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IMPROVED DESIGN GUIDANCE FOR SOIL-STRUCTURE INTERACTION

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Abstract

This paper provides an interim summary of a study nearing completion to provide improved design guidance for soil-structure interaction (SSI). Funded by the U.S. Federal Emergency Management Agency, and led by an Applied Technology Council team, the ATC-144 project has three components: (1) case study analyses to test the SSI provisions in ASCE/SEI 7-16 *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, (2) a design guide for practicing engineers, and (3) recommended code changes to the SSI provisions in ASCE/SEI 7-16.

The *case study analyses* use direct analysis where the soil and building are both modeled with nonlinear finite elements, and ground motion inputs include spatial variability. Initial case studies compare recordings from two instrumented buildings with results from analytical models to help validate and calibrate the modeling techniques and assumptions. The instrumented buildings are a 12-story concrete shear wall hotel and a four-story concrete shear wall hospital, each with recordings from multiple California earthquakes. Comparisons will be made between free-field motion and foundation motion to study kinematic interaction effects from base slab averaging and foundation embedment, as well as superstructure drift, floor acceleration, and base shear. Subsequent case studies focus on two archetypes: a two-story buckling-restrained braced frame building on spread footings and a 12-story concrete building on piles with a moment frame in one direction and a shear wall and moment frame dual system in the other direction. Each archetype is designed per ASCE/SEI 7-16 without incorporating SSI and then again using different SSI provisions. These sets of archetypes are then analyzed in the direct analysis framework using earthquake records scaled to different levels of shaking. Comparisons will be made between the changes predicted by the ASCE/SEI 7-16 SSI provisions and the analytical findings. A key area of study is to determine if the kinematic interaction provisions in ASCE/SEI 7-16, which were largely based on linear response of buildings in low and moderate levels of shaking, remain valid at higher levels of shaking when both the soil and building experience nonlinear behavior. Case study results are in progress and are not ready to be provided, but the paper discusses analysis plans, including the instrumented and case study buildings considered, earthquake records studied, the general approach used for direct analysis, the metrics used for comparisons, and the permutations in modeling assumptions considered to evaluate different issues.

The *design guide* is intended to help practicing engineers know when incorporating SSI would be important and to show them examples of how to implement different SSI techniques. It describes situations where SSI effects can reduce or increase demands on the building or simply change the pattern of yielding in the foundation and superstructure. It covers period lengthening, foundation damping, base slab averaging, embedment effects, soil flexibility, and modeling of basements; and it includes worked design examples for the two-story braced frame building and 12-story concrete building used in the analytical case studies.

Finally, *potential code changes* for the SSI provisions in ASCE/SEI 7-16 were identified, based on the analytical efforts and issues illuminated in developing the design guide.

Keywords: soil-structure interaction; SSI; ASCE/SEI 7-16; base slab averaging; embedment effects

1. Introduction

This paper provides an interim summary of a study nearing completion to provide improved design guidance for soil-structure interaction (SSI). Funded by the U.S. Federal Emergency Management Agency, and led by an Applied Technology Council team, the ATC-144 project has three components: (1) case study analyses to test the SSI provisions in ASCE/SEI 7-16 [1], (2) a design guide for practicing engineers, and (3) recommended code changes to the SSI provisions in ASCE/SEI 7-16. The project extends work that was developed in NIST GCR 12-917-21 [2].

The *case study analyses* use what is termed the “direct analysis approach” where the soil and building are both modeled with nonlinear finite elements. The ground motion inputs include spatial variability so that the effects of this variability on foundation input motions can be compared with semi-empirical models used in current procedures [2]. Case studies cover both instrumented buildings and archetype buildings. Recordings from instrumented buildings are compared with results from analytical models to help validate and calibrate the modeling techniques and assumptions. Two archetype buildings—a two-story buckling-restrained braced frame building on spread footings and a 12-story concrete building on piles with a moment frame in one direction and a shear wall/moment frame dual system in the other direction—were then used to conduct a number of parameter studies. Each archetype is designed per ASCE/SEI 7-16 without incorporating SSI and then again using different SSI provisions. Parameter studies included varying the level and spatial variability of ground shaking, the soil-to-structure interface assumptions, and nonlinearity in the soil and superstructure. Comparisons will be made between the changes predicted by the ASCE/SEI 7-16 SSI provisions and the analytical findings. Some of the designs performed with SSI ignored certain SSI code provisions that would prevent such applications. This approach was taken as part of a broader objective of understanding whether current code limits are needed or could be reconsidered in future code cycles.

