Revisions to Soil-Structure Interaction Procedures in NEHRP Design Provisions

Jonathan P. Stewart,[a) M.EERI], Seunghyun Kim,[b)] Jacobo Bielak,[c) M.EERI], Ricardo Dobry,[d) M.EERI], and Maurice S. Power,[d) M.EERI]

The *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* have contained procedures for soil-structure interaction analysis that were originally developed between 1975 and 1977 by the Applied Technology Council Committee on Soil-Structure Interaction (ATC3 Committee 2C). These procedures affect the analysis of seismic demand in structures by modifying the base shear for a fixed-base structure to that for a flexible-base structure with a longer fundamental mode period and a different (usually larger) system damping ratio. In the 2000 *NEHRP Provisions* and *Commentary*, several changes were made to these procedures that affect the analysis of foundation stiffness, and in turn affect the SSI adjustment to base shear. In this paper, SSI analysis procedures in the pre-2000 and 2000 *NEHRP Provisions* are examined relative to a database of "observed" SSI effects previously evaluated using system identification analyses. Through this calibration exercise and focused numerical analyses, we discuss the motivation and justification for the modifications to the NEHRP SSI analysis procedures. [DOI: 10.1193/1.1596213]

INTRODUCTION

The effects of inertial soil-structure interaction (SSI) on the seismic response of buildings can be quantified for response spectrum-based seismic demand analyses by the ratio of flexible- to fixed-base first-mode natural period ($\tilde{T}/T$) and by system damping (β_0) attributable to foundation-soil interaction, first introduced by Jennings and Bielak (1973). Bielak (1975, 1976) and Veletsos and Nair (1975) expressed the flexible-base first-mode damping ratio ($\tilde{\beta}$) as

$$\tilde{\beta} = \beta_0 + \beta/(\tilde{T}/T)^3, \tag{1}$$

where β = fixed-base damping ratio. The representation of SSI effects in terms of $\tilde{T}/T$ and β_0 has been utilized in the *NEHRP Recommended Provisions for Seismic Regula-*

a) Associate Professor, University of California, Los Angeles, 5731 Boelter Hall, Los Angeles, CA 90095-1593
b) Project Engineer, URS Corporation, 911 Wilshire Blvd., Suite 800, Los Angeles, CA 90017
c) Professor, Dept. of Civil & Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA 15213
d) Professor, Dept. of Civil Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180
e) Principal Engineer, Geomatrix Consultants, 2101 Webster St., 12th Floor, Oakland, CA 94612

Earthquake Spectra, Volume 19, No. 3, pages 677–696, August 2003; © 2003, Earthquake Engineering Research Institute

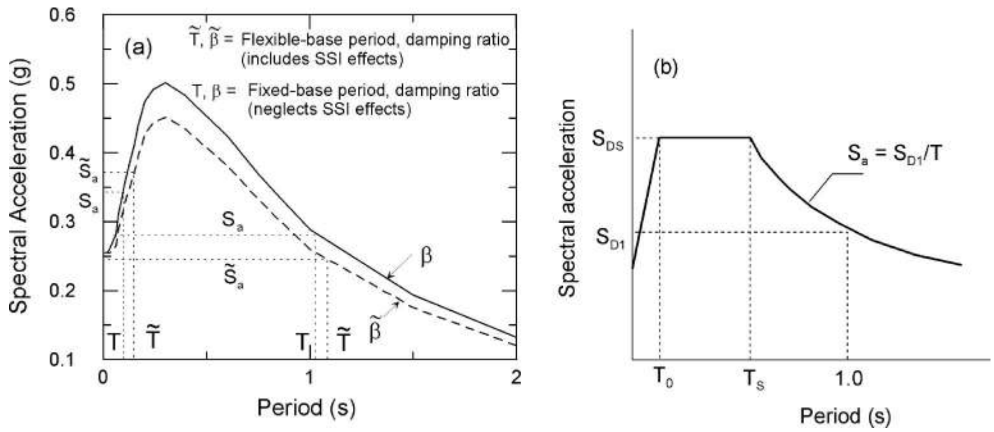

Figure 1. (a) Schematic showing effects of period lengthening and foundation damping on design spectral accelerations for realistic spectral shape, and (b) spectral shape in the *NEHRP Provisions*.

tions for New Buildings and Other Structures (BSSC 1998, 2001) as a means by which to incorporate SSI effects into evaluations of seismic base shear forces in structures. These provisions are optional, and are rarely used in practice.

It should be noted that several other issues related to SSI are not considered in the NEHRP document. These include kinematic interaction effects on foundation motions and nonlinear foundation-soil interaction modeling for detailed system response analyses and the structural design of foundation elements. These effects are not the subject of this paper. Guidelines on such effects can be found in Kim and Stewart (2003) and the *FEMA-356* document (ASCE 2000).

Figure 1a illustrates two possible effects of SSI on the peak base shear, which is commonly computed from spectral acceleration at the first mode. The spectral acceleration for a flexible-based structure ($\tilde{S}_a$) is obtained by entering the spectrum drawn for effective damping ratio $\tilde{\beta}$ at the corresponding elongated period $\tilde{T}$. For buildings with periods greater than about 0.5 s, using $\tilde{S}_a$ in lieu of S_a typically reduces base shear demand, whereas in very stiff structures SSI can increase the base shear. Clearly spectral shape controls the SSI effect on base shear. The spectral shape in the *NEHRP Provisions* for response spectrum-based analyses of base shear is illustrated in Figure 1b, which is drawn for NEHRP Site Class D and highly seismic regions (S_{D1}=0.4, S_{DS}=1.0, T_0 =0.08 s and T_S=0.4 s). The more commonly used equivalent lateral force method in the *NEHRP Provisions* features a spectral shape similar to Figure 1b, but is flat for $T < T_s$. This flatness of the spectral shape at small periods (as well as a NEHRP requirement that $\tilde{\beta} > \beta$) ensures that modeling SSI can only decrease the base shear demand when the equivalent lateral force method is used.

It should be noted that the NEHRP SSI analysis procedures have a significant shortcoming, which is the lack of a link between base shear reduction factors intended to represent structural ductility (i.e., R-values) and SSI effects. As noted by Crouse (2002), existing R-values may to some extent reflect beneficial effects of SSI, and modifying base shear for both effects may be unconservative in some cases. Accordingly, there is a research need to revisit R-values, and define values that truly represent only structural ductility effects. This issue is beyond the scope of this paper, which is focused on the analysis of soil-structure interaction as a stand-alone issue.

The objective of this paper is to describe changes to SSI components of the *NEHRP Provisions* that were implemented in the 2000 provisions update cycle and the motivation for making those changes. We utilize period lengthening and foundation damping parameters evaluated from field case histories in previous work (Stewart et al. 1999b) to illustrate bias in the pre-2000 NEHRP SSI model. Modifications incorporated into the current *Provisions* are shown to remove this bias. The paper is concluded with practical guidelines on the conditions for which SSI analyses are most important.

SSI MODEL IN NEHRP PROVISIONS

The original NEHRP analysis procedure for SSI was developed by a committee comprised of A. S. Veletsos (Chair), M. S. Agbabian, J. Bielak, P. C. Jennings, F. E. Richart, and J. M. Roesset (Committee ATC3-2C) for the ATC *Tentative Provisions for the Development of Seismic Regulations for Buildings* (ATC 1978). The procedure was subsequently adopted into the *NEHRP Provisions*, and was not significantly modified through the 1997 version (BSSC 1998). The SSI model consists of a single-degree-of-freedom structure with a rigid circular foundation resting on the surface of a viscoelastic half-space. The intended use of the model is to evaluate the fundamental-mode system period and damping ratio (denoted $\tilde{T}$ and $\tilde{\beta}$, respectively), which in turn enable an evaluation of the system response to ground motion.

For the sake of brevity, we will not show the various equations, tables, and figures describing the model here. Rather, we synthesize below the major steps of the analysis, with appropriate references to the *NEHRP Provisions* and *Commentary* for details. Section and equation numbers given in the following refer to the current (2000 version) of the *NEHRP Provisions* and *Commentary* (BSSC 2001).

1. Evaluate parameters describing the structure.

    - The first-mode, fixed-base period and damping ratio (T and β, respectively). Note that higher modes are not considered to be affected by SSI (Jennings and Bielak 1973), hence only fundamental-mode structural parameters are required for the analysis of SSI effects on base shear.
    - Stiffness of fixed-base structure ($\bar{k}$) from T and building weight (NEHRP Eq. 5.8.2.1.1-2).
    - Effective height ($\bar{h}$). For a single-story building, $\bar{h}$ is taken as the building height, h. For multistory structures, $\bar{h}$ is taken as the distance from the base to the centroid of the inertial forces associated with the first mode, which is assumed to be 70% of h.

- Normalized structure weight, calculated as structure weight divided by weight of soil within volume defined by foundation footprint area and $\bar{h}$ (NEHRP Eq. 5.8.2.1.1-4).

