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A new interpretation of large amplitude earthquake acceleration from non-linear local soil-structure interaction

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HIGHLIGHTS

- A new interpretation of large earthquake accelerations is provided.
- Non-linear interaction between an embedded building and its surrounding soil is a key.
- A bi-linear restoring-force characteristic with a gap-slip process is used for analysis.
- Ricker wavelet and a continuous sweep sinusoidal wave are adopted as input.
- The amplification is induced by a higher mode due to the change of a support condition.

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ABSTRACT

A new interpretation of large amplitude earthquake accelerations recorded at the Kashiwazaki-Kariwa nuclear power station during the Niigata-ken Chuetsu-oki earthquake in 2007 is provided from the viewpoint of non-linear local interaction between an embedded building and its surrounding soil. An occurrence mechanism is investigated by the dynamic response analysis in which a bi-linear restoring-force characteristic with a gap-slip process is used. The Ricker wavelet and the continuous sweep sinusoidal wave are adopted as an input. The amplification is explained to be induced by an additional higher mode due to the change of a support condition, such as a gap between an embedded building and its surrounding soil.

1. Introduction

Three earthquakes, Niigata-ken Chuetsu-oki earthquake in 2007, Suruga-bay earthquake in 2009 and the 2011 off the Pacific coast of Tohoku earthquake, stopped the operation of nuclear power stations located near each epicenter (see Fig. 1). At the sacrifice of high seismic hazard, many precious seismic records were obtained, since a high density array of seismometers had been arranged in each nuclear power station.

Since the maximum acceleration 6.8 m/s^2 at the foundation of the No. 1 unit reactor building exceeded the maximum design value 2.7 m/s^2, the re-examination of seismic design force was started after the Niigata-ken Chuetsu-oki earthquake in 2007 (Nuclear Safety Commission of Japan, 2012; Japan Nuclear Energy Safety Organization, 2008, 2009a). The authors analyzed the seismic records and investigated the occurrence mechanism of the large acceleration value (Kamagata and Takewaki, 2013a). One of the authors participated in the field investigation of the Kashiwazaki-Kariwa nuclear station one month after the earthquake and paid attention to the non-linear behavior between the embedded building and the surrounding soil (Kamagata, 2009; Japan Nuclear Energy Safety Organization, 2009b).

Two years after the above-mentioned earthquake, the maximum acceleration 4.38 m/s^2 was measured at the Hamaoka nuclear power station during the Suruga-bay earthquake in 2009. The authors analyzed the seismic records and detected a local vibration mode in the underground soil beneath the building and the rocking behavior of building foundation by the numerical integrated displacement profiles (Kamagata and Takewaki, 2013b).

During the 2011 off the Pacific coast of Tohoku earthquake, the operation of Fukushima Daiichi nuclear power station was automatically stopped and the tsunami after the earthquake caused the blackout of the station, which stopped the cooling system and caused the meltdown of the nuclear reactor, the hydrogen explosion and the radioactive contamination. The authors analyzed the seismic records at the Onagawa nuclear power station and

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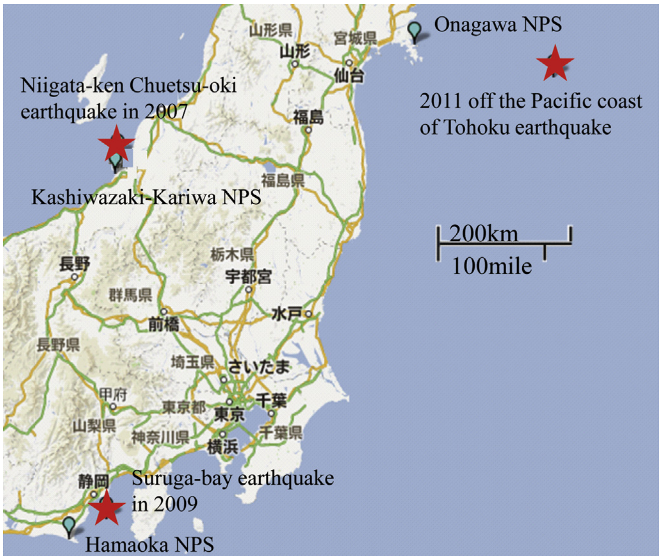

Fig. 1. Epicenter of three earthquakes (Niigata-ken Chuetsu-oki earthquake in 2007, Suruga-bay earthquake in 2009, the 2011 off the Pacific coast of Tohoku earthquake) and location of nuclear power stations (http://www5.ocn.ne.jp/ botan/map_g.html).

Table 1
Specification of seismic records (m/s^2).

