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Seismic soil–structure interaction analysis of a nuclear power plant building founded on soil and in degraded concrete stiffness condition

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HIGHLIGHTS

- Three dimensional finite element modeling of a Nuclear Power Plant (NPP) building founded on soil is described.
- A simplified technique to consider degraded stiffness of concrete members in seismic analysis of NPP buildings is presented.
- The effect of subsurface profiles on the seismic response of a NPP building is investigated.

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ABSTRACT

This study describes three-dimensional (3-D) finite element (FE) modeling and seismic Soil-Structure Interaction (SSI) analysis of a Nuclear Power Plant (NPP) Diesel Generator Building (DGB) that is founded on soil in degraded concrete stiffness condition. A new technique is presented that uses two horizontal and vertical FE models to consider the concrete stiffness reduction of NPP buildings subjected to orthogonal ground motion excitations, in which appropriate stiffness reduction factors, based on the input motion orientation, are applied. Seismic SSI analysis is performed for each model separately, and dynamic responses are calculated in the three global directions. The results of the analysis for the two FE models are then combined, using the square-root-of-the-sum-of-squares (SRSS) combination rule. A sensitivity analysis is also performed to investigate the subsurface profile effect on the In-Structure (acceleration) Response Spectra (ISRS) of the building when subjected to site-specific Foundation Input Response Spectra (FIRS) that exhibit high spectral amplifications in the high-frequency range. The sensitivity analysis considers three strain-compatible subsurface profiles that represent Lower-Bound (LB), Best-Estimate (BE), and Upper-Bound (UB) conditions at the DGB site. The sensitivity analysis results indicate that the seismic response of the DGB founded on soil highly depends on the subsurface profile; i.e., each of the LB, BE, and UB subsurface profiles can maximize building seismic response when subjected to FIRS that exhibit high spectral amplifications in the high-frequency range. Therefore, it is important to consider SSI parameter variability in the seismic design or evaluation of NPP buildings that bear on soil.

1. Introduction

The conventional and most commonly used approach to building design assumes that the building is fixed at its base, and any deformation in the foundation will cause conservative seismic design (Bhaumik and Raychowdhury, 2013). However, due to soil deformation during a severe earthquake, the base movement of a building founded on soil can change the structure's overall dynamic characteristics, including its global stiffness and period, such that seismic demand may increase. In fact, the effect of Soil-Structure Interaction (SSI) on the seismic response of a structure depends on the structure-to-earthquake frequency ratio, foundation-to-structure stiffness ratio, damping coefficient

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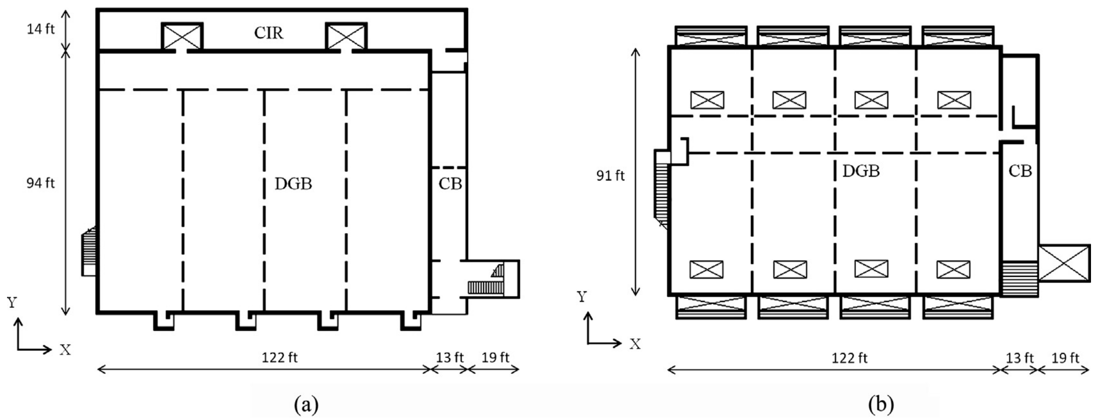

Fig. 1. Plan view of DGB complex: (a) top of foundation, El. 742 ft (b) second floor, El. 760 ft.

Table 1
Subsurface profiles considered for DGB site.