The *design guide* is intended to help practicing engineers know when incorporating SSI would be important and to show them examples of how to implement different SSI techniques. It covers period lengthening, foundation damping, base slab averaging, embedment effects, soil flexibility, and modeling of basements; and it includes worked design examples for the two-story braced frame building and 12-story concrete building used in the analytical case studies. The design guide examples use what is called the “substructure approach” where the soil is represented by springs, which is the typical current practice of structural engineers for buildings, rather than finite element modeling of the soil.

Finally, *potential code changes* for the SSI provisions in ASCE/SEI 7-16 were identified, based on the analytical efforts and issues illuminated in developing the design guide.

The case study analysis approach is summarized in Section 2; the design guide is addressed in Section 3; and potential code changes are reviewed in Section 4.

2. Case Study Analyses

The case study analysis effort is nearing completion. Interim results are both under development and under review at the time of preparation of this paper and are not ready to be provided, but this section discusses analysis plans, including the instrumented and case study buildings considered, earthquake records studied, the general approach used for direct analysis, the metrics used for comparisons, and the permutations in modeling assumptions considered to evaluate different issues. The finite element software used for the direct analysis models is Real-ESSI Simulator System developed at UC Davis [3].

2.1 Instrumented Buildings Evaluated

Direct analysis models were created for two different instrumented buildings: the 12-story Ventura Hotel (California Strong Instrumentation Program or CSMIP Station #25339) and the four-story Loma Linda Hospital (National Strong Motion Program or NSMP Station #5229).

The Ventura Hotel is a concrete shear wall building founded on piles. The CSMIP staff in the California Geological Survey provided the structural drawings that were used to construct a model. The soil profile at the site comes from Stewart and Stewart [4] and includes two main layers. The top 15 m is a silt and clay layer with a shear wave velocity of approximately 250 m/s, underlain by a second layer of interbedded clay and sand with a shear wave velocity of approximately 425 m/s. Equivalent viscous damping of 10% for the soil and 3% for the structure were used. Free-field records from nearby CSMIP Station #25340 were used. Both free-field and building records were available and investigated for the January 17, 1994 **M**6.4 Northridge Earthquake, the March 12, 2016 **M**4.1 Ojai Earthquake, and the July 4, 2019 **M**6.4 Ridgecrest Earthquake. The Northridge Earthquake had a fault distance of 55 km from the building, a ground PGA of 0.12g and a peak acceleration at the roof of 0.31g. The Ojai Earthquake had an epicentral distance of 34 km from the building, but it produced smaller levels of shaking with a PGA of 0.027g and an acceleration of 0.052g at the roof. The Ridgecrest Earthquake had a fault distance of 214 km from the building, with a PGA of 0.012g and a peak acceleration at the roof of 0.045g. Note that instruments at the building have been updated over time, so more recent earthquakes are recorded with higher resolution. Sensor layouts are shown in Fig. 1; views from the direct analysis model are shown in Fig. 2.

The Loma Linda Hospital is a very stiff and strong concrete shear wall structure. After initial modeling and results, where the first 50 eigen-modes were found to be out-of-plane oscillations of the floor plates and limited inelastic behavior in the walls is anticipated, it was decided to concentrate analysis and validation efforts on the Ventura Hotel.

