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Stochastic seismic response and stability reliability analysis of a vertical retaining wall in front of the pumping station of a nuclear power plant using the probability density evolution method

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ABSTRACT

Vertical retaining walls are widely used to protect the water intake and drainage structures of nuclear power plants (NPPs); in particular, they are built as the inlet in front of the pumping station pool. It is of great significance to investigate the seismic behavior of the vertical retaining walls considering the uncertain nature of earthquakes according to the nuclear safety design requirements. The probability density evolution method (PDEM), which is a new and efficient methodology, is proposed here to study the stochastic seismic response and stability reliability of a vertical retaining wall in front of the pumping station pool of a NPP. Firstly, a set of representative acceleration time histories of non-stationary earthquake ground motions are generated by the spectral representation random function method according to the RG1.60 spectra for the NPP project design. Then, a series of deterministic stochastic seismic response analysis of a 26-m-high vertical retaining wall are performed. Finally, the probability information and seismic reliability of the vertical retaining wall under two seismic levels (SL-1 (operating-basis earthquake) and SL-2 (safety shutdown earthquake)) are obtained based on two physical parameters: the anti-sliding safety factor and anti-overturning safety factor. The results demonstrate that the proposed method of investigating the stochastic responses and seismic reliability of vertical retaining walls can provide more objective indices to evaluate the seismic safety during SL-1 and SL-2 seismic events. Furthermore, the proposed method can effectively investigate the ultimate seismic capacity of vertical retaining walls and other geo-structures in NPPs.

1. Introduction

As a type of clean energy, nuclear power has advanced considerably in recent years in China. Maritime structures, including the circulating cooling system and protection structures, are among the important parts to ensure the safe operation of nuclear power plants (NPPs). Vertical retaining walls are widely used to protect the water intake and drainage structures of NPPs, especially built as the inlet in front of the pumping station pool, as shown in Fig. 1. The vertical retaining wall in a NPP always consists of a cast-in-place caisson structure and internal rockfills. Damage to the vertical retaining wall during an earthquake will impact the circulating cooling system and may even result in a nuclear accident (Ha and Kim, 2014). Therefore, the vertical retaining wall should be designed as a nuclear safety-related structure. Over the past decade, the nuclear industry has moved toward performance-based design and risk-informed regulation, particularly for seismic loading (ASCE 43, 2005; USNRC, 2007; Syed and Gupta, 2015a,b). The risk-informed analysis method mainly focuses on reinforced-concrete (RC) shear walls (Syed and Gupta, 2015a,b; Zentner et al., 2017), nuclear piping (Prasad et al., 2013), isolated safety-related nuclear facilities (Kumar et al., 2017), RC walls and slabs (Lle and Frau, 2017), and NPPs (Watanabe et al., 2003). However, there are few related reports regarding the vertical retaining walls of NPPs that consider the wall performance during an earthquake.

Retaining walls are used to ensure the soil/gravel stability and prevent erosion due to water. Liu et al. (2014) used a validated finite-element procedure to investigate the similarities and differences in the seismic performances of single- and multi-tiered reinforced backfill soils and retaining walls. Huang and Liu (2016) proposed a theoretical model of the seismic rotational stability of gravity retaining walls using the multi-block upper-bound method. Li and Zhang (2008) presented a simple numerical deterministic method to evaluate the stochastic properties and reliabilities of earth-retaining walls with uncertain parameters under random seismic excitations. GuhaRay and Baidya

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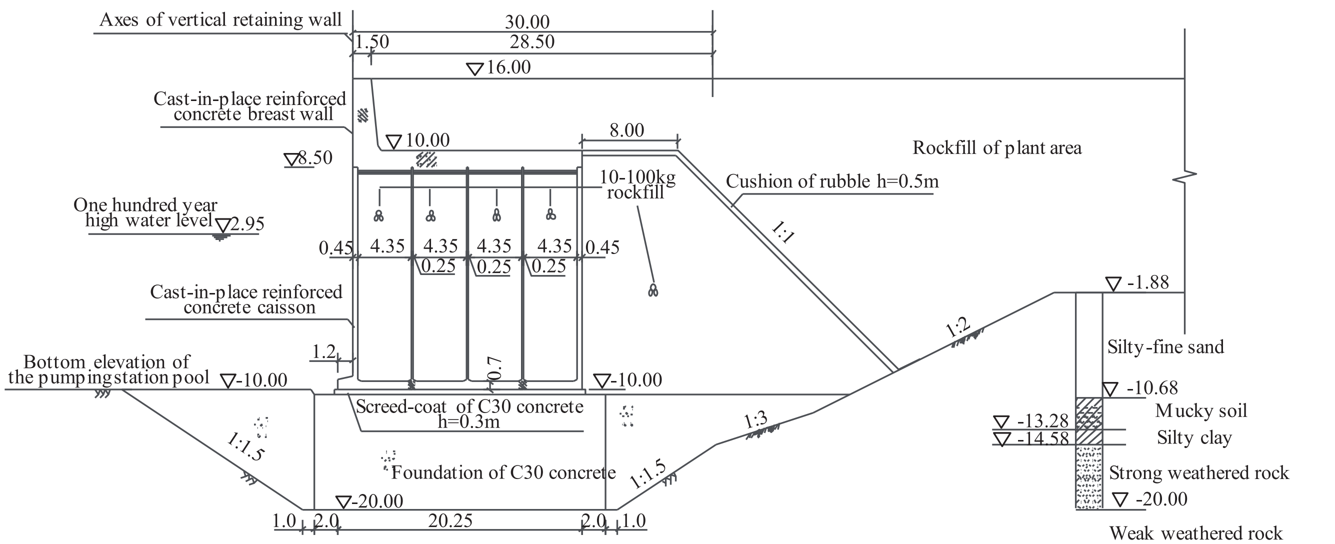

Fig. 1. Section of vertical retaining wall.