Depth (ft)	Unit weight (kcf)	S-wave velocity (ft/s)			P-wave velocity (ft/s)			S-wave damping (%)			P-wave damping (%)			Poisson's ratio
		BE	UB	LB	BE	UB	LB	BE	UB	LB	BE	UB	LB	
0–23	0.142	1609	2208	1173	4195	5535	3180	2.5	1.3	4.7	1.0	0.5	1.9	0.41
23–405	0.157	5793	7295	4602	10890	13570	8741	3.8	2.0	7.2	3.1	1.7	5.9	0.30

of foundation impedance, rocking of the foundation, and the development of nonlinearity in the structure (Zhang and Tang, 2009). Because structural damage or failure in Nuclear Power Plant (NPP) buildings can threaten the health and safety of the population in the vicinity of the plant, accurate estimation of seismic demand is vital.

In general, the behavior of buildings subjected to severe earthquakes is nonlinear, and concrete members crack. Concrete cracking reduces the stiffness of the building; subsequently, the fundamental frequencies of the building decrease. Depending on ground motion input, a frequency shift can increase or decrease seismic demand (Morante et al., 2011). Thus, in the seismic design of important concrete structures such as NPP buildings, it is important to consider cracking of the concrete members.

Due to complexity of concrete cracking in the seismic analysis of NPP buildings, American standards such as ASCE/SEI 43-05 (2005) provide guidance for simplifying concrete cracking by reducing the elastic stiffness of concrete members. This study uses the simplified guidance of ASCE/SEI 43-05 (2005) to account for concrete cracking in the seismic SSI analysis of an existing NPP building bearing on soil. The NPP structure is a Diesel Generator Building (DGB) constructed on a crushed-stone site located in the continental U.S. region commonly referred to as Central and Eastern United States (CEUS). The site-specific Foundation Input Response Spectra (FIRS) was developed for this building based on the Probabilistic Seismic Hazard Analysis (PSHA) performed for the site using the CEUS Seismic Source Characterization (CEUS-SSC) model. The developed FIRS exhibited high spectral amplifications in the high-frequency range that exceeded the corresponding spectral amplifications of the original design response spectra.

The primary objectives of this study are to present a simple technique for implementing ASCE/SEI 43-05 (2005) recommended reduction factors to account for concrete cracking in the seismic SSI analysis of NPP buildings subjected to three orthogonal components of a ground motion excitation and to investigate subsurface profile effect on the DGB seismic response when the building is subjected to the FIRS with high spectral amplifications in the high-frequency range.

2. Structural configuration of DGB and Site condition

The NPP building considered for this study is a DGB complex, a 34.5-foot (ft) -tall, two-story, reinforced concrete shear wall structure with a foundation footprint of about 135 ft in the *X* direction and 108 ft in the *Y* direction. The DGB complex consists of three sub-buildings: the main Diesel Generator Building (DGB), the Corridor Building (CB), and a Conduit Interface Room (CIR), as shown on Fig. 1. The DGB has plan dimensions of about 122 ft × 94 ft, and a 9.75 ft thick reinforced concrete (RC) foundation. The CB has plan dimensions of 13 ft × 87 ft and includes a 3.5 ft thick RC foundation. Finally, the CIR is a 135 ft × 14 ft, one-story structure, with a 2-ft-thick RC foundation. The top of the foundations of the DGB, CB, and CIR are at elevation (El.) 742 ft; the DGB has the lowest foundation elevation, at El. 732.25 ft. The second floor and roof of the DGB are at El. 760 ft and El. 773 ft, respectively.

The building is founded on crushed rock approximately 23 ft deep, which overlies shale-limestone bedrock. Three strain-compatible subsurface profiles – Lower Bound (LB), Best Estimate (BE), and Upper Bound (UB) – are defined for the plant site (Table 1). These subsurface profiles are developed through a site response analysis, which considered 30 randomized soil profiles to accommodate the variability in shear wave velocity, layer thickness, and strain-dependent nonlinear material properties (shear modulus and damping). This study investigates the effect of these subsurface profiles on the seismic SSI analysis results of the DGB subjected to the site-specific FIRS.

3. Ground motion input

The seismic input for the DGB is the site-specific FIRS developed based on the site-specific Probabilistic Seismic Hazard Analysis (PSHA), using the CEUS Seismic Source Characterization (CEUS-SSC)