Soil Dynamics and Earthquake Engineering 110 (2018) 28–42

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

A simplified model to estimate non-liquefiable NEHRP F site design spectra

Brian Carlton[a,*,1], Juan Pestana[a], Jonathan Bray[a], Kohji Tokimatsu[b]

[a] University of California, Berkeley, CA 94720-1710, USA
[b] Tokyo Institute of Technology, Tokyo 152-8550, Japan

ARTICLE INFO

Keywords:
Response spectra
Seismic analysis
Seismic design
Standards and codes
Deep soft soil deposits

ABSTRACT

The International Building Code requires a site-specific investigation for NEHRP F sites. However, established procedures for performing site-specific investigations of NEHRP F sites are limited. This study developed a simplified model to estimate design spectra for non-liquefiable NEHRP F sites to provide guidance for these cases. The model is based on the results of 4695 one-dimensional effective stress nonlinear site response analyses. It is intended to be used jointly with site-specific response analyses. The model is dependent on the period, design ground motion intensity, and site properties, and it characterizes the uncertainty of the estimate. The sensitivity of the results to reasonable variations in input parameters is investigated. The model is validated against field observations and compared with 80% NEHRP E site design spectra. The simplified model can capture the trends and magnitude of acceleration response spectra calculated from the site response analyses for all ground motions tested. Design spectra may fall below the 80% NEHRP E site design spectra for moderate to large levels of shaking intensity due to soil nonlinearity.

1. Introduction

Scientists have known since at least the 1800s that near surface soils can have a strong influence on ground motions [1]. However, the influence of site effects was not seriously studied quantitatively until after a series of devastating earthquakes in the 1960s [2], and the first recommended design spectra that differentiated between soil types was not published until 1978 [3]. In 1991 and 1992, the National Center for Earthquake Engineering Research held workshops to improve how building codes dealt with site effects [4,5]. These workshops developed seismic site factors and categories that were later integrated in the National Earthquake Hazards Reduction Program (NEHRP) provisions [6]. A major improvement of these site categories and factors over earlier code methods was the fact that they provided an unambiguous definition of the site class, introduced both short-period and long-period amplification factors, and accounted for soil nonlinearity.

The International Building Code [7] defines six site categories for seismic design of structures, which are based on the sites defined by the NEHRP provisions. Site categories A, B, C, D, and E are typically defined by the time-averaged shear wave velocity over the top 30 m of the soil deposit (V_{s30}). Site category F is defined as any site that includes liquefiable or sensitive soils, as well as sites with three or more meters of peat or highly organic clays, 7.5 or more meters of soil with plasticity index PI > 75, and 37 or more meters of soft to medium stiff clays. The IBC specifies simplified procedures to calculate design spectra for NEHRP sites A through E, and requires a site-specific investigation for NEHRP F sites. Established procedures for performing site specific investigations for NEHRP F sites are limited, and there are little empirical data with which to compare the results.

One of the few comprehensive investigations that provides simplified tools to engineers for estimating the design spectrum of some non-liquefiable NEHRP F sites is the paper of Seed et al. [8]. The site classification system of [8] takes into account soil stiffness, strength, and thickness, as well as ground motion intensity. They provide recommendations for calculating design spectra for sites with deep soft cohesive soils and high plasticity soils, but not organic soils or liquefiable soils.

The objective of this research was to develop a simplified procedure to estimate design spectra for non-liquefiable NEHRP F sites; specifically, sites with the required thicknesses of peat or organic clays, high plasticity clays, and soft soil deposits. Due to the lack of empirical data, this study developed a model based on the results of 4695 one-dimensional effective stress nonlinear site response analyses conducted with the program DEEPSOIL ([9]). This paper presents a brief overview of the seismic site response analyses and their results, a comparison with 80% NEHRP E site design spectra, which the IBC has established as a design floor for site-specific analyses, describes the development of the simplified model, a sensitivity analysis of the input parameters and