(2016) quantified the uncertainties of geotechnical parameters and proposed a modification factor (probabilistic risk factor) for each geotechnical random variable. Bao et al. (2014) discussed the anti-seismic capacity of steel-sheet-pile-quay (SSPQ) retaining walls and the dynamic performance of the ground during an earthquake by comparing the calculated results with the results obtained from centrifuge model vibration tests. Franchin and Cavalieri (2014) quantified the performance and explicitly considered all relevant uncertainties using refined analysis methods from the conventional design in terms of the target performance. The vertical retaining walls in NPPs have a higher seismic design standard than ordinary retaining walls due to their importance. In addition, earthquakes are uncertain events. For example, the value of the design earthquake of the Kashiwazaki-Kariwa NPP in Japan was 273 Gal, but the NPP suffered a 680 Gal earthquake in 2007 (Fukushima, 2007). Hence, the seismic behavior of the vertical retaining wall in front of the pumping station pool of a NPP must be investigated considering the stochastic properties of the input seismic motion.

This paper presents an efficient method to analyze the seismic stability reliability of a vertical retaining wall in front of the pumping station pool of a NPP under stochastic earthquake excitation. A set of representative acceleration time histories of non-stationary earthquake ground motions are generated by the spectral representation-random function method with the iteration approach based on RG1.60 (USAEC, 1973) for the seismic design of NPP structures. Then, the stochastic seismic response analysis of a 26-m-high vertical retaining wall is calculated using the dynamic time history finite element method. The probability information and seismic reliability of the vertical retaining wall under two seismic levels (SL-1, which corresponds to the OBE (operation-basis earthquake), and SL-2, which corresponds to the SSE (safety shutdown earthquake)) are compared based on two physical parameters: the anti-sliding safety factor and anti-overturning safety factor. A new probability density evolution method (PDEM), which was developed by Li and Chen (2009), is used to analyze the stochastic seismic response and stability reliability after performing the deterministic finite element time history analyses. The results can provide references to evaluate the seismic safety of a vertical retaining wall in front of the pumping station pool of a NPP during an earthquake.

2. Stochastic earthquake excitation

To analyze the stochastic seismic response and stability reliability based on the PDEM, first, the time series of the stochastic earthquake excitation should be obtained. The acceleration time series of the stochastic seismic ground motions are generated based on the spectral representation of the random function method of the non-stationary stochastic function (Liu et al., 2016), which can be expressed as

$$\ddot{X}_g(t) = \sum_{k=1}^{N} \sqrt{2S_{\ddot{X}_g}(t,\omega_k)\Delta\omega}\,[\cos(\omega_k t)X_k + \sin(\omega_k t)Y_k] \tag{1}$$

where $\omega_k = k\Delta\omega$, $S_{\ddot{X}_g}(t,\omega_k)$ is the improved evolutionary power spectral density function of the non-stationary acceleration time series of the seismic ground motion, which reflects the frequency components and energy distribution of the ground motions. $\{X_k,Y_k\}$ $(k = 1, 2, \ldots, N)$ are the standard orthogonal random variables. The interval frequency is $\Delta\omega = 0.15$ rad/s, and the number of truncated items is $N = 1600$.

Assuming that the orthogonal random variables X_k and Y_k $(k = 1, 2, \ldots, N)$ are functions of mutually independent random variables Θ_1 and Θ_2. Then, the standard orthogonal variables are defined as random functions with two independent elementary random variables (double-variable scheme) as follows:

$$X_k = \mathrm{cas}(k\Theta_1), Y_k = \mathrm{cas}(k\Theta_2) \tag{2}$$

where $cas(x) = \cos(x) + \sin(x)$ denotes the Hartley function; the elementary random variables Θ_1 and Θ_2 are mutually independent and follow a uniform distribution within the interval $[0, 2\pi]$.

A time power spectrum model proposed by Clough and Penzien (Deodatis, 1996) is introduced as

$$S_{\ddot{X}_g}(t,\omega) = A^2(t)\frac{\omega_g^4(t) + 4\xi_g^2(t)\omega_g^2(t)\omega^2}{[\omega^2-\omega_g^2(t)]^2 + 4\xi_g^2(t)\omega_g^2(t)\omega^2}\frac{\omega^4}{[\omega^2-\omega_f^2(t)]^2 + 4\xi_f^2(t)\omega_f^2(t)\omega^2}S_0(t) \tag{3}$$

where $A(t)$ is the intensity modulation function, which is represented by

$$A(t) = \left[\frac{t}{c}\exp\left(1-\frac{t}{c}\right)\right]^d \tag{4}$$

where c is the arrival time of the peak ground acceleration and d is the parameter that controls the shape of $A(t)$.

The following parameters reflect the non-stationary characteristics of the ground motions:

$$\omega_g(t) = \omega_0 - a\frac{t}{T},\ \xi_g(t) = \xi_0 + b\frac{t}{T} \tag{5}$$

$$\omega_f(t) = 0.1\omega_g(t),\ \xi_f(t) = \xi_g(t) \tag{6}$$

where ω_0 and ξ_0 are the initial frequency and damping ratio of the site soil, respectively, a and b are parameters determined according to the field classification and seismic environment categories, respectively,