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Evaluation of seismic behavior of soils under nuclear containment structures via dynamic centrifuge test

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HIGHLIGHTS

- A series of dynamic centrifuge tests were performed for NPP structure to investigate the soil–foundation-structure interaction with various soil conditions from loose sand to weathered rock.
- SFSI phenomena for NPP structure were observed directly using experimental method.
- Effect of the soil stiffness and nonlinear characteristics on SFSI was estimated.
- There are comparisons of the control motions for seismic design of a NPP structure.
- Subsoil condition, earthquake intensity and control motion affected to seismic load.

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ABSTRACT

To evaluate the earthquake loads for the seismic design of a nuclear containment structure, it is necessary to consider the soil–foundation-structure interaction (SFSI) due to their interdependent behavior. Especially, understanding the effects of soil stiffness under the structure and the location of control motion to SFSI are very important. Motivated by these requirements, a series of dynamic centrifuge tests were performed with various soil conditions from loose sand to weathered rock (WR), as well as different seismic intensities for the bedrock motion. The different amplification characteristics in peak-accelerations profile and effects of soil-nonlinearity in response spectrum were observed. The dynamic behaviors were compared between surface of free-field and foundation of the structure for the evaluation of the control motion for seismic design. It was found that dynamic centrifuge test has potentials to estimate the seismic load considering SFSI.

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1. Introduction

The destruction of nuclear containment structures during earthquakes may cause a catastrophic loss of life, property damage, or disruption to society. Therefore, the safe and reliable seismic design of structures is crucial. To evaluate the earthquake loads for the seismic design of a nuclear containment structure, it is necessary to consider the soil-structure interaction (SSI) due to their interdependent behavior. Recently, the Nuclear Regulatory Commission (NRC) raised the shear wave velocity standard for a general rock outcrop to 2800 m/s (9200 ft/s) (Regulatory Guide 1.208). This means that the region where the soil-structure interaction is considered to occur has been increased and requires a more advanced research and design methodology.

When estimating the seismic load, because most nuclear structures have been built on hard rock, the local site effects are not considered, and the soil-structure analyses are normally performed in the frequency domain, while assuming that the soil is a linear elastic material (Roesset, 1998). However, the demand for the construction of nuclear power plant structures on deep soil deposits has been increasing. In this soil condition, a seismic wave is trapped, leading to large soil deformations, and the soil shows significant nonlinear characteristics. The seismic behavior of a nuclear containment structure can be greatly altered by these local site conditions.

During the evaluation of the earthquake load in the seismic design of nuclear power plant structures, another controversial point is the location of the control motion where the design motion is specified (Roesset, 1998; Avilés and Pérez-Rocha, 1998; Kim and

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Stewart, 2003; Pitilakis et al., 2008). In most cases, the free field surface level-ground motion is selected as the control motion and used at the foundation level, neglecting the kinematic interaction effects (Verma, 2004). However, recent researches about seismic design have referred the importance of considering SSI effects to defer the earthquake input motion (Rayhani and El Naggar, 2008; Yamahara, 1970; Hradilek et al., 1973). Roesset (1998) discussed five possible choices for the design earthquake motion: the free surface of the soil deposit at the site, a hypothetical outcropping of rock, bedrock when there is rock at some finite depth at the site, the elevation of the foundation in the free field, and directly at the foundation. To reliably estimate the seismic load, it is of interest to assess the characteristics and amplitude differences between these potential motions.

So far, most of the seismic analyses considering SSI have been performed based on numerical methods. Although numerical methods have been successfully applied to the design of nuclear containment structures, they also contain numerous uncertainties, including nonlinear soil characteristics, an impedance problem, etc. (Roesset, 1998; Finn et al., 1986). Motivated by the need to calibrate numerical analysis tools for SSI analyses, large-scale seismic model tests have been utilized (Hualian, Lotong). Even though a large-scale seismic test (LSST) is the most precise method to evaluate the SSI, it is difficult to use it to perform various parametric studies because of the expense and difficulty in adjusting the test conditions.

To complement it, a dynamic centrifuge test that reproduces the field stress condition indoors and provides a relatively cost saving can be used as an alternative. Ghosh and Madabhushi (2006) used a dynamic centrifuge test as a tool to investigate the foundation response of a typical power plant during an earthquake. Ha et al. (2012) successfully simulated the seismic behavior of the Hualien LSST in a centrifuge.