2. Evaluate equivalent circular disk radii to represent the foundation geometry. These radii are used because of the availability of simple, closed-form solutions for the impedance of circular foundations (e.g., Kausel 1974, Veletsos and Verbic 1973). These radii are calculated for the translational and rocking deformation modes, r_y and r_m, to match the area (A_0) and area moment of inertia (I_0), respectively, of the actual foundation (NEHRP Eqs. 5.8.2.1.1-5 and 5.8.2.1.1-6).
3. Evaluate dynamic properties of the soil medium, which is represented by an equivalent, uniform viscoelastic half-space. This half-space is described by a shear strain-dependent shear wave velocity (v_s) and a Poisson's ratio (υ). The small-strain v_s value is an average value over the profile depth. The current *NEHRP Commentary* recommends effective profile depths of $0.75 \times r_m$ for rocking and $0.75 \times r_a$ for translations, while earlier versions recommended $1.5 \times r_m$ for rocking and $4 \times r_a$. These adjustments of profile depths are one of the major changes to the SSI procedures implemented in the 2000 *NEHRP Provisions*. The strain-dependence of the v_s profile is correlated with peak ground acceleration using NEHRP Table 5.8.2.1.1. The *NEHRP Commentary* recommends $\upsilon = 0.33$ for clean sands and gravels, $\upsilon = 0.40$ for stiff clays and cohesive soils, and $\upsilon = 0.45$ for soft clays.
4. Evaluate the translational and rocking foundation stiffnesses (K_y and K_θ), given by NEHRP Eqs. C5.8.2.1.1-5 for translation and C5.8.2.1.1-3 for rocking when the foundation is at the ground surface and the soil is represented by a half-space, and NEHRP Eqs. C5.8.2.1.1-9 & 10 when the foundation is embedded and/or the soil is represented by a finite layer overlying a rigid base. These equations are based on the assumed conditions of a rigid foundation slab in continuous contact with a uniform, isotropic soil. The 2000 *Provisions* introduced guidelines recommending that the finite soil layer over rigid base model be used for profiles with a surface layer overlying a material with twice the surface layer's v_s. Also introduced to the *Commentary* were guidelines for a dynamic modifier (α_θ) to the rocking impedance (i.e., rocking stiffness K_θ is taken as product of α_θ and static rocking stiffness). The pre-2000 *NEHRP Provisions* did not include dynamic modifiers (i.e., assumed $\alpha_\theta = 0$).
5. Evaluate period lengthening ratio ($\tilde{T}/T$) using NEHRP Eq. 5.8.2.1.1-1. Evaluate foundation damping factor (β_0) using NEHRP Figure 5.8.2.1.2. In this figure, parameter β_0 is uniquely determined from $\tilde{T}/T$ and soil hysteretic damping ratio, which is related to the level of shaking through parameter S_{DS}. Parameter β_0 is assigned a maximum value of 20%.
6. Evaluate the change in base shear (ΔV) from $\tilde{T}/T$ and β_0 using NEHRP Eq. 5.8.2.1-2. The maximum permitted value of ΔV is 30% of the fixed-base V.

The above procedure contains several new features introduced in the 2000 *NEHRP Provisions* and *Commentary*. These include the adjustment of effective profile depth, the introduction of guidelines on the use of the finite soil layer over rigid base model for foundation stiffness, and the introduction of the dynamic modifier for rocking stiffness, α_θ. These changes were motivated by verification exercises in which predictions from the pre-2000 NEHRP SSI model were found to be biased relative to a field performance data set evaluated from system identification studies. The remainder of this paper describes the calibration exercises, the process by which the new features of the analysis procedure were developed, and the extent to which the modified analysis procedures remove the bias present in the pre-2000 model.

VERIFICATION ANALYSIS FOR PRE-2000 *NEHRP* PROVISIONS

SYSTEM IDENTIFICATION ANALYSIS

System identification analyses are processes by which the properties of an unknown system are estimated given a known input into, and output from, that system. For the applications considered here, the system is the structure alone or the soil-foundation-structure system, and the inputs and outputs are acceleration time histories. Stewart et al. (1999a, b) used parametric system identification analyses to evaluate modal frequencies and damping ratios for 53 structures. Their database of 53 sites had 69 processed data sets, and covered a wide range of ground shaking intensities (peak ground accelerations between 0.04 g and 0.84 g), soil/rock shear moduli (small strain v_S between about 140 and 1400 m/s), structural types (shear wall, frame, and base isolated), fixed-base fundamental mode periods (0.1 to 6 s), and foundation types (piles, drilled shafts, footings, mats). This inventory of structures is representative of typical building construction in California. This compilation includes all available sites with sufficient instrumentation to enable the identification of period lengthening ratios and foundation damping factors, according to procedures in Stewart and Fenves (1998). For the present study we include from the original database only 47 sites (listed in Table 1) with the following foundation conditions:

- 26 sites have mat foundations or continuous interconnected footing foundations, and
- 21 sites have pile or drilled shaft foundations with (a) caps interconnected with grade beams, and (b) v_s profiles across the pile length that do not have large, sudden increases, such that the deep foundations may be considered not to be end bearing.

These constraints on the foundation conditions are applied to ensure at least "first-order" compatibility between the foundation conditions and the assumption of a rigid, shallow foundation that underlies the NEHRP procedure. Sites with deep foundations included in the database contain stiff foundation soils with small expected settlement. Therefore, the soil and base slab are likely in contact. This is important, as the opening of a gap between the base slab and the soil may strongly influence SSI effects. Such a gap would be expected for end bearing piles and/or soft foundation soils, and would cause the foundation/soil interaction to be governed principally by soil-pile interaction

Table 1. Site list and observed/computed period lengthening ratios and foundation damping factors