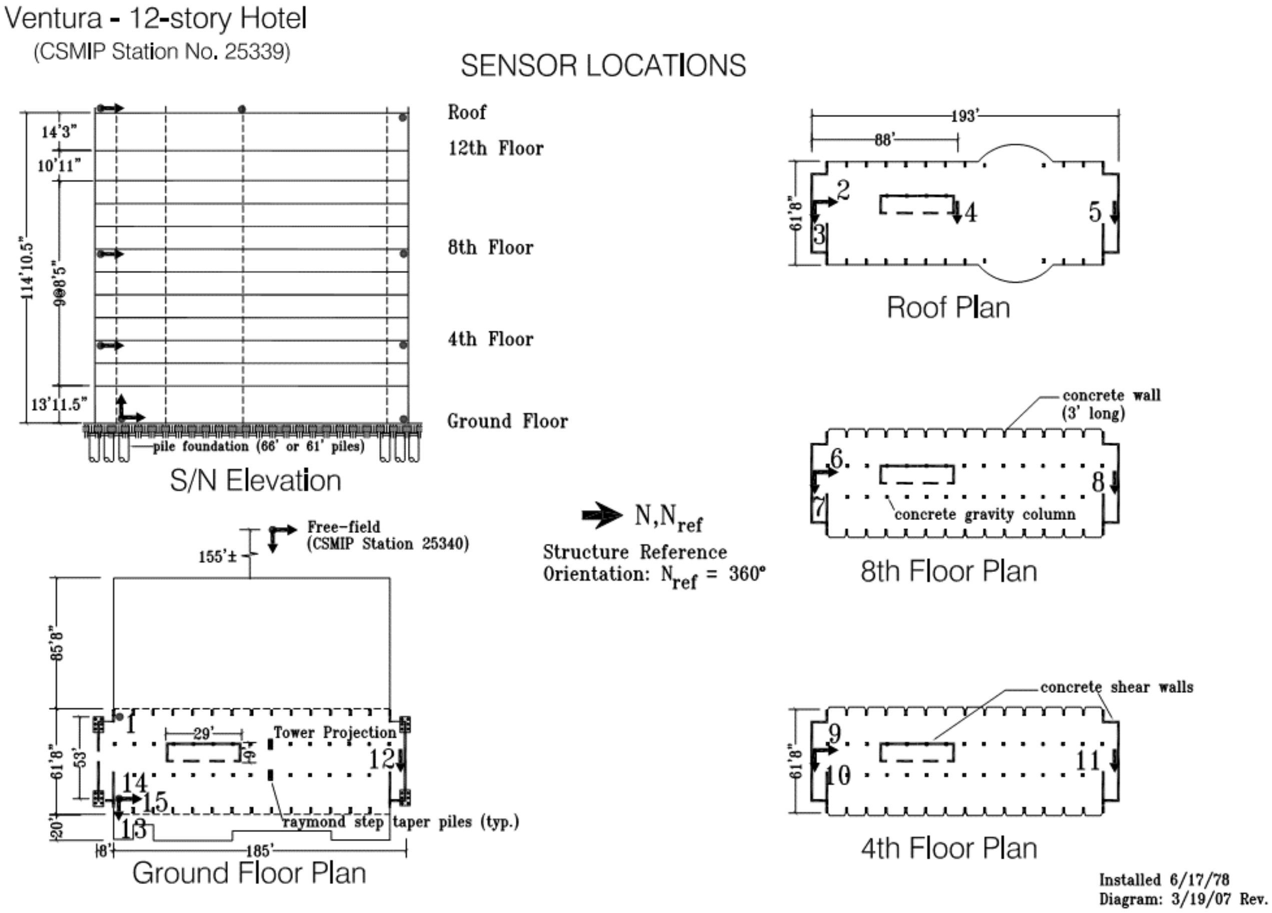

Fig. 1 – Sensor layout for instrumented building: Ventura Hotel
(from https://www.strongmotioncenter.org/NCESMD/photos/CGS/bldlayouts/bld25339.pdf)

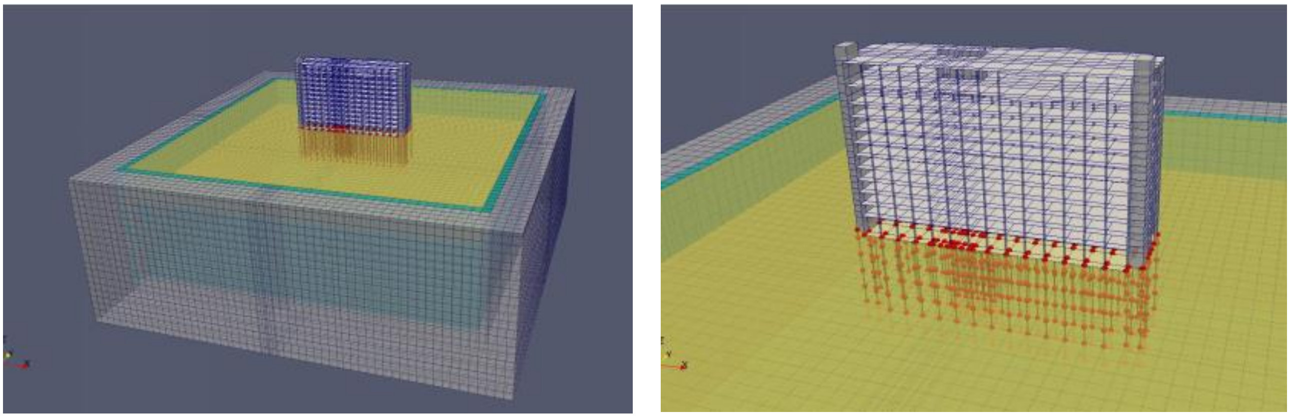

Fig. 2 – Direct analysis model for instrumented building: Ventura Hotel. The one-story extension at grade is not shown for clarity.

2.2 Archetype Buildings Studied

Two archetype buildings were developed to allow for various parameter studies: the first is a two-story buckling-restrained braced frame building supported by spread footings; the second is a 12-story concrete building with a moment frame in one direction and a dual frame in the other direction. They were designed using ASCE/SEI 7-16, initially without using SSI provisions and then using SSI provisions. Direct analysis models were also created for each building and are shown in Fig. 3.