* Corresponding author.
E-mail addresses: brian.carlton@ngi.no (B. Carlton), jmpestana@berkeley.edu (J. Pestana), jonbray@berkeley.edu (J. Bray), tokimatsu@arch.titech.ac.jp (K. Tokimatsu).
1 Present address: Norwegian Geotechnical Institute, Oslo, 0855, Norway.

https://doi.org/10.1016/j.soildyn.2018.04.009
Received 19 May 2017; Received in revised form 11 December 2017; Accepted 3 April 2018
0267-7261/

validation of the model. The simplified model presented in this paper does not replace a seismic site response analysis, but rather augments it. The simplified model helps practicing engineers gain a better understanding of the likely response of their site before they conduct more in-depth site response analyses.

2. Database of site response analyses

2.1. Overview

We conducted 14,541 seismic site response analyses with the program DEEPSOIL using 12 ground motion scenarios, 15 sites, and total stress equivalent linear, total stress nonlinear, and effective stress nonlinear analysis methods. We developed the simplified model presented in this paper from a subset of this database composed of 4695 effective stress nonlinear site response analyses from 10 ground motion scenarios and 15 sites. The following sections describe briefly the ground motion scenarios, sites, and results of the site response analyses. Carlton [10] provides a more detailed discussion of the site response analyses.

2.2. Ground motion scenarios and selected acceleration time series

We selected five base-case earthquake scenarios that are representative of those that may be commonly encountered in many seismic areas of the world. Fig. 1 shows the target response spectra for the five base case scenarios. Scenarios ACR1 and ACR2 have a target moment magnitude $M_w = 6.7$ and rupture distance $R_{rup} = 5$ km, and correspond to near fault ground motions from shallow earthquakes in active crustal regions with and without pulse-like features, respectively. Scenario ACR3 represents medium distance ground motions from shallow earthquakes in active crustal regions, with $M_w = 7.8$ and $R_{rup} = 30$ km. Scenario SUB corresponds to ground motions from subduction zones with $M_w = 9.0$ and $R_{rup} = 100$ km, and scenario SCR corresponds to ground motions from earthquakes in stable continental regions with $M_w = 6.0$ and $R_{rup} = 17$ km. We calculated the target 5% damped acceleration response spectrum for each scenario from ground motion prediction equations (GMPEs) relevant to the earthquake scenario's tectonic environment and for a "rock" site ($Vs_{30} = 760$ m/s for all scenarios, except $Vs_{30} = 2000$ m/s for scenario SCR).

We selected potential seed ground motions for each scenario based on several criteria. First, the recordings had to be from the same tectonic environment and have similar magnitude and distance characteristics as the target scenario. Second, input "rock" ground motion records were required to have $Vs_{30} > 400$ m/s and both components of the ground motion had to have $PGA > 0.03\,g$.

Ground motions for active crustal regions (i.e., ACR1, ACR2 and

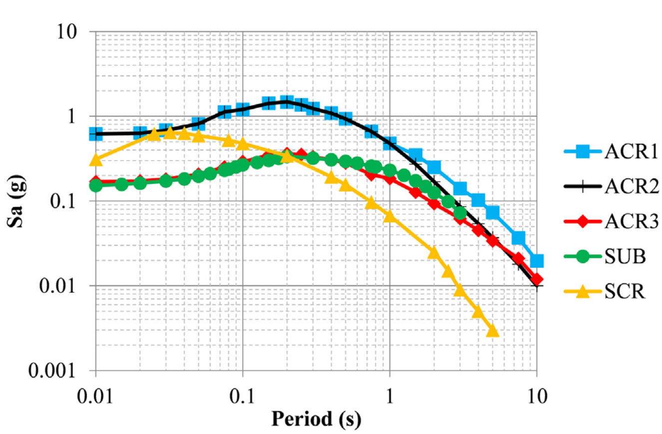

Fig. 1. Target 5%-damped acceleration response spectra for the 5 base-case ground motion scenarios.