Site & Eqk.*	No. Stories	Foundation (Shallow/Deep)	v_{sa} (m/s)**	v_{sm} (m/s)**	v_{sa} (m/s)***	v_{sm} (m/s)***	Confidence	$\bar{h}/r_m$		T (sec.)		$\bar{h}/(v_S \cdot T)$		Observed				Pre-2000 NEHRP				Pre-2000 NEHRP + α_θ mod.				2000 NEHRP			
														$\tilde{T}/T$		β_0		$\tilde{T}/T$		β_0		$\tilde{T}/T$		β_0		$\tilde{T}/T$		β_0	
								Tr.	L.	Tr.	L.	Tr.	L.	Tr.	L.	Tr.	L.	Tr.	L.	Tr.	L.	Tr.	L.	Tr.	L.	Tr.	L.	Tr.	L.
A1PT	5	S	182	187	310	209	A	0.7	0.4	0.15	0.22	0.35	0.23	1.57	1.09	15.4	8.6	1.34	1.08	14.6	5.6	1.46	1.10	13.3	7.1	1.69	1.20	14.5	19.0
A5LP	11	D	621	581	837	708	A	1.5	1.0	1.11	0.85	0.04	0.05	1.04	1.03	0.7	0.0	1.01	1.00	0.1	0.1	1.01	1.00	0.1	0.1	1.01	1.01	0.1	0.1
A8LP	3	S	470	439	935	641	A	0.5	0.4	0.16	0.17	0.1	0.10	1.16	1.00	3.4	2.0	1.02	1.01	0.6	0.4	1.02	1.01	0.7	0.4	1.06	1.04	2.6	2.1
A9CGA	1	S	357	360	384	354	L	1.3	0.6	0.53	-	0.08	-	1.00	-	3.0	-	1.04	-	0.5	-	1.04	-	0.5	-	1.04	-	0.5	-
A10LP	3	S	240	243	352	234	A	0.6	0.3	0.28	0.26	0.15	0.16	1.08	1.03	6.1	13.1	1.10	1.06	5.0	3.8	1.12	1.07	5.0	4.7	1.16	1.12	5.8	10.8
A11LP	3	S	781	755	858	817	A	0.5	0.3	0.67	0.66	0.02	0.02	1.00	1.00	0.0	0.0	1.00	1.00	0.0	0.0	1.00	1.00	0.0	0.0	1.00	1.00	0.0	0.0
A12IMP	6	D	144	144	198	144	A	1.0	0.8	0.50	1.25	0.24	0.10	1.47	1.00	8.8	0.0	1.20	1.02	6.0	0.6	1.23	1.02	6.2	0.6	1.28	1.03	6.5	0.9
A13LD	4	D	223	215	217	235	A	1.0	0.7	0.67	0.64	0.11	0.12	1.05	1.03	3.8	1.0	1.06	1.05	1.3	1.6	1.07	1.05	1.3	1.7	1.07	1.05	1.4	1.7
A14WT	3	D	258	246	336	291	A	0.6	0.4	0.20	-	0.15	-	1.00	-	1.1	-	1.08	-	3.8	-	1.09	-	3.9	-	1.13	-	6.3	-
A15NR	5	D	292	284	333	313	A	0.5	0.3	0.69	0.71	0.07	0.07	1.06	1.02	3.6	0.0	1.02	1.02	0.8	0.7	1.02	1.02	0.8	0.7	1.03	1.02	1.0	1.0
A16NR	5	S	290	290	280	290	L	3.8	3.8	0.27	0.24	0.18	0.20	1.28	1.34	0.0	3.3	1.24	1.28	0.5	0.6	1.24	1.29	0.5	0.6	1.24	1.28	0.5	0.6
A17NR	4	D	351	351	910	566	A	0.2	0.2	0.25	0.29	0.18	0.15	1.17	1.09	11.3	5.7	1.05	1.03	4.5	2.9	1.05	1.04	4.7	3.0	1.27	1.20	21.0	16.2
A18WT	7	D	190	190	250	191	A	1.3	1.1	-	1.14	-	0.09	-	1.00	-	0.0	-	1.02	-	0.3	-	1.02	-	0.3	-	1.03	-	0.4
A20NR	11	S	386	386	507	447	A	1.2	1.1	0.52	0.55	0.16	0.16	1.07	1.05	0.0	1.0	1.07	1.06	1.2	1.1	1.08	1.06	1.2	1.1	1.12	1.10	1.9	1.7
A21SM	2	S	281	267	435	333	L	0.4	0.3	0.78	0.82	0.03	0.03	1.01	1.00	0.0	3.9	1.00	1.00	0.1	0.1	1.00	1.00	0.1	0.1	1.01	1.01	0.2	0.2
A21LD			283	269	436	334	L			0.98	0.90	0.02	0.03	1.00	1.00	0.0	0.0	1.00	1.00	0.0	0.0	1.00	1.00	0.0	0.0	1.00	1.00	0.1	0.1
A21NR			274	261	426	325	L			0.90	0.84	0.03	0.03	1.00	1.00	0.0	0.0	1.00	1.00	0.1	0.1	1.00	1.00	0.1	0.1	1.01	1.01	0.2	0.2
A23NR	5	S	107	107	260	139	A	2.7	2.5	0.82	-	0.21	-	1.08	-	0.0	-	1.16	-	1.6	-	1.16	-	1.6	-	1.28	-	2.4	-
A24NR	6	D	256	252	450	319	A	0.3	0.9	0.51	0.28	0.1	0.19	1.04	1.60	1.1	4.5	1.03	1.08	2.0	7.9	1.03	1.10	2.1	8.3	1.08	1.24	6.4	20.0
A25LD	7	S	318	318	452	387	A	0.6	0.6	1.18	1.11	0.07	0.07	1.00	1.00	0.0	0.0	1.01	1.01	0.2	0.2	1.01	1.01	0.2	0.2	1.02	1.02	0.4	0.4
A25NR			293	293	426	360	A			1.27	1.19	0.07	0.07	1.00	1.01	0.0	0.0	1.01	1.01	0.2	0.2	1.01	1.01	0.2	0.2	1.02	1.02	0.4	0.5
A26NR	7	S	233	228	382	261	L	2.2	1.8	0.63	1.09	0.14	0.08	1.04	1.00	0.0	0.0	1.09	1.02	0.8	0.2	1.09	1.02	0.8	0.2	1.12	1.02	1.0	0.3
A27LD	17	S	328	314	528	370	A	1.6	1.1	3.20	3.10	0.05	0.05	1.00	1.00	1.0	0.3	1.01	1.00	0.0	0.0	1.01	1.00	0.0	0.0	1.02	1.01	0.1	0.1
A27NR			315	302	510	357	A			3.20	3.09	0.05	0.05	1.00	1.00	5.6	6.8	1.01	1.00	0.1	0.0	1.01	1.00	0.1	0.0	1.02	1.01	0.1	0.1
A28NR	19	D	294	287	493	354	A	2.9	1.9	3.45	3.89	0.07	0.06	1.00	1.00	-	-	1.03	1.01	0.1	0.1	1.03	1.01	0.1	0.1	1.04	1.01	0.2	0.1
A29WT	14	D	266	262	392	286	L	2.3	1.1	1.77	-	0.07	-	1.01	-	3.9	-	1.04	-	0.1	-	1.04	-	0.1	-	1.05	-	0.1	-
A29NR			254	252	358	270	L			2.05	0.75	0.06	0.17	1.02	1.06	3.9	0.9	1.03	1.04	0.1	0.8	1.03	1.04	0.1	0.8	1.04	1.06	0.1	1.4
A30NR	6	D	315	320	610	406	A	0.4	0.4	0.92	-	0.09	-	1.08	-	1.9	-	1.01	-	0.5	-	1.01	-	0.5	-	1.04	-	2.0	-
A31LD	11	S	295	297	452	339	A	1.8	1.3	0.70	-	0.15	-	1.19	-	3.0	-	1.10	-	0.6	-	1.11	-	0.6	-	1.15	-	0.8	-

Table 1 (cont.).

A31NR			283	285	443	327	A			0.75	0.67	0.15	0.16	1.16	1.14	0.0	0.9	1.10	1.04	0.6	0.6	1.10	1.04	0.6	0.6	1.14	1.09	0.9	1.3
A32WT	7	D	227	220	272	252	A	0.8	0.7	-	1.54	-	0.07	-	1.00	-	1.1	-	1.01	-	0.3	-	1.01	-	0.3	-	1.02	-	0.4
A33WT	7	D	243	231	260	259	A	0.7	0.4	1.32	1.22	0.07	0.08	1.00	1.00	0.2	0.5	1.03	1.02	0.8	1.0	1.03	1.02	0.8	1.1	1.04	1.03	1.0	1.3
A33NR			281	266	318	297	A			1.30	1.22	0.07	0.07	1.00	1.00	1.4	1.2	1.02	1.01	0.5	0.6	1.02	1.02	0.5	0.6	1.03	1.02	0.7	0.8
A34NR	4	S	434	410	629	490	A	0.5	0.2	0.12	0.16	0.14	0.10	1.66	1.22	13.1	9.7	1.08	1.03	4.7	1.9	1.09	1.03	4.7	2.1	1.15	1.06	7.9	4.9
A35WT	2	D	403	402	433	420	A	0.5	0.4	0.25	0.26	0.09	0.08	1.02	1.02	3.6	0.0	1.03	1.03	1.4	1.3	1.03	1.03	1.5	1.3	1.04	1.03	1.7	1.5
A35UP			383	383	406	397	A			0.29	0.30	0.08	0.07	1.01	1.00	4.4	0.0	1.03	1.02	1.2	1.1	1.03	1.02	1.2	1.1	1.03	1.03	1.4	1.2
A36LD	6	S	400	394	424	415	L	1.2	0.9	1.07	0.87	0.04	0.05	1.17	1.39	1.0	6.2	1.01	1.01	0.1	0.1	1.01	1.01	0.1	0.1	1.01	1.01	0.1	0.1
A37RD	4	S	356	355	458	398	A	0.6	0.3	0.59	0.60	0.08	0.08	1.03	1.00	0.9	1.4	1.03	1.02	1.0	0.8	1.03	1.02	1.0	0.8	1.05	1.03	1.5	1.5
A37WT			352	351	455	396	A			0.63	0.65	0.08	0.07	1.02	1.01	0.0	2.5	1.03	1.01	0.8	0.7	1.03	1.01	0.8	0.7	1.04	1.02	1.3	1.3
A37UP			314	310	430	369	A			0.77	0.77	0.07	0.07	1.00	1.00	0.0	0.0	1.02	1.01	0.6	0.5	1.02	1.01	0.6	0.5	1.03	1.02	1.1	1.1
A37LD			321	324	422	373	A			0.85	0.87	0.06	0.06	1.01	1.02	0.0	0.9	1.02	1.01	0.5	0.4	1.02	1.01	0.5	0.4	1.03	1.02	0.8	0.8
A37NR			340	340	446	388	A			0.75	0.79	0.07	0.06	1.02	1.02	0.0	0.0	1.02	1.01	0.6	0.4	1.02	1.01	0.6	0.4	1.03	1.02	1.0	0.8
A38LD	3	S	268	268	262	272	L	0.4	0.4	0.52	0.55	0.06	0.06	1.07	1.03	0.4	0.0	1.02	1.02	1.3	1.1	1.02	1.02	1.3	1.1	1.02	1.02	1.2	1.1
A39NR	5	S	419	416	435	434	L	0.6	0.5	0.65	0.51	0.06	0.08	1.00	1.00	3.9	1.3	1.02	1.02	0.5	0.9	1.02	1.02	0.5	1.0	1.02	1.03	0.5	1.1
A40LD	9	D	240	239	301	275	A	1.4	1.3	2.01	2.08	0.05	0.05	1.00	1.00	0.0	1.3	1.01	1.01	0.1	0.1	1.01	1.01	0.1	0.1	1.01	1.01	0.1	0.1
A41NR	5	D	297	297	333	319	A	0.3	0.3	0.51	0.91	0.09	0.05	1.01	1.02	0.0	0.7	1.04	1.01	1.9	0.4	1.04	1.01	1.9	0.4	1.05	1.02	2.5	0.5
A42NR	8	S	721	722	1673	1440	L	4.4	3.3	0.53	0.55	0.06	0.06	1.02	1.00	4.9	3.1	1.01	1.00	0.0	0.0	1.01	1.00	0.0	0.0	1.05	1.02	0.0	0.0
A43LD	8	D	318	312	354	341	A	0.9	0.7	1.26	1.12	0.07	0.08	1.02	1.04	0.0	0.0	1.02	1.02	0.3	0.3	1.02	1.02	0.3	0.3	1.02	1.02	0.3	0.4
A43NR			304	300	332	324	A			1.18	1.06	0.08	0.09	1.03	1.03	0.0	1.1	1.03	1.02	0.4	0.5	1.03	1.02	0.4	0.5	1.03	1.02	0.4	0.6
A44WT	6	S	426	430	643	486	A	0.5	0.5	0.27	0.25	0.18	0.19	1.10	1.17	1.7	4.1	1.07	1.08	4.2	5.2	1.08	1.10	4.6	5.8	1.15	1.17	8.6	10.3
A44NR			302	305	477	336	A			0.37	0.26	0.18	0.26	1.04	1.29	1.7	15.2	1.07	1.13	4.7	10.3	1.09	1.19	5.1	11.7	1.15	1.29	9.3	18.2
A45NR	12	D	249	251	358	282	A	1.5	0.8	0.53	-	0.16	-	1.34	-	1.6	-	1.12	-	1.1	-	1.12	-	1.1	-	1.17	-	1.5	-
B2LP	9	S	276	271	269	280	A	1.1	-	0.97	-	0.08	-	1.13	-	4.7	-	1.04	-	0.4	-	1.04	-	0.4	-	1.04	-	0.5	-
B5LP	10	D	221	205	265	241	A	1.2	-	0.29	-	0.32	-	1.64	-	2.5	-	1.46	-	5.1	-	1.50	-	4.9	-	1.71	-	5.4	-
B6LP	12	S	221	221	275	258	A	1.3	-	2.13	2.17	0.08	0.08	1.01	1.01	0.0	0.6	1.02	1.02	0.2	0.2	1.02	1.02	0.2	0.2	1.03	1.03	0.3	0.2
B7LP	10	D	454	455	442	451	A	3.4	-	0.66	-	0.09	-	1.17	-	0.0	-	1.10	-	0.1	-	1.10	-	0.1	-	1.09	-	0.1	-
B10NR	9	S	349	347	323	321	A	1.8	-	1.25	1.04	0.07	0.09	1.00	1.03	2.5	0.0	1.06	1.03	0.2	0.3	1.06	1.03	0.2	0.3	1.05	1.04	0.2	0.4
B11LD	17	D	355	347	376	366	A	2.6	-	0.85	-	0.11	-	1.13	-	1.7	-	1.08	-	0.4	-	1.08	-	0.4	-	1.09	-	0.4	-
B11NR			341	334	355	349	A			0.90	-	0.1	-	1.17	-	2.5	-	1.08	-	0.4	-	1.08	-	0.4	-	1.08	-	0.4	-
B12NR	32	S	513	513	501	507	A	3.3	-	1.84	-	0.11	-	1.06	-	1.7	-	1.10	-	0.1	-	1.10	-	0.1	-	1.10	-	0.1	-
B13NR	54	S	479	466	603	554	A	4.8	-	5.70	-	0.05	-	1.02	-	0.0	-	1.02	-	0.1	-	1.02	-	0.1	-	1.03	-	0.1	-
B14NR	8	S	240	228	357	264	A	1.7	-	0.49	-	0.14	-	1.14	-	3.4	-	1.08	-	1.4	-	1.08	-	1.4	-	1.13	-	2.1	-