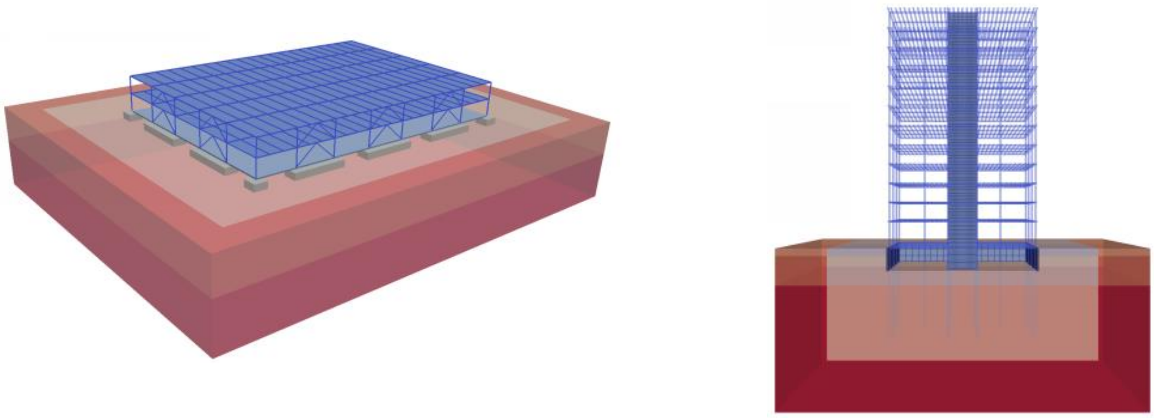

Fig. 3 – Direct analysis models for archetype buildings:
Left—Two-story braced frame, Right—12-story dual system

The two-story braced frame building is rectangular and symmetrical for simplicity. It has three bays of braces on the longer sides and two bays on the shorter sides, to generate different member sizes and overturning considerations. Spread footings are designed to be large enough to have enough capacity to meet code level demands for resisting overturning on the compression side in the soil bearing and to provide enough weight to resist overturning uplift on the tension side. The building is assumed to be at the same location as the Loma Linda Hospital (Latitude 34.049601°, Longitude -117.250073°) with the same soil conditions, with sands and gravels, with increasing density at depth. The soil profile at the site comes from

Stewart and Stewart [4]. The shear wave velocity in the upper 30 m is 290 m/s, resulting in a site classification per ASCE/SEI 7-16 of Site Class D, as it is between 183 m/s and 366 m/s. USGS ground motion parameters at the site per online web applications yield S_S=2.355, S_1=0.943, S_{MS}=2.355g, and S_{DS}=1.570g. Without a site response analysis and with Site Class D, an exception in ASCE/SEI 7-16 Section 11.4.8 allows consideration of a conservative spectral shape with C_S taken as the value determined by Eq. 12.8-2 for periods up to 1.5T_S and taken as 1.5 times the value computed by ASCE/SEI 7-16 Eq. 12.8-3 for longer periods considering F_v=1.7. Designs use the equivalent lateral force (ELF) procedures of ASCE/SEI 7-16 Section 12.8. Designs with SSI provisions incorporated the reductions from period lengthening per ASCE/SEI 7-16 Section 19.2, foundation damping from ASCE/SEI 7-16 Section 19.3, and base slab averaging per ASCE/SEI 7-16 Section 19.4 (ignoring the current provision that limits this to only nonlinear response history analysis or NRHA).

The 12-story concrete building is also rectangular and symmetrical for simplicity. It has a one-story basement and is founded on piles. It is assumed to be located in Antioch, California (Latitude 38.0021°, Longitude -121.7976°). The soil profile was defined for the example and includes loose sand/fill for 2 m, then soft clay to 9 m, underlain by medium dense sand to 30 m. The average shear wave velocity in the upper 30 m is 275 m/s, yielding Site Class D. Site-specific ground motion parameters are S_S=1.537, S_1=0.525, S_{DS}=1.0g and S_{D1}=0.7. Designs use the Modal Response Spectrum procedures of ASCE/SEI 7-16 Section 12.9, with scaling to the base shear from the ELF procedures of ASCE/SEI 7-16 Section 12.8. Designs with SSI provisions incorporated the reductions from period lengthening per ASCE/SEI 7-16 Section 19.2, foundation damping from ASCE/SEI 7-16 Section 19.3, and base slab averaging and embedment effects per ASCE/SEI 7-16 Section 19.4 (ignoring the current provision that limits this to only NRHA). Also, permutations with and without a basement will be considered, as well as the use of upper and lower bound soil properties.