The objective of this study was to evaluate the seismic load applied to a nuclear containment structure while considering the soil–foundation-structure interaction (SFSI) in dynamic centrifuge tests. This study focused on two main points: (i) the effect of the soil stiffness and corresponding nonlinear characteristics on SFSI and (ii) the comparison of the control motions for the seismic design of a nuclear containment structure. A series of dynamic centrifuge tests were performed with various soil conditions from loose sand to weathered rock (WR), as well as different seismic intensities for the bedrock motion. The dynamic soil properties of the weathered soil, WR, and sandy soil (SS), in terms of the shear wave velocity profile, modulus reduction, and damping curves, were evaluated using in-flight bender element tests and laboratory resonant column tests. With small-scale model structures, the soil and structure responses were measured during a series of shakings in the centrifuge test, and an assessment was made of the importance of considering the soil nonlinearities and determining the control motions when evaluating the earthquake load for nuclear power plants.

Table 1
Scaling law for centrifuge modeling.

Parameters	Centrifuge model scaling
Length	$1/N$
Velocity	1
Acceleration	N
Strain	1
Stress	1
Time (dynamic)	$1/N$

2. Centrifuge equipment

The basic idea of physical modeling using a centrifuge is to accelerate a reduced-scale geotechnical structure to the appropriate high g-level to simulate the prototype-scale stress field in the model structure. Centrifuge modeling with shaking table equipment provides an excellent opportunity to observe the SSI in a scale model. To make good use of this test method, reasonable scaled-down modeling with a proven scaling law is important. Schofield (1980) derived the scaling law for centrifuge tests. Some of the variables related to the modeling in this study are listed in Table 1.

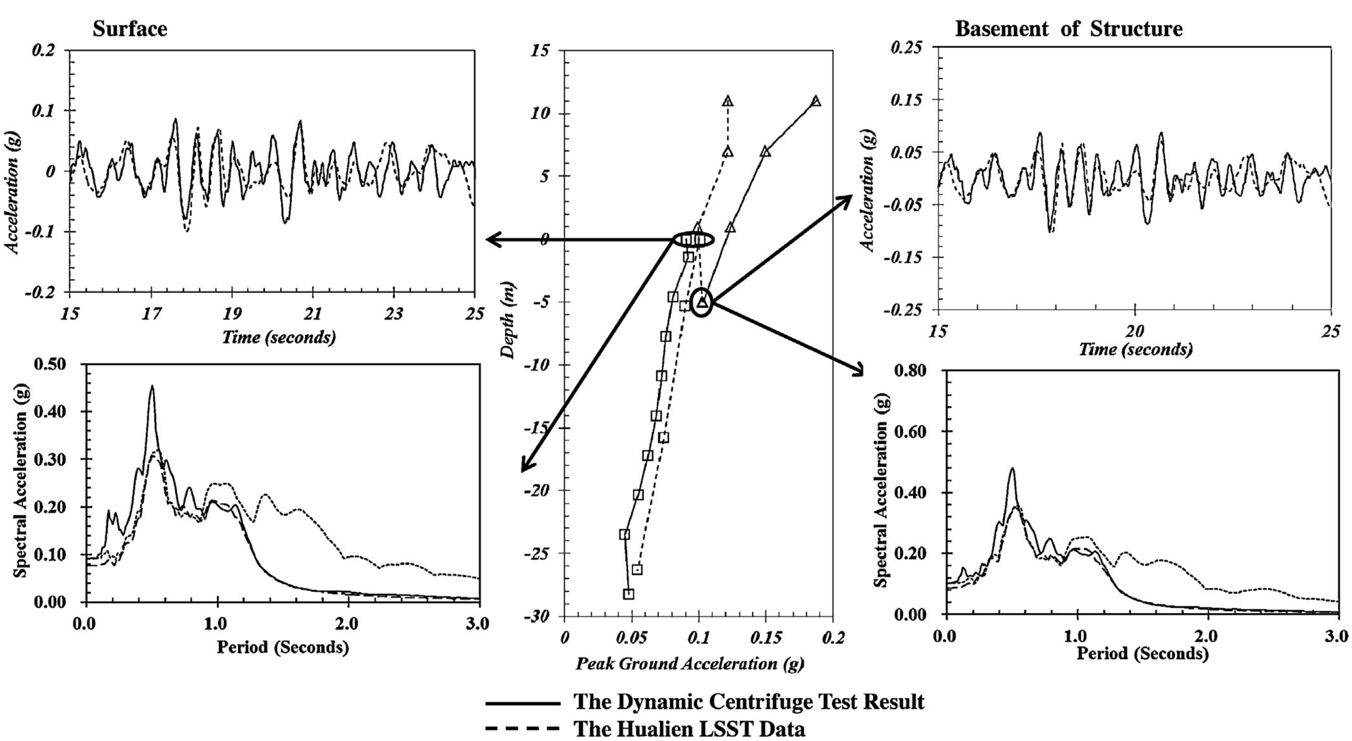

Fig. 1. Test result for simulation of Hualien large-scale seismic test (Ha et al., 2012).

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