* Earthquakes: CGA=Coalinga Aftershock, IMP=Imperial Valley, LD=Landers, LP=Loma Prieta, NR=Northridge, PT=Petrolia, PTA=Petrolia Aftershock, RD =Redlands, SM=Sierra Madre, UP=Upland, WT=Whittier

** Shear wave velocity=average strain-dependent profile velocity to depth of 0.75 r_a and 0.75 r_m (r_m in the transverse direction)

*** Shear wave velocity=average strain-dependent profile velocity to depth of 4 r_a and 1.5 r_m (r_m in the transverse direction)

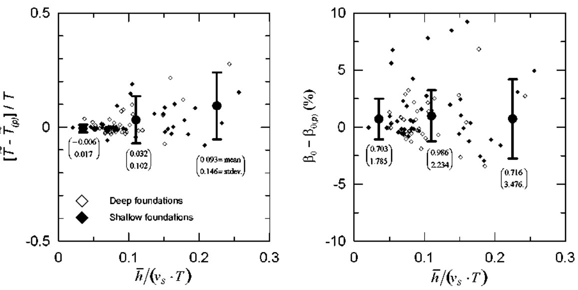

Figure 2. Residuals of period lengthening and foundation damping for pre-2000 NEHRP SSI model (data outside of axis range not shown).

and not soil-slab interaction. The *NEHRP Commentary* contains separate procedures for calculating the stiffness of pile-supported foundations, but calibration of these procedures is beyond this paper's scope.

Listed in Table 1 are period lengthening ratios and foundation damping factors for the sites along with basic structural, foundation, and soil data, as well as the ratio $\bar{h}/(v_S \cdot T)$. The ratio $\bar{h}/T$ is sensitive to the type of lateral load-resisting system, being large for stiff systems (e.g., shear walls, braced frames) and relatively small for flexible systems such as moment frames. Since v_s represents soil stiffness, parameter $\bar{h}/(v_S \cdot T)$ represents in an approximate way the ratio of structure-to-soil stiffness. The soil shear-wave velocities in Table 1 are evaluated across the 2000 NEHRP profile depths of $0.75r_a$ and $0.75r_m$ and the pre-2000 NEHRP profile depths of $4r_a$ and $1.5r_m$. The strain dependence of v_s was evaluated from deconvolution analyses with the program SHAKE91 (Idriss and Sun 1992), using typical soil modulus reduction curves provided by Idriss and Sun. Such analyses only account for primary soil nonlinearity in the free-field; secondary nonlinearity from SSI near the foundation elements is neglected. Table 1 also lists designations for acceptable (A) and low (L) confidence in the analysis results. Low confidence generally results from limited geotechnical data (i.e., insufficient data to evaluate v_s to a depth of $0.75r_a$).

COMPARISON TO PRE-2000 *NEHRP* PROVISIONS

Period lengthening ratios and foundation damping factors calculated using the pre-2000 NEHRP model are listed in Table 1. Residuals between observed and predicted inertial interaction effects are shown in Figure 2 for all sites with acceptable confidence designations. In this and subsequent figures, symbols $\tilde{T}_{(p)}$ and $\beta_{0(p)}$ denote predictions. The residuals were found to be approximately normally distributed within the $\bar{h}/(v_S \cdot T)$ ranges of 0–0.07, 0.07–0.15, and >0.15. The mean of these distributions is also shown in Figure 2 with a large dot, and error bars indicate the mean$\pm$one standard deviation range. These statistical quantities are also listed in Table 2 in the row labeled "pre-2000 NEHRP."

Table 2. Summary of statistics for prediction residuals; quantities shown are mean/standard deviation

	$\bar{h}/(v_S \cdot T)<0.07$		$0.07<\bar{h}/(v_S \cdot T)<0.15$		$\bar{h}/(v_S \cdot T)>0.15$	
	$\frac{(\tilde{T}-\tilde{T}_{(p)})}{T}$	$\tilde{\beta}_0-\tilde{\beta}_{0(p)}$ (%)	$\frac{(\tilde{T}-\tilde{T}_{(p)})}{T}$	$\tilde{\beta}_0-\tilde{\beta}_{0(p)}$ (%)	$\frac{(\tilde{T}-\tilde{T}_{(p)})}{T}$	$\tilde{\beta}_0-\tilde{\beta}_{0(p)}$ (%)
Pre-2000 NEHRP	−0.006/0.017	0.703/1.785	0.032/0.102	0.986/2.234	0.093/0.146	0.716/3.476
Pre-2000 NEHRP with α_θ	−0.017/0.011	0.701/1.786	0.030/0.102	0.968/2.223	0.072/0.138	0.471/3.327
2000 NEHRP	−0.012/0.017	0.536/1.863	0.013/0.095	0.049/2.621	−0.018/0.135	−3.417/4.903

The results indicate consistently low residuals for sites with small $\bar{h}/(v_S \cdot T)$, which have small to negligible SSI effects. These sites generally consist of long-period structures on stiff soil or rock. As $\bar{h}/(v_S \cdot T)$ increases, period lengthening ratios increase and the associated positive prediction residuals also increase, indicating underprediction. Structures with large values of $\bar{h}/(v_S \cdot T)$ tend to have small periods, which in turn tend to occur when the lateral force-resisting system consists of shear walls or braced frames.