A key aspect of the direct analyses of the archetype buildings is loading of the systems at various shaking levels. Because the instrumental recordings that are available do not reach the design earthquake level, a suite of ground motions are selected and scaled to the design earthquake (DE) level and beyond. For each building, three records were identified from the FEMA P-695 [5] far-field suite and amplitude scaled at the building fundamental period to the 0.25DE, 0.50DE, 1.0DE, and MCE levels. The three records were selected by examining the RotD50 [6] spectral acceleration amplitude of each ground motion pair in the FEMA P-695 far-field suite and identifying the record pairs at the high end, low end, and at the median at a period 1.5 times the fixed-base fundamental period.

2.3 Direct Analysis Considerations

For each direct analysis model, nonlinear finite elements are developed to represent the soil and the superstructure. A summary of some key features of the models is as follows.

- Size of models for soil: The soil typically is extended beyond the footprint of the building a distance that is far enough from past experience to sufficiently capture SSI effects. For example, at the two-story braced frame building, the out-to-out spacing of columns is 46 m x 64 m in plan, with spread footings that go down about 2 m below the top of the slab-on-grade. The overall finite element model for the soil is 70 m x 90 m in plan and about 12 m deep.
- Finite element size for soil: The soil finite elements are typically about 1 m to 1.5 m in all x, y, and z directions.
- Soil properties: The finite elements for the soil include material parameters for inelastic modeling that include von Mises Armstrong-Frederick kinematic hardening with a vanishing elastic region.
- Spatial variability: A key feature of the project has been to include spatial variability in the ground motions used. The recorded motions for the instrumented buildings or the scaled FEMA P-695 are seed records that apply at the surface of the ground. If the same seed records were applied to every point,

then the input motions would be "coherent." Actual waves differ across the site. Spatial variability or "incoherence" has been simulated on a 2D grid conditioned on the seed input ground motion and Fourier amplitude and phase variability models from [7] and [8] using the process in [9].

- Deconvolution of surface ground motions: Seismic motions at different vertical depths are developed from the surface motions with spatial variability through deconvolution of one component (1C) of motions to a certain depth and then propagating those motions vertically into the soil-structure model using the Domain Reduction Method in [10] and [11]. More details about approach used for seismic input are available in Chapter 502.5 of [12]. Free field seismic motion development, including seismic wave deconvolution, is described in some detail in Chapter 502.3 of [12].

2.4 Metrics Considered

The size of the models is large, and with response history recordings, the amount of data collected is vast. Time history traces and peak values during the record are generated and documented for many parameters in both the x-direction and y-direction. Key metrics include the following.

- Free field PGA: This is recorded at two corners at the edge of the modeled soil field, at a point a few meters from the building, and directly below the building, with values taken both at the surface and at the base of the soil field.
- First floor PGA.
- Roof peak floor acceleration and peak displacement.
- Base shear.
- Ratio of PGA at the ground level to the free field PGA: This ratio represents the reduction that can occur from kinematic SSI effects and is termed "RRS" in ASCE/SEI 7-16. The ratio of the full response spectrum is plotted, and values are recorded for the following periods (in seconds): 0.10, 0.25, 0.50, 0.75, 1.0, 1.5, and 2.0.
- Foundation lift off: Whether the foundation lifts off from the soil in tension is recorded.

2.5 Permutations Considered

Many permutations were developed for the direct analysis models, including both fixed base and flexible base. Traditional fixed based models are included for context and to help validate the modeling effort, including comparisons of modal periods for the design models and the direct analysis models. There are two permutations, one with a linear superstructure and one with a nonlinear superstructure.

The focus of the work, however, is on the direct analysis models that include foundation and soil flexibility, and parameters include structural properties (linear vs. nonlinear), general soil properties (linear vs. nonlinear), soil stiffness and nonlinearity, whether the soil and foundation are forced to remain in contact or not, the soil-to-foundation coefficient of friction, spatial variability of ground motion across the soil field in the model, wave passage effects, ground motion scaling, and foundation types and details.

The spatial variability modeling conditioned on a seed input motion does not assume there is a presumed direction of motion of the ground motion waves. One permutation studied varies this approach by assigning a direction of movement from one corner of the model towards an opposing corner. This is called the wave passage effect, and it introduces a time component to the ground motion characterization where waves hit one side of the model earlier than the other side, due to a non-vertical wave propagation [13].

ASCE/SEI 7-16 Section 19.4.1 limits the use of base slab averaging for "structures that have structural mats or foundation elements interconnected with concrete slabs or that are continuously connected with grade beams or other foundation elements of sufficient lateral stiffness so as not to be characterized as flexible under the requirements of Section 12.3.1.3." Whether base slab averaging can be used with less restrictive requirements is explored through several foundation interconnectivity permutations for the two-story steel building. These include (1) a full mat under the building, (2) spread footings interconnected by grade beams, (3) a slab-on-grade that is positively connected to the top of the spread footings through concrete overpours onto the footing and doweling between the slab and footing, (4) a slab-on-grade that is separated from the top of the footings by soil but is poured tight to the columns, and (5) a slab-on-grade that is separated from the top of the footings and has a typical sealant gap around the columns for crack control.