	Earthquake magnitude	Focal depth (km)	Epicentral distance (km)	PGA (m/s^2)
Onagawa NPS 2011	M9.0	24	123	4.20
Hamaoka NPS 2009	M6.5	23	37	4.38
Kashiwazaki-Kariwa NPS 2007	M7.2	17	15	6.8

have found that the level of measured seismic records was almost equivalent to the extreme design basis earthquake (Kamagata and Takewaki, 2013c).

The typical seismic records during these three seismic events are compared in Fig. 2, in which the acceleration $6.8\,m/s^2$ in the EW component at the foundation of the reactor building No.1 unit during Niigata-ken Chuetsu-oki earthquake in 2007 (designated as 1R2(EW)) is the largest among three records.

The specification of three seismic records is listed in Table 1. The profiles of shear-wave velocity in depth direction at three NPS sites are illustrated in Fig. 3. The surface soil at the Kashiwazaki-Kariwa NPS and Hamaoka NPS is soft-rock with the shear-wave velocity smaller than 500 m/s. On the other hand the soil of Onagawa NPS is the hard rock with the shear-wave velocity larger than 1500 m/s. The maximum amplitude spectra of three seismic records are compared in Fig. 4. The maximum amplitude spectra of the seismic record at the Kashiwazaki-Kariwa NPS exceeded those of other records. The record 1R2 (EW) is compared with an artificial wave at

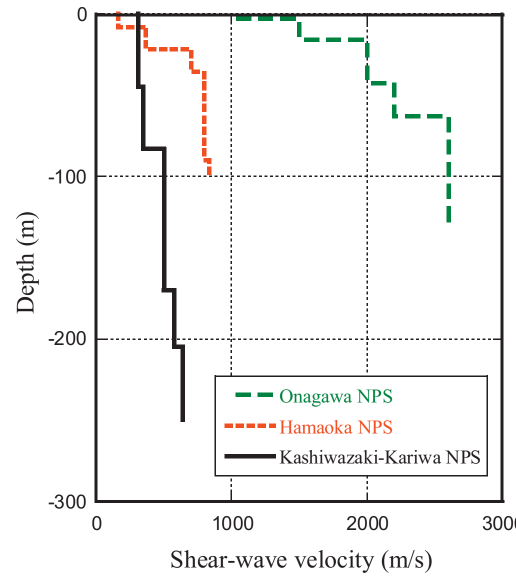

Fig. 3. Comparison of shear-wave velocity

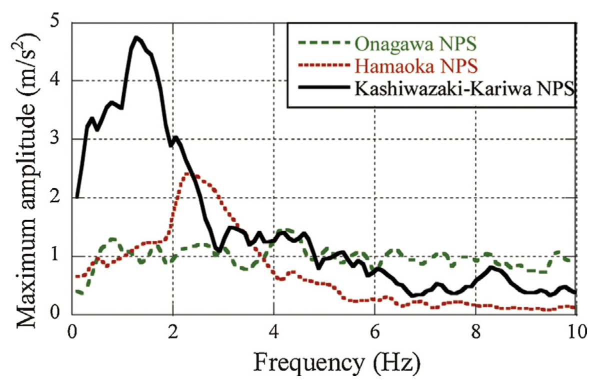

Fig. 4. Comparison of maximum amplitude spectra

the Kashiwazaki-Kariwa NPS by the non-stationary Fourier spectra (see Fig. 5). The dominant components of the artificial wave scatter in the frequency and time domains with the amplitude of $2.0\,m/s^2$. On the other hand the single dominant component is observed in 1R2(EW) and the amplitude exceed $4.0\,m/s^2$, which is more than two times larger than the maximum amplitude of the artificial wave (see Fig. 6). The pulse wave of 1R2(EW) is an extraordinary seismic event. In the previous research (Kamagata and Takewaki, 2013a), the authors focused on the pulse wave of 1R2(EW) and investigated the non-stationary property of the seismic records.

Different from the approach in Kamagata and Takewaki (2013a), the occurrence mechanism of large accelerations at the

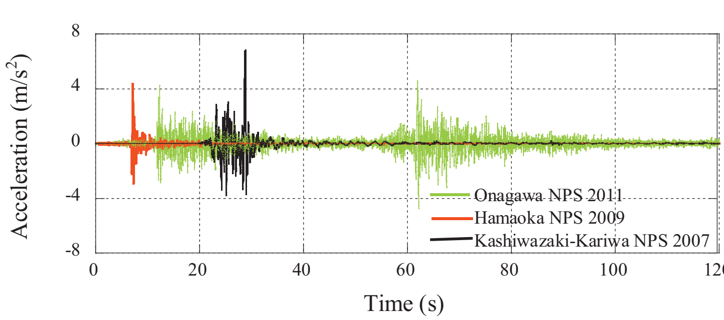

Fig. 2. Comparison of ground motions of three seismic events.