The observed underprediction biases for $\tilde{T}/T$ motivated adjustments to the pre-2000 *NEHRP Provisions* that are discussed further below. The bias in foundation damping is less clear given the large dispersion. However, when judging the efficacy of a computational model relative to field performance data, more weight should be given to the $\tilde{T}/T$ results than to the β_0 results. There are two reasons for this. First, system identification results (i.e., the "data" against which the models are calibrated) are more reliable for modal frequencies than for modal damping ratios. Second, estimates of damping from simple models are sensitive to poorly constrained parameters such as soil hysteretic damping ratio, and are highly sensitive to period lengthening ratio (actually, β_0 varies as $(\tilde{T}/T)^3$). Hence, subsequent discussion focuses principally on results for $\tilde{T}/T$.

The dispersion of the residuals (as measured by standard deviation) is large, being about 0.1–0.15 for period lengthening and about 2–4% for foundation damping. Dispersion is a measure of the ability of the analysis to capture site-to-site variations of SSI effects, and is therefore an index of model quality.

In Figure 2, results for shallow foundations (mats, grade beams, footings) are plotted separately from those for deep foundations (piles or drilled shafts). We do not observe statistically significant differences between results for deep and shallow foundation sites. Accordingly, the aforementioned statistics regarding prediction residuals were compiled using data from sites with both foundation types.

SOURCES OF PREDICTION BIAS

FREQUENCY DEPENDENCE OF IMPEDANCE TERMS

The pre-2000 NEHRP SSI model neglects the frequency-dependence of the foundation stiffness terms. This is generally acceptable for translational stiffness, because the frequency-dependence of this term is small over the frequency range of typical engineering interest. As described in the following sections, we proposed a simple model for the frequency-dependence of rocking stiffness and investigate its significance in terms of period lengthening and foundation damping residuals.

Development of 2000 NEHRP Recommendations

The development of simple design guidelines for α_θ are complicated by the fact that α_θ depends on system period $\tilde{T}$, and $\tilde{T}$ is in turn affected by α_θ. Existing theoretical models (e.g., Veletsos and Nair 1975) show that period lengthening is a function of the structure-to-soil stiffness ratio $\bar{h}/(v_S \cdot T)$, structure aspect ratio $\bar{h}/r_m$, and soil Poisson's ratio (υ), whereas α_θ is a function of dimensionless frequency $a_0 = r_m/(2\pi\tilde{T}v_s)$ and υ (e.g., Veletsos and Verbic 1973). Accordingly, if $\bar{h}/r_m$ and υ are assumed, knowledge of $\bar{h}/(v_S \cdot T)$ yields $\tilde{T}/T$, which can then be multiplied by $2\pi a_0$ to yield the dimensionless frequency r_m/Tv_s, which is uniquely related to α_θ for the originally assumed values of $\bar{h}/r_m$ and υ. This relationship is plotted in Figure 3 for several values of $\bar{h}/r_m$ (assuming υ=0.4).

For the development of NEHRP guidelines, it was thought that a model for α_θ that depends on $\bar{h}/r_m$ might be too cumbersome. Values of α_θ were selected in recognition of the strong dependence of period lengthening on $\bar{h}/(v_S \cdot T)$, which is generally only large for relatively stiff (low-period) structures. As shown in Table 1, structures with the largest $\bar{h}/(v_S \cdot T)$ (i.e., values $\geqslant \sim 0.2$), tend to have low aspect ratios (i.e., sites A1, A12, A44, B5). Since it was desired to develop α_θ recommendations for conditions where SSI effects are most significant in practice, recommendations for α_θ were weighted towards low values of $\bar{h}/r_m$. Based on this rationale, the following recommended values of α_θ were provided in the *NEHRP Commentary*:

$r_\theta / V_s T$	α_θ
<0.05	1.0
0.15	0.85
0.35	0.7
0.5	0.6

These values of α_θ are shown with an "$\times$" in Figure 3. Note that use of these recommendations does not require iteration to evaluate α_θ at period $\tilde{T}$. Alternatively, designers could use the curves in Figure 3 for the appropriate aspect ratio; this would be more accurate.

Model Calibration with Field Performance Data

New predictions of period lengthening and foundation damping were computed using a revised impedance model in which α_θ is evaluated using the above recommendations. Shown in Table 1 for each site are predictions of $\tilde{T}/T$ and β_0 based on this revised model. The prediction residuals are presented in Figure 4 for acceptable confidence sites,

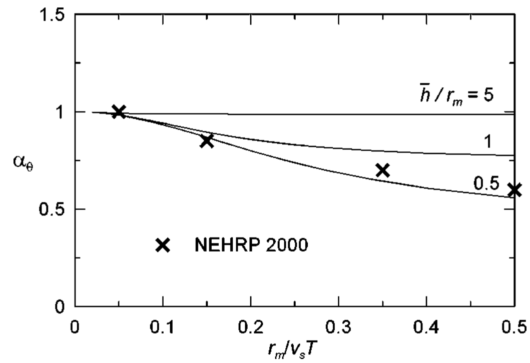

Figure 3. Variation of α_θ with dimensionless variables and 2000 NEHRP recommendations (for $\upsilon = 0.4$).

and summary statistics for various ranges of $\bar{h}/(v_S \cdot T)$ are summarized in Table 2. The results show that the average underprediction bias is slightly reduced for sites with large SSI effects (i.e., large $\bar{h}/[v_S \cdot T]$) and that the prediction dispersion remains essentially unchanged. The small reduction occurs because almost all of the sites in our database have small values of r_m/Tv_s (typically <0.1), even sites with large SSI effects. The one exception is Site A1PT, which has $r_m/Tv_s \approx 0.4$ and $\bar{h}/r_m = 0.7$ (in transverse direction). As shown in Table 1, inclusion of the α_θ term for this site is significant, raising the $\tilde{T}/T$ prediction from pre-2000 NEHRP by 35%, which significantly reduces the underprediction bias. Accordingly, the apparently small effect of the α_θ term in Figure 4 (as shown

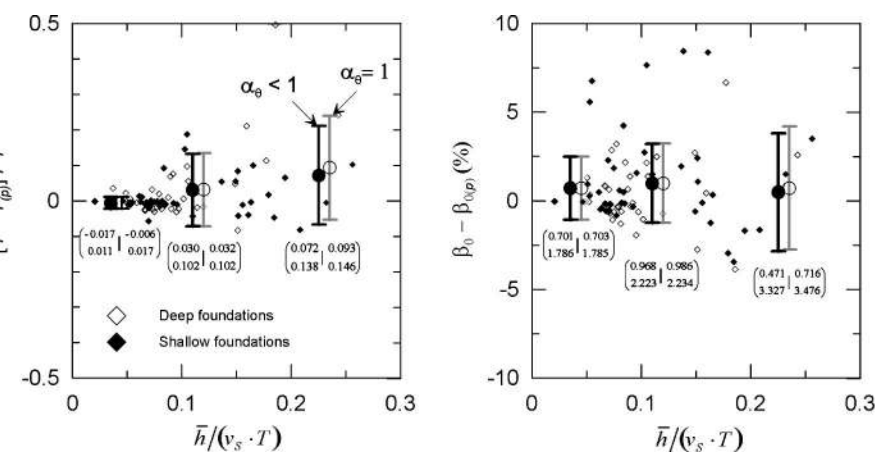

Figure 4. Period lengthening and foundation damping residuals from pre-2000 NEHRP SSI model with α_θ modification (data outside of axis range not shown).

by the summary statistics) should be interpreted with caution—for sites with large values of r_m/Tv_s the effect is actually quite significant, which is why the 2000 NEHRP SSI model includes the α_θ term.

REPRESENTATIVE DEPTH FOR EVALUATION OF V_S

Development of 2000 NEHRP Recommendations

The selection of a representative shear wave velocity (v_s) must account for the non-uniformity of the profile and the reduction of modulus/velocity with increasing shear strain. For non-uniform soil deposits, representative half-space shear wave velocities (denoted for this discussion as $v_{s,H}$) can be calculated as the ratio of effective profile depth (Z_p) to shear-wave travel time through the profile. Effective profile depths that have been recommended include:

Pre-2000 NEHRP: $Z_p=4\times r_a$ for translation and $Z_p=1.5\times r_m$ for rocking.

2000 NEHRP: $Z_p=0.75\times r_a$ for translation and $Z_p=0.75\times r_m$ for rocking.

Roesset (1980): For circular foundations, evaluate soil properties at depth$=1/2\times r$ (analogous to $Z_p=1.0\times r$ if velocity varies linearly with depth)

Gazetas (1991): For square foundations with side dimension $2a$, evaluate soil properties at depth $1/2\times a$ for translations and $1/3\times a$ for rocking (analogous to $Z_p=1.0\times a$ and $2/3\times a$ for translation and rocking, respectively).

Note the pre-2000 NEHRP recommendations differ significantly from the 2000 recommendations, which are similar to those of Roesset and Gazetas. In this section, we describe the development of the 2000 NEHRP recommendations for Z_p.