The baseline direct analysis model has a nonlinear structure, expected nonlinear soil properties, expected soil-to-foundation coefficient of friction, the ability for the soil and foundation to lose contact, spatial variability but no wave passage effects, design earthquake level shaking, and a slab-on-grade in contact with the superstructure for the two-story building. Individual parameters are then varied to study their effects on the metrics noted in Section 2.4 and how well they predict the results of related equations in ASCE/SEI 7-16. These include softening and stiffening the baseline soil properties, then modifying the coefficient of friction, then reducing and increasing the level of shaking by scaling the records, then modifying soil contact assumptions and slab-to-structure contact, and finally studying the impact of the wave passage effect.

3. Design Guide

SSI can make a substantial difference in how buildings behave during earthquake shaking and how they should be designed, yet there is relatively little implementation of SSI effects by practicing engineers. Provisions are available in Chapter 19 of ASCE/SEI 7-16 and in Chapter 8 of ASCE/SEI 41-17 [14] that can be used to address SSI. A key product of the ATC-144 effort is a design guide of examples, preliminarily titled “A Practical Guide to Soil-Structure Interaction.” FEMA has assigned it a publication report number of FEMA P-2091.

3.1 Purpose of the *Guide*

The overall goal of this *Guide* is to present information regarding SSI as implemented in code provisions but in an easy-to-understand, concise format targeted towards practicing engineers. The purpose of the *Guide* is (1) to help practicing engineers know when incorporating SSI would be important and (2) to show examples of how to implement different SSI techniques.

3.2 Scope of the *Guide*

The *Guide* covers the SSI topics in ASCE/SEI 7-16 Section 12.13 and Chapter 19, including period lengthening, foundation damping, base slab averaging, foundation embedment, and soil flexibility. It also provides advice on modeling of basements and gives easy-to-use rules-of-thumb on when SSI is likely to be of significance. The focus is on techniques that practicing engineers can use. As such, soil flexibility is addressed through the use of springs, rather than by finite element modeling as used in direct analysis.

3.3 Target Audience for the *Guide*

The primary target audience for the *Guide* is practicing engineers who are familiar with seismic design using ASCE/SEI 7 but who have little to no experience with SSI. A secondary audience is engineers who have some experience with some SSI techniques, such as using springs, but may need advice on other SSI techniques they have not utilized.

3.4 Organization of the *Guide*

The remainder of the *Guide* is organized into the following chapters.

- **Chapter 1, Introduction,** introduces SSI terminology; covers the purpose, scope, and target audience for the Guide; and summarizes some key high-level advice on SSI implementation (see Section 3.5 below).
- **Chapter 2, Situations Where SSI is Important,** provides a series of example images and related discussion of situations that engineers commonly encounter where SSI can impact the forces used in design and the way the structure responds to earthquake shaking. These include (1) a large building

footprint where base slab averaging has been shown to reduce spectral demands, primarily in the short period range, (2) substantial foundation embedment which can reduce spectral demands, also primarily in the short period range, due to the typical decrease in ground motion amplitudes with depth, (3) high structure-to-soil stiffness ratios that will lengthen periods and impact the associated spectral demands, and (4) buildings governed by foundation rocking that can significantly change the mechanism of behavior in the superstructure and associated demand-to-capacity ratios.

- **Chapter 3, Rule-of-Thumb Test for SSI Importance,** describes a simple test that can be used at the start of a project when only very limited information is available to help determine if using SSI will be likely to make a difference in results. The rule of thumb is targeted at inertial interaction and does not provide information about the potential significance of kinematic interaction.
- **Chapter 4, Base Slab Averaging,** addresses how the interconnectivity of the foundation can help reduce the demands into the structure. It provides examples of common foundation and slab-on-grade situations and whether base slab averaging can be used.
- **Chapter 5, Foundation Embedment,** discusses how foundation embedment can reduce the demands on the structure.
- **Chapter 6, Soil Flexibility,** reviews different methods for adding vertical and horizontal springs to represent soil flexibility.
- **Chapter 7, Period Lengthening,** covers provisions for how soil flexibility leads to period lengthening in the structural response and the resulting impact on seismic demands.
- **Chapter 8, Foundation Damping,** shows how and when to apply two types of foundation damping—called radiation damping and soil damping—that can reduce demands on the structure.
- **Chapter 9, How to Model a Basement,** discusses different simple but accurate analytical approaches to modeling basements.
- **Chapter 10, Conclusions,** summarizes key points regarding SSI discussed in the *Guide* and provides recommendations on revisions needed to code SSI provisions and further SSI studies that should be undertaken
- **Appendix A, Two-Story Building Example,** provides a detailed example of applying different SSI techniques for the two-story steel buckling-restrained braced frame building. SSI topics include implementation of soil springs; change in response mode and reduction in seismic demands due to foundation flexibility, soil flexibility and damping; and base slab averaging.
- **Appendix B, Twelve-Story Building Example,** provides a detailed example of applying different SSI techniques for the 12-story concrete building that has a moment frame in one direction and a dual system with a moment frame and shear wall in the other direction. It includes variations with and without a basement. SSI topics covered include reduction in design demands due to base slab averaging and foundation embedment, adjustments to demands from period elongation and foundation damping, and impacts of limitations imposed by ASCE/SEI 7-16 provisions.