ACR3) were selected from the PEER NGA West 2 database ([11]). Selected ground motions for scenario ACR1 were classified as pulse type motions by both [12] and [13] and had $6.0 < M_w < 7.2$ and $R_{rup} < 20$ km. For scenario ACR2, we selected ground motions that had $6.0 < M_w < 7.2$ and $R_{rup} < 20$ km and were not classified as pulse type motions by either [12] or [13]. For scenario ACR3, motions had $7.0 < M_w < 8.4$ and $20\text{ km} < R_{rup} < 90$ km.

We selected the initial ground motions for scenarios SUB and SCR from several sources (see [10]). The criteria for subduction zone ground motion records were $M_w > 8.0$ and $50\text{ km} < R_{rup} < 200$ km, and for stable continental region ground motions the only criteria was $M_w > 4.0$.

We used the program SigmaSpectra ([14]) to calculate the five suites of scaled ground motions that best matched the target response spectrum median and standard deviation for each scenario, for a total of 25 suites. We selected the final suite of ground motions from the five best fit suites for each scenario based on other target ground motion parameters such as peak ground acceleration (PGA), peak ground velocity (PGV), significant duration (D_{5-95}), mean period (T_m), arias intensity (I_a), and for pulse-like motions the pulse period (T_v). Scenarios ACR2 and ACR3 had a total of 40 ground motions each so that statistically robust assessments could be made for these scenarios. The other scenarios (ACR1, SUB, and SCR) had a total of eleven ground motions each.

To investigate the effect of ground motion intensity, we further scaled the scenario ACR3 ground motions by factors of 0.125, 0.25, 0.5, 2, and 4, which produced a total of 10 ground motion scenarios. Table 1 summarizes the ground motion scenarios used in this study.

2.3. Sites

Table 2 lists the 15 sites used in this study. The 12 site properties listed in Table 2 are mostly features of the "special" soil layers that classify the site as a NEHRP F site (organic soil layers, soil layers with $PI > 75$, or thick deposits of soft soil). The 12 site properties are: the thickness of the special soil layers (Th); the elastic site period (Ts); the minimum and mean shear wave velocity of the special soil layers (Vs_{min}, Vs_{mean}); the minimum and mean values of the cyclic resistance ratio (CRR_{min}, CRR_{mean}) of the special soil layers, where CRR is the dynamic shear strength of the soil divided by the vertical effective confining pressure; the minimum and mean value of the dynamic shear strength of the special soil layers (τ_{min}, τ_{mean}); the minimum and mean value of the shear strain when $G/G_{max} = 0.5$ of the special soil layers ($\gamma_{0.5,min}$, $\gamma_{0.5,mean}$); and the minimum and mean value of the small strain damping of the special soil layers ($Dmin_{min}$, $Dmin_{mean}$).

Seven of the sites are based on actual soil profiles from the San Francisco Bay Area; New York City; Ottawa, Canada; Guayaquil, Ecuador; and Hokkaido, Japan that are categorized as NEHRP site classes E or F. Fig. 2 shows the shear wave velocity and soil layering profiles for the seven base case sites. The other eight sites are variations of the seven base case sites that explore the effects of soil shear strength

Table 1
Ground motion scenarios used for the regression analysis.

ID	# of GM	LUP (s)	HUP (s)	Notes
12ACR3	40	0.04	13.33	Scenario ACR3 multiplied by 0.125
25ACR3	40	0.04	13.33	Scenario ACR3 multiplied by 0.25
50ACR3	40	0.04	13.33	Scenario ACR3 multiplied by 0.50
100ACR3	40	0.04	13.33	Scenario ACR3
200ACR3	40	0.04	13.33	Scenario ACR3 multiplied by 2
400ACR3	40	0.04	13.33	Scenario ACR3 multiplied by 4
ACR1	11	0.04	8.85	Near fault pulse type motions
ACR2	40	0.04	6.15	Near fault no pulse motions
SUB	11	0.04	5	Subduction zone
SCR	11	0.02	10	Stable continental region

LUP = lowest useable period, HUP = highest useable period.