The evaluation of optimal profile depth (Z_p) is investigated by comparing static impedance solutions for square foundations on various non-uniform soil profiles (Wong and Luco 1985) with static stiffnesses calculated for an "equivalent" half-space using the following closed form expressions for a square foundation on a half-space (Gazetas 1991),

$$K_{y,H}=\frac{9}{2-v}G_H a,\ K_{\theta,H}=\frac{3.6}{1-v}G_H a^3, \tag{2}$$

where $G_H=v_{s,H}^2\rho_H$ is the effective half-space shear modulus, ρ_H=half-space mass density, and $2a$=foundation length. The objective is to evaluate the effective profile depths for which the half-space solution represents the actual static stiffness in translation and rocking with acceptably small errors. These analyses were performed for a rigid square foundation of side dimension $2a$ resting on two different profile configurations: (1) a stepped half-space and (2) a linearly increasing velocity profile overlying a half-space. These configurations are drawn in the upper right-hand corners of Figures 5a and b. For both the uniform and non-uniform soil layers, the mass densities of the half-space and overlying surface layer were assumed to form a ratio of $\rho_2/\rho_1=1.13$ by Wong and Luco (1985). In the case of the non-uniform layer, mass density increases from ρ_1 at the top of the layer to ρ_2 at the bottom of the layer. Half-space density (ρ_H) was taken as a weighted average across the profile depth.

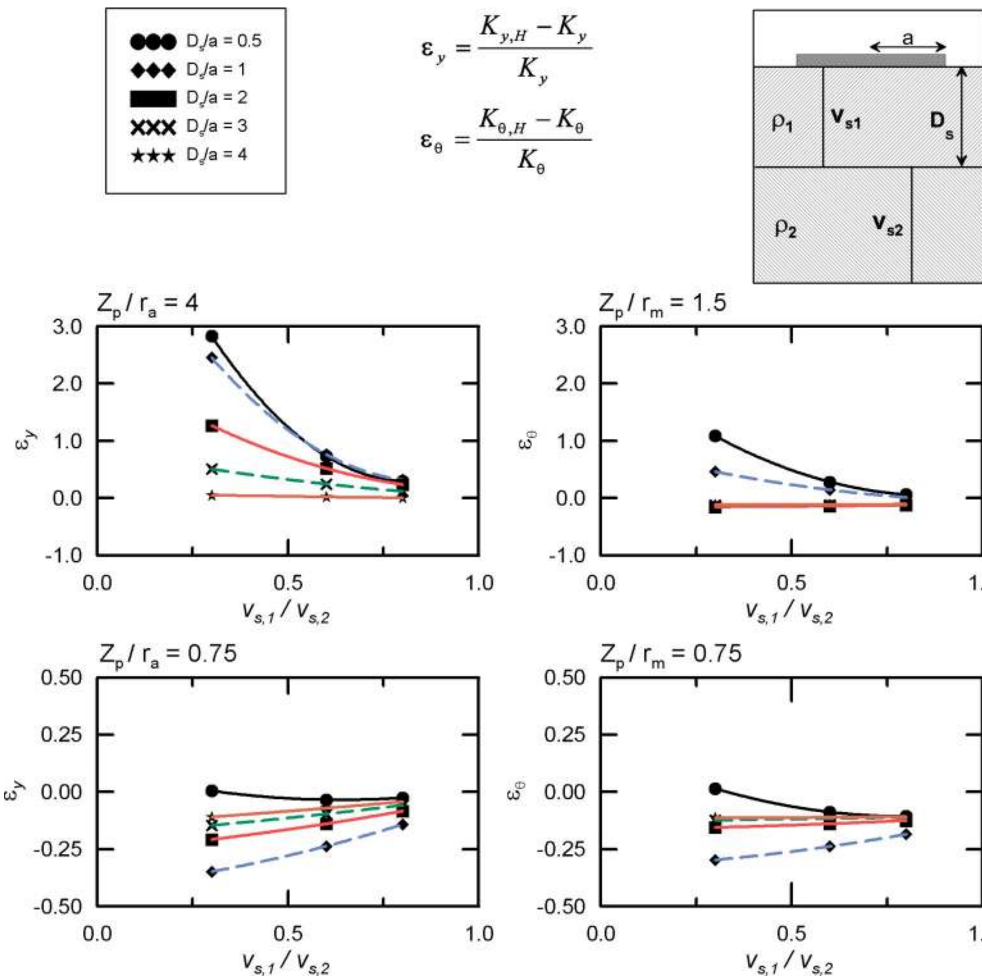

Figure 5(a). Static stiffness residuals for finite soil layer over half-space.

Plotted in Figure 5 are normalized residuals of the static translational and rocking stiffnesses, calculated as follows:

$$\varepsilon_y = \frac{K_{y,H} - K_y}{K_y}, \quad \varepsilon_\theta = \frac{K_{\theta,H} - K_\theta}{K_\theta}, \tag{3}$$

where K_y and K_θ are the "actual" static stiffnesses for lateral translation and rocking, respectively, of the profiles based on the solution by Wong and Luco (1985). As shown in the top frames of Figures 5a and b, the pre-2000 NEHRP values of $Z_p/r_a = 4$ for translation and $Z_p/r_m = 1.5$ for rocking lead to significant overestimates of foundation stiffness for strongly non-uniform profiles. As expected, residuals decrease with increasing

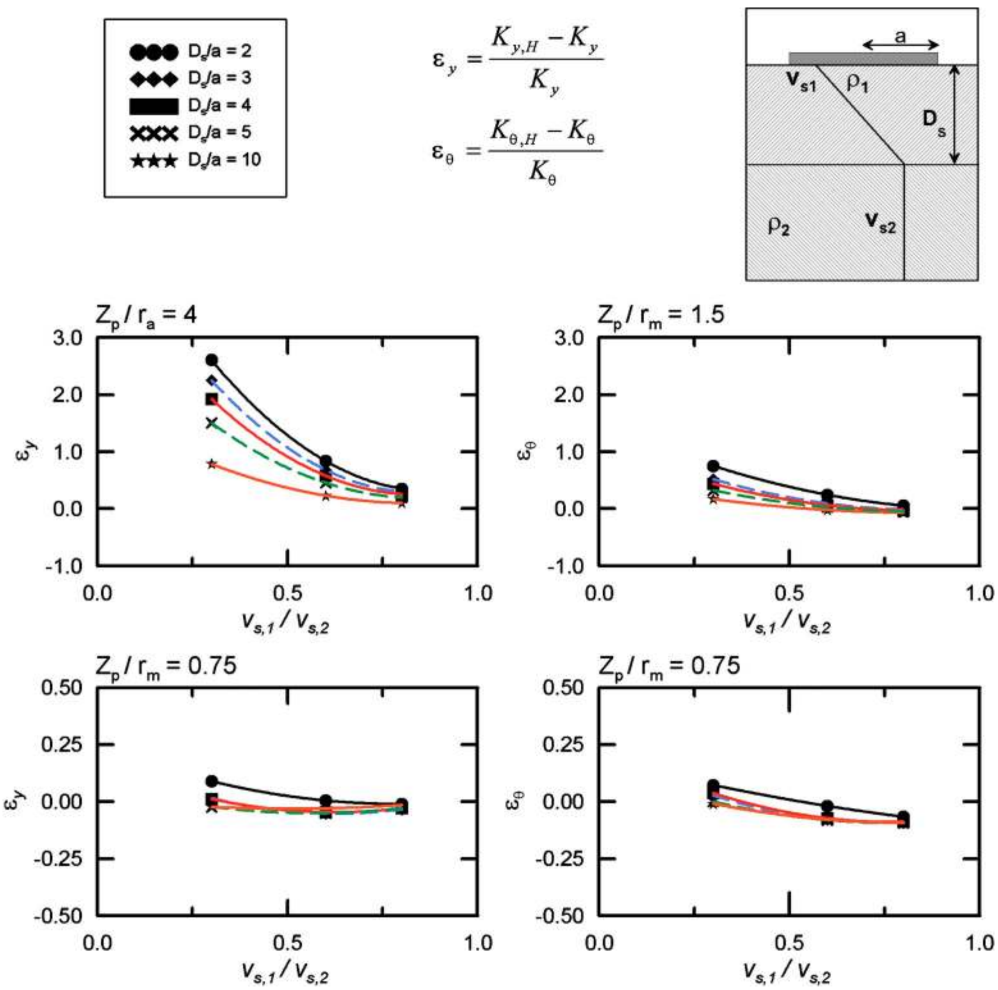

Figure 5(b). Static stiffness residuals for non-uniform layer over half-space.

profile uniformity (v_{s1}/v_{s2} approaching unity and $D_s/a \rightarrow \infty$). The largest errors occur for profiles having the shallowest depth range across which v_s varies (Figure 5a, $D_s/a = 0.5$, Figure 5b, $D_s/a = 2$).