3.5 Tips for Understanding and Implementing SSI

Based on experience in performing SSI analyses, the following general observations are offered. These observations are discussed in detail in the *Guide*.

- SSI is not that difficult to implement.
- SSI is typically iterative, so it may require additional rounds of analysis, as compared to a fixed base analysis, to converge on the final solution.

- SSI typically reduces the seismic demands that are used for design, but there are unusual cases with site-specific response spectra where demands can increase because period elongation may lead to climbing up the response spectrum with increasing levels of spectral acceleration.
- Adding foundation flexibility to a model can affect how the building behaves in some situations and associated deformation patterns, particularly for situations where foundation flexibility would lead to rocking of shear walls or braced frames in the superstructure. This can increase shear and/or flexural demands in certain structural elements relative to what would be evaluated from fixed base analyses.
- Effective shear wave velocity, v_s, is a key parameter in several SSI equations and techniques. The effective shear wave velocity differs from the low strain shear wave velocity, v_{so}, used for site classification in ASCE/SEI 7-16 Chapter 21. Modifications are made based on soil type, site spectral acceleration, and the depth of importance. The *Guide* provides guidance on this subtle, important issue.
- There are a number of code provisions, both in ASCE/SEI 7-16 Chapter 12 and in Chapter 19, that can limit the extent of SSI reductions that can be utilized. These restrictions may be discouraging application of SSI and lack a strong technical basis.
- Although ASCE/SEI 7-16 is the standard that is referenced and used in the *Guide*'s design examples, ASCE/SEI 41-17 has a similar set of SSI provisions. In some cases, ASCE/SEI 41-17 has more relaxed requirements and limitations regarding the use of SSI. The *Guide* highlights these differences.

4. Possible Code Change Proposals

As part of the ATC-144 project, review of the ASCE/SEI 7-16 Chapter 19 SSI provisions was undertaken, including comparison with the SSI provisions in ASCE/SEI 41-17 Chapter 8. The provisions in the two standards are similar, but the ASCE/SEI 41-17 provisions have fewer limitations, except in a couple of cases. Table 1 provides a comparison.

Table 1 – Comparison of SSI provisions

Issue	ASCE/SEI 41-17	ASCE/SEI 7-16	Comment/Justification
Site Class	Class C, D, E for kinematic (§8.5.1.1)	No Class A or B for any SSI (§19.1)	SSI effects in Class A and B assumed minimal (§C19.1)
Kinematic SSI (base slab averaging and embedment)	Permitted for any method	Only permitted for NRHA	No ELF or response spectrum studies (§C19.2)
Kinematic reduction floor	RRS_{bsa} x $RRS_e \geq 0.5$ (§8.5.1.1)	RRS_{bsa} x $RRS_e \geq 0.7$ (§19.4)	To be conservative (§C19.4)
Kinematic connectivity	Mat, grade beam, connected slab (§8.5.1.1)	Mat, grade beam, connected slab (§19.4.1)	Under study in ATC-144.
Kinematic restrictions	$b_e < 260$ ft (§8.5.1.1)	$T \geq 0.2$ and $b_e < 260$ ft (§19.4.1)	No studies of larger b_e
Embedment depth limit	20 ft (§8.5.1.2)	20 ft (§19.4.2)	No case study over 20 ft
ELF reduction floor	Not applicable	Capped at 0.9 if R>6 (§19.2)	No ELF studies (§C19.2)
Overall SSI reduction floor	0.7 x non-SSI results for procedures besides NRHA	None	No justification given
Minimum base shear	No minimum	Chapter 12 minimums	Limits SSI in tall buildings
Upper and lower bounds	Required (§8.4.2)	Required (§19.1.1, 12.3.3)	Under study in ATC-140
When SSI is required	Required if longer period increases S_a (§7.2.7)	Optional (§19.1.1)	Provisions are typically ignored in practice

The ATC-144 team is studying potential code changes to the ASCE/SEI 7-16 SSI provisions that include both technical and editorial changes. These include the following.

