thus, compared with pre-stressed concrete containment vessels, it is more urgent to investigate the dynamic response and failure modes of reinforced concrete containment vessels considering beyond-design situations, such as mainshock-aftershock sequences. This work can help engineers better understand the seismic capacity of non-prestressed containment vessels, thereby taking measures to improve the seismic safety margin of the older Nuclear Power Plant.

For the purpose of studying the impact of mainshock-aftershock seismic sequences on the response of structures, a variety of related investigations have been conducted by researchers. Goda [1] employed Cloud method and IDA approach to study the fragility of wood-frame houses under aftershocks, using numerous sets of as-recorded seismic sequence. Meera et al. [2] conducted nonlinear IDAs for intact and damaged ductile framed structures to quantify the effect of aftershocks on the vulnerability of ductile structures; the results showed that the structural collapse capacity can be significantly reduced due to the post-mainshock damage. A performance-based probabilistic framework was proposed by Tesfamariam and Goda [3] to estimate the loss caused by seismic sequences for non-ductile reinforced concrete structures, considering multiple demand parameters. Li and Ellingwood [4] carried out damage assessment of steel frame structures at different hazard levels of mainshock with the EUMRHA method. The probabilistic framework in the work of Dong and Frangopol [5] was used to assess seismic performance of highway bridges. Loss and resilience of bridges were also estimated. Tesfamariam et al. [6] compared the response of bare frame with that of masonry RC ones by examining their fundamental periods and inter-story drifts. It was shown that the infilled frames sustained less damage than the bare frames. Hatzigeorgiou and Liolios [43] presented an extensive parametric study on the inelastic response of RC frames under sequential ground motions. Efraimiadou, Hatzigeorgiou, and Beskos [44,45] investigated the effect of collision between adjacent reinforced concrete building frames under multiple earthquakes. The containment structure of nuclear power plants, which offers a high stiffness and shear capacity, resists seismic loading mainly by a cylindrical shell. Therefore, both the damage pattern and damage measurement of containment structures are different from those of other types of structures. However, related researches on containment structures are quite limited.

Since the focal mechanism of mainshocks is different from that of aftershocks, there are obvious differences between the characteristics of the mainshock and following aftershocks. Song and Li [7] investigated the relationship between characteristics of mainshocks and those of aftershocks. They found that the mainshocks usually have higher mean periods, in comparison with aftershocks. Similarly, Ruiz-García and Miranda [8] studied the correlation between frequency content of mainshocks and aftershocks. They concluded that the predominant periods of aftershocks tend to be shorter than those of mainshocks. This is because a) the energy released by aftershocks is smaller, and b) site effects are weakened in aftershocks. It is noteworthy that containment structures typically share a short fundamental vibration period of about 0.2 s which is close to the predominant periods of aftershocks. Therefore, the influence of the aftershock hazard and its record features should be taken explicitly into account to assure accurate assessment of the earthquake-resistant capacity of containment structures. The importance of ground motion's features such as the intensity and frequency content has been widely identified [21–23]. However, the duration, which is also one of the crucial features contributing significantly to the accumulative damage of structures [24–29], has not been thoroughly elucidated in the current response spectrum-based seismic design codes. Particularly, mainshock-damaged buildings may be subject to following aftershocks with various durations, which can cause greater accumulative damage and then pose a significant threat to the structure. Therefore, it is of great urgency and importance to investigate the effect of aftershocks on the nonlinear dynamic behavior and cumulative damage of containment structures, considering the post-mainshock damage conditions of structures and characteristics of aftershock durations.

The main purpose of this study is to gain further understanding on the impact of aftershocks on the response of containment structures. For that purpose, the additional accumulative damage of containment structures is analyzed, explicitly considering aftershock durations and damage states of structures after mainshocks. The time-history analyses are implemented using 15 as-record mainshock-aftershock seismic sequences with varying durations. In addition, the time domain method using wavelets is used to modify the aftershock accelerograms to match the target spectrum, which can minimize the influence of frequency content and other factors on the analyses of aftershock durations. The concrete damage plasticity model that can account for strain hardening and softening behavior is employed to capture the damage process of the reinforced concrete containment during seismic sequences. The nonlinear dynamic response of containment structures under mainshocks at different levels of intensity is investigated to define the initial damage states caused by mainshocks. For the quantification of structural damage from seismic sequences, accumulative tensile and compressive damage are measured in terms of a normalized damage ratio. The effect of aftershock durations on the structural behavior and damage pattern of a containment structure is evaluated and discussed in this research. This paper provides a valuable reference for the selection of input ground motion in seismic safety evaluation of nuclear power