The bottom frames of Figures 5a and b show residuals for normalized profile depths of $Z_p/r_a = Z_p/r_m = 0.75$. Note that the vertical scales on these frames have a much narrower range of ordinates than those in the upper frames due to the large reduction of residuals. Kim (2001) performed analyses similar to those synthesized in Figures 5 for $Z_p/r = 0.5$, 0.67, 0.75, and 1.0. The value of $Z_p/r = 0.75$ was found to minimize the residuals across the range of D_s/a considered for both the translation and rocking deformation modes for both linearly varying and stepped half-space profiles. Smaller values of Z_p/r tended to provide negative residuals (foundation stiffnesses too small), whereas larger Z_p/r provided positive residuals (foundation stiffnesses too large). As shown in Figures 5a and b, with $Z_p/r_a = Z_p/r_m = 0.75$, normalized residuals are generally less than 15%, with the exception of stepped half-space profiles with $v_{s1}/v_{s2} < 0.5$—a condition addressed below. The residuals are not asymptotic exactly to zero as v_{s1}/v_{s2} approaches unity because of the non-uniform density profile used by Wong and Luco (1985). It may be noted that if ρ_H was taken as ρ_2, the residuals at $v_{s1}/v_{s2} = 0.8$ would effectively be eliminated.

For profiles having adjacent layers with a large shear-wave velocity contrast (e.g., $v_{s1}/v_{s2} < 0.5$), we investigate the accuracy of the finite soil layer over rigid base model. Errors are again compiled relative to "actual" static stiffnesses of two-layer systems by Wong and Luco,

$$\varepsilon_y = \frac{K_{y,FL} - K_y}{K_y}, \quad \varepsilon_\theta = \frac{K_{\theta,FL} - K_\theta}{K_\theta}, \tag{4}$$

where $K_{u,FL}$ and $K_{\theta,FL}$ are the finite soil layer stiffnesses, evaluated as the product of the square foundation half-space stiffnesses from Equation 2 and the NEHRP finite soil layer corrections (multiplicative factors of $1 + r/2D_s$ for translation and $1 + r/6D_s$ for rocking, where D_s = finite soil layer thickness). Figure 6 shows residuals for a range of velocity ratios (v_{s1}/v_{s2}) and profile depths (D_s/a). The results indicate that residuals associated with the rigid base model are small (<~5%) for $v_{s1}/v_{s2} < 0.5$ and that the re-

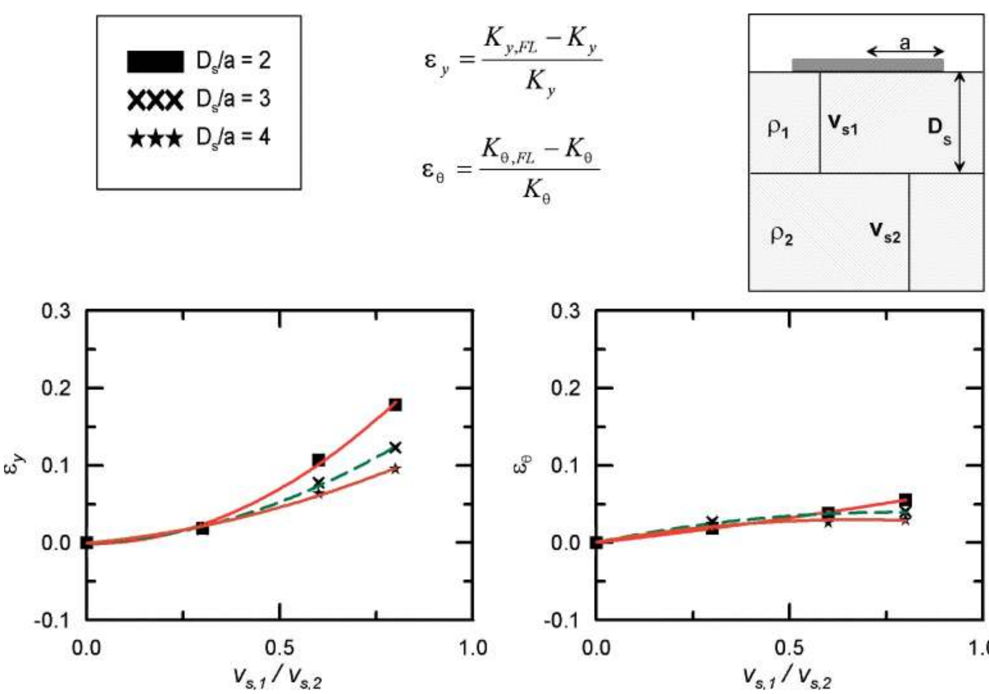

Figure 6. Static stiffness residuals for finite soil layer over rigid base model.

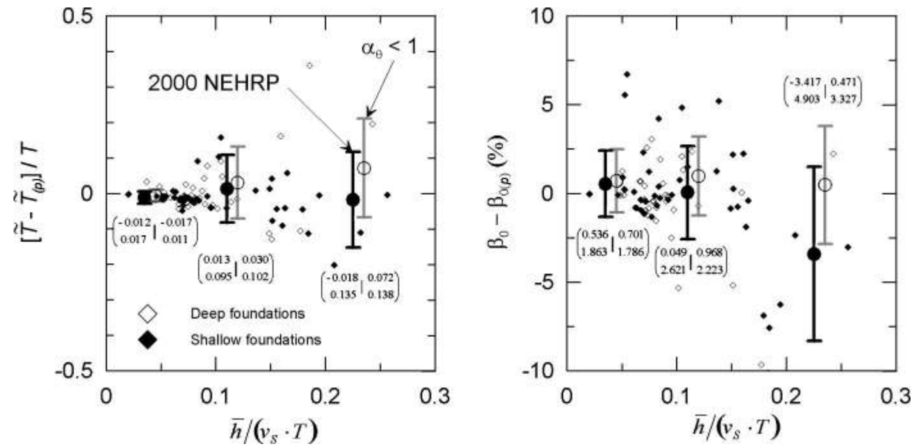

Figure 7. Period lengthening and foundation damping residuals from 2000 NEHRP SSI model and pre-2000 NEHRP model with α_θ modification (data outside of axis range not shown).

siduals are not sensitive to D_s/a for v_{s1}/v_{s2}<0.5. Hence, use of the finite soil layer over rigid base model is recommended for profiles with v_{s1}/v_{s2}<0.5. It should be noted that the NEHRP finite soil layer corrections are only for static stiffness, and the frequency dependence of impedance functions for layered media differs from that of a half-space. The *NEHRP Provisions* allow analysis of foundation damping factor for finite soil layers, using NEHRP Eq. 5.8.2.1.2-4. However, the NEHRP documents do not contain guidelines for the effects of foundation layering on the frequency dependence of static stiffness. Such effects can be analyzed using formulations summarized by Gazetas (1991).

Model Calibration with Field Performance Data

Predictions of period lengthening and foundation damping were compiled using the 2000 NEHRP SSI model, which includes the α_θ correction from the previous section and static foundation stiffnesses derived using the above recommendations. Shown in Table 1 are predictions of $\tilde{T}/T$ and β_0 for each site based on the revised model. Prediction residuals are presented in Figure 7 for acceptable confidence sites, and summary statistics for various ranges of $\bar{h}/(v_S \cdot T)$ are presented on the figure and in Table 2. The results show that the 2000 NEHRP model reduces the bias in each statistical "bin" except for foundation damping at large $\bar{h}/(v_S \cdot T)$, for which the underprediction bias becomes an overprediction bias. The mean underprediction bias for period lengthening is essentially eliminated for each range of $\bar{h}/(v_S \cdot T)$. The dispersion of period lengthening residuals was essentially unchanged. Based on the above results, and recalling the argument presented previously that judgment of model efficacy should focus principally on the period lengthening results, the use of relatively shallow profile depths appears to be beneficial in terms of bias reduction, but does not significantly affect prediction dispersion.

As a result of the β_0 underprediction bias reported above for $\bar{h}/(v_S \cdot T) > 0.1$, for projects where a proper analysis of damping is critical (i.e., sites where the change in base shear due to foundation damping is large based on NEHRP Eq. 5.8.2.1-2), it is recommended that detailed analyses be performed in lieu of the generalized procedures described herein. One relatively detailed procedure is the "Modified Veletsos" procedure presented in Stewart et al. (1999a). This procedure utilizes the same principles and dimensionless variables as those in the *NEHRP Provisions*. The procedure is based on the Veletsos and Nair (1975) model for a rigid foundation on the surface of a soil half-space, but includes modifications to β_0 for foundation embedment, flexibility, and shape. As reported in Stewart et al. (1999b), for essentially the same data set considered herein, this procedure produces essentially unbiased damping estimates for $\bar{h}/(v_S \cdot T) > 0.1$.