4.1 Technical Revisions

- **Require SSI unless it can be shown not including SSI is conservative:** There are some cases, such as short period structures with site-specific response spectra that are not capped at short periods all the way to the zero period, where the increase in period from inclusion of foundation flexibility will lead to climbing up the response spectrum and an increase in design forces. This is already required by ASCE/SEI 41-17 Section 7.2.7. A potential proposal would be change ASCE/SEI 7-16 Section 12.7.1 as follows:
    - ***Current Text:*** **Section 12.7.1 Foundation Modeling.** For the purposes of determining seismic loads, it is permitted to consider the structure to be fixed at the base. Alternatively, where foundation flexibility is considered, it shall be in accordance with Section 12.13.3 or Chapter 19.
    - ***Proposed Text:*** **Section 12.7.1 Foundation Modeling.** For the purposes of determining seismic loads and analytical results, foundation flexibility shall be considered in accordance with Section 12.13.3 or Chapter 19, unless it can be shown that this flexibility does not substantially change the analytical results.

- **Relax limitations when kinematic SSI provisions can be used:** ASCE/SEI 41-17 permits use of kinematic SSI provisions for all analysis methods; ASCE/SEI 7-16 limits their use to only NRHA. ATC-144 is investigating whether there is analytical justification for relaxing the ASCE/SEI 7-16 provisions.

- **Clarify extent of foundation interconnectivity to use kinematic SSI provisions:** ASCE/SEI 7-116 Section 19.4.1 limits the use of base slab averaging for structures with a full mat foundation, a grid of grade beams, or a slab-on-grade connected to the footings by overpours and dowels. ATC-144 case studies are investigating differences in response to foundations for those cases and those where the slab-on-grade is separated from the top of the footings by soil but is either poured tight to the columns or separated by a typical sealant gap for crack control.

- **Relax limitations on kinematic SSI provisions:** There are limits on embedment depth (6 m), effective foundation size, b_e (80 m), and average effective shear wave velocity ($200 \leq v_s$ m/s) that are now somewhat dated. There may be some justification from new data to relax these limits.

- **Remove limit without charging language:** ASCE/SEI 7-16 Equation 19.4-4 has a limitation on the average effective shear wave velocity of $200 \leq v_s \leq 500$ m/s in the base slab averaging provisions, but since this parameter is not used in the equations, it is unclear how it should be interpreted. Can base slab averaging only be used if v_s is within those limits? One proposal would be to remove this requirement, as base slab averaging is already restricted to Site Classes C, D, and E, and a v_s value less than 200 m/s should not reduce the effects of base slab averaging.

4.2 Editorial Revisions

- **Shear wave velocity definitions:** There are several similar shear wave velocity parameters in ASCE/SEI 7-16 in Chapters 19 and 20. ASCE/SEI 7-16 is not consistent with the terms. This should be clarified.
    - In Chapter 20, $\overline{v}_s$ is the "average shear wave velocity." It is taken over the top 30 m of soil. This is often designated as V_{s30} for 30 m. Both $\overline{v}_s$ and V_{s30} are the *low strain* shear wave velocity, though this is never stated in Chapter 20.

  - In Chapter 19, v_{so}, is the "average low strain shear wave velocity over a depth of B (half the smaller dimension of the base of the structure)" for damping considerations and the "average low strain shear wave velocity over the embedment" for embedment considerations. If the embedment depth were 30 m, it would be the same as $\overline{v}_s$. When the embedment depth is shallower, they are not the same. Clarification is also needed that v_{so} is determined using ASCE/SEI 7-16 Equation 20.4-1.
  - In Chapter 19, the *low strain* shear wave velocity needs to be modified by Table 19.3-1 to obtain the *average effective* shear wave velocity, v_s.

- **Clarifying when SSI can be used for linear procedures:** The current provisions have overlapping requirements in Chapters 12, 16, and 19 regarding which SSI provisions can be used with linear procedures. Explicit statements and reordering of text are being considered to assist in clarity. An example is the linear analysis that is required to accompany a NRHA covered by ASCE/SEI 7-16 Section 16.1.2. The intent is that both inertial and kinematic interaction SSI effects can be applied to the Section 16.1.2 linear analysis check, but only kinematic interaction can be used to modify the spectral shape and thus the time histories used with NRHA.

- **Reordering equations:** A minor revision under consideration is to reorder equations such that they appear in the order in which they need to be calculated.

5. Project Participants

The ATC-144 project participants include the following individuals.

- FEMA: Mike Mahoney (Project Officer), Robert Hanson (Subject Matter Expert).
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- Design Example Reviewers: Ricardo Henoch and Jiejing Zhou (Skidmore, Owings & Merrill).

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