EFFECT OF REVISED PROCEDURES ON BASE SHEAR

The revisions to the NEHRP SSI analysis procedures described in the previous sections directly affect estimates of period lengthening and foundation damping, which in turn affect base shear. Table 2 indicates that for sites with $\bar{h}/(v_S \cdot T) > 0.15$, the average increase in flexible-base period from the pre-2000 to the 2000 *NEHRP Procedures* would be expected to be about $0.1T$. However, individual sites may have much larger changes, particularly if they have large increases in velocity with depth or stiff (low-period) structures. Several such sites are A1, A12, and B5, and as shown in Table 1, changes in flexible-base period for these sites can be on the order of $0.1T$–$0.3T$. The effect on base shear of this change in period is a function of the shape of the design spectrum, as discussed in the introduction. Referring to Figure 1b, when the flexible-base period from pre-2000 NEHRP ($\tilde{T}_{<2000}$) is $\geqslant T_s$, an increase of flexible-base period (due to the revised procedures) of $0.10T$–$0.30T$ will reduce the base shear (relative to the pre-2000 *Provisions*) by an amount of the same order (about 10 to 30%). Changes in foundation damping factor will cause additional change to the base shear (per NEHRP Eq. 5.8.2.1-2). Much smaller changes to the base shear would occur for $\bar{h}/(v_S \cdot T) < 0.15$.

With reference to the above discussion, it is of interest to consider the "fixed-base" period being lengthened by the NEHRP SSI analysis procedures. The NEHRP documents provide approximate formulas for calculating building period that are based in part on work by Goel and Chopra (1997, 1998). The building periods evaluated by Goel and Chopra were derived from base and roof lateral motions, and hence correspond to a pseudo flexible-base condition that incorporates structural flexibility and foundation-soil flexibility in rocking, but neglects foundation-soil flexibility in translation (Stewart and Fenves 1998). Since SSI effects are partially incorporated into these periods, one might argue that increasing such periods for SSI would be inappropriate and unconservative. However, the actual building period formulas that appear in the *NEHRP Provisions* do not provide the best fit to the observed periods, but give conservatively biased, low values. The amount of the bias is approximately 50%, which is larger than typical period lengthening ratios. Accordingly, lengthening of building periods estimated from these formulas to account for SSI is not likely to produce an unconservatively low base shear. Obviously, fundamental-mode periods evaluated from building-specific, fixed-based analyses can also be safely increased to account for SSI effects.

SUMMARY AND CONCLUSIONS

In this paper, SSI analysis procedures in the pre-2000 and 2000 *NEHRP Provisions* (BSSC 1998, 2001) are verified against field performance data derived from system identification analyses. The analysis procedures affect the design base shear force in building structures by adjusting the fixed-base modal period and damping ratio to corresponding flexible-base values that account for inertial SSI. The analysis procedures are based on the assumed conditions of a single-degree-of-freedom structure model, a rigid, circular foundation slab, and uniform, isotropic soil.

Despite the highly idealized conditions associated with the model formulation, the 2000 NEHRP model is found to provide reasonably accurate and unbiased predictions of the SSI effects of period lengthening and foundation damping. The types of structures for which application of the model are considered appropriate are relatively regular building structures with foundations that consist of thickened mats, interconnected continuous footings, and interconnected footings that are supported by deep foundation elements but which remain in contact with the soil. SSI effects are found to be most significant in stiff structures (shear wall or braced frame lateral load-resisting systems typically having small aspect ratios) founded on soil. SSI effects are found to be negligible in long-period (e.g., high-rise) structures due to their large structural flexibility. The 2000 NEHRP SSI procedure is able to capture the SSI effects for both classes of structures.

One of the major thrusts of this paper was to present several revisions to the NEHRP SSI procedure that were made in the 2000 provisions update cycle. These changes affect the calculation of foundation stiffness, one change introducing dynamic modifiers to rocking stiffness, another change decreasing the depth range over which representative half-space velocities are evaluated. Guidelines were also added for use of a finite soil layer over rigid base representation of the soil profile. These modifications appear in the 2000 *NEHRP Commentary* on pages 130, 133, and 131, respectively. The introduction of these modifications to the NEHRP SSI model is found to remove statistically significant biases in period lengthening predictions from the pre-2000 NEHRP model.

We find little difference between the prediction residuals for sites with shallow foundations (footings, grade beams, mats) and deep foundations (piles, drilled shafts). It should be noted, however, that the deep foundation sites used in this study have no significant increase in v_s across the length of the deep foundations, and different results would be expected for end-bearing piles. Guidelines for more rigorous analyses of impedance functions for pile-supported foundations without cap-soil contact can be found in Gazetas (1991).

ACKNOWLEDGMENTS

Partial support for this project was provided by a CAREER grant (to JPS) from the National Science Foundation (NSF Award No. 9733113). Partial support was also provided (to JPS) by the Pacific Earthquake Engineering Research Center's Program of Applied Earthquake Engineering Research of Lifeline Systems supported by Pacific Gas and Electric Company. This work made use of Earthquake Engineering Research Centers Shared Facilities supported by the National Science Foundation under Award #EEC-9701568. The views and conclusions contained in this document are those of the writers and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. government. The authors would like to thank the three anonymous reviewers of this manuscript for their helpful comments.

REFERENCES

Applied Technology Council (ATC), 1978. *Tentative Provisions for the Development of Seismic Regulations for Buildings, ATC 3-06*, Redwood City, CA.

American Society of Civil Engineers (ASCE), 2000. *Prestandard and Commentary for the Seismic Rehabilitation of Buildings*, prepared for the SAC Joint Venture, published by the Federal Emergency Management Agency, *FEMA-356*, Washington, DC.

Bielak, J., 1975. Dynamic behavior of structures with embedded foundations, *Earthquake Eng. Struct. Dyn.* **3**, 259–274.

Bielak, J., 1976. Modal analysis for building-soil interaction, *J. Eng. Mech.* **102**, 771–786.

Building Seismic Safety Council (BSSC), 1998. *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*, Federal Emergency Management Agency, Washington, DC.

Building Seismic Safety Council (BSSC), 2001. *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures*, Federal Emergency Management Agency, Washington DC.

Crouse, C. B., 2002. Commentary on soil-structure interaction in U.S. seismic provisions, *Proceedings of the 7th U.S. National Conference on Earthquake Engineering, Boston, July 21–25*, Earthquake Engineering Research Institute.

Gazetas, G., 1991. *Foundation vibrations, Foundation Engineering Handbook*, 2nd Edition, H.-Y. Fang, ed., Chapter 15.

Goel, R. K., and Chopra, A. K., 1997. Period formulas for moment-resisting frame buildings, *J. Struct. Eng.* **123**, 1454–1461.

Goel, R. K., and Chopra, A. K., 1998. Period formulas for concrete shear wall buildings, *J. Struct. Eng.* **124**, 426–433.

Idriss, I. M., and Sun, J. I., 1992. *SHAKE91: A Computer Program for Conducting Equivalent Linear Seismic Response Analyses of Horizontally Layered Soil Deposits*, Center for Geotech. Modeling, University of California, Davis.

Jennings, P. C., and Bielak, J., 1973. Dynamics of building-soil interaction, *Bull. Seismol. Soc. Am.* **63**, 9–48.

Kausel, E., 1974. Forced vibrations of circular foundations on layered media, *Report No. R74-11*, Dept. of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA.

Kim, S., 2001. Calibration of Simple Models for Seismic Soil-Structure Interaction from Field Performance Data, Ph.D. Dissertation, Dept. of Civil Eng., University of California, Los Angeles.

Kim, S., and Stewart, J. P., 2003. Kinematic soil-structure interaction from strong motion recordings, *J. Geotech. Geoenviron. Eng.* **129** (4), 323–335.

Roesset, J. M., 1980. A review of soil-structure interaction, in *Soil-Structure Interaction: The Status of Current Analysis Methods and Research*, J. J. Johnson, ed., *Report No. NUREG/CR-1780*, U.S. Nuclear Regulatory Commission.

Stewart, J. P., and Fenves, G. L., 1998. System identification for evaluating soil-structure interaction effects in buildings from strong motion recordings, *Earthquake Eng. Struct. Dyn.* **27**, 869–885.

Stewart, J. P., Seed, R. B., and Fenves, G. L., 1999a. Seismic soil-structure interaction in buildings. I: Analytical aspects, *J. Geotech. Geoenviron. Eng.* **125**, 26–37.

Stewart, J. P., Fenves, G. L., and Seed, R. B., 1999b. Seismic soil-structure interaction in buildings. II: Empirical findings, *J. Geotech. Geoenviron. Eng.* **125**, 38–48.

Veletsos, A. S., and Nair, V. V., 1975. Seismic interaction of structures on hysteretic foundations, *J. Struct. Eng.* **101**, 109–129.

Veletsos, A. S., and Verbic, B., 1973. Vibration of viscoelastic foundations, *Earthquake Eng. Struct. Dyn.* **2**, 87–102.

Wong, H. L., and Luco, J. E., 1985. Tables of impedance functions for square foundations on layered media, *Soil Dyn. Earthquake Eng.* **4**, 64–81.

(Received 23 August 2001; accepted 18 February 2003)