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Publication Date
2014-07-01

Peer reviewed

Incorporating Soil-Structure Interaction into Seismic Response Analyses for Buildings

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ABSTRACT: Soil-structure interaction (SSI) analysis evaluates the collective response and dynamic interplay of three linked systems: the structure, the foundation, and the soil underlying and surrounding the foundation. Problems associated with practical application of SSI for building structures are rooted in a poor understanding of fundamental SSI principles. Implementation in practice is hindered by a literature that is difficult to understand, and codes and standards that contain limited guidance and, in some cases, are proprietary. A recent report published by the National Institute of Standards and Technology (NIST) provides a mechanism for advancing the state of practice in SSI for practicing engineers. It offers a synthesis of the body of SSI literature, distilled into a concise narrative and harmonized under a consistent set of variables and units. Techniques are described by which SSI phenomena such as foundation-soil compliance and damping (inertial interaction), and foundation-to-free-field ground motion change (kinematic interaction) can be evaluated in engineering practice. Specific recommendations for modeling these and other seismic soil-structure interaction effects on building structures are provided. The resulting recommendations are illustrated and tested though simulations of two example buildings with earthquake recordings.

Stewart, JP, Mylonakis G, Givens, MJ, Crouse CB, Hutchinson T, Lizundia B, Naeim F, Ostadan F, and Heintz JA. Incorporating soil-structure interaction into seismic response analyses for buildings. *Proceedings of the 10th National Conference on Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, AK, 2014.

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DOI: 10.4231/D3TT4FT6D

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Introduction

This paper provides a brief summary of a guidelines document recently published by the National Institute of Standards and Technology (NIST) entitled "Soil-Structure Interaction for Building Structures" [1]. The report was prepared as part of a project organized by the Applied Technology Council (ATC), one the principal objectives of which was to develop consensus guidance for implementing soil-structure interaction in design procedures involving response history analyses.

In effect, this brief paper is an executive summary of the NIST report. We do not attempt to repeat the detailed recommendations and findings of that document.

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Under What Conditions are SSI Effects Likely to be Significant?

Technical issues addressed in the NIST report include flexibility at the soil-foundation interface, foundation damping, and ground motion modifications from the free-field to the foundation level of structures. The conditions under which SSI effects are most pronounced are different when viewed from a foundation stiffness/damping (inertial interaction) as compared to a ground motion variation standpoint (kinematic interaction).

The structure-to-soil stiffness ratio, $h/(V_sT)$, can be used as a relative measure for determining when inertial SSI effects will become significant. In this expression, h is related to the structure height, V_s is the average soil shear wave velocity close to the foundation; and T is the fixed-base building period. In applying the structure-to-soil stiffness ratio, values of h, V_s, and T for a given soil-foundation-structure system should be evaluated as follows:

- **Height.** Height, h, is the effective height to the center of mass for the first mode shape, taken as approximately two-thirds of the modeled building height.
- **Shear wave velocity.** Shear wave velocity should be taken as the average effective profile velocity, $V_{s,avg}$, calculated based on overburden-corrected shear wave velocities below the foundation, $V_{s,F}$ (z). As discussed in Section 2.2.2 of [1], average effective profile velocities are computed as ratios of a depth parameter to shear wave travel time, with the depth parameter being related to the lateral dimensions of the foundation.
- **Period.** Period should be taken as the best estimate value of the fixed-based building period in the direction under consideration. The structure-to-soil stiffness ratio should be evaluated separately in each direction.

When $h/(V_sT) > 0.1$, inertial SSI can significantly lengthen the building period and modify (i.e., generally increase) damping in the system. This will modify the design base shear (up or down, depending on spectral shape) and the distribution of force and deformation demands within the structure, relative to a fixed-base analysis. The use of springs and dashpots to represent the flexibility and damping at the soil-foundation interface will be most significant for stiff structural systems such as shear walls and braced frames.

When using the structure-to-soil stiffness ratio, it is important to recognize that the ratio is an approximate relative measure, and not an absolute criterion. Even when $h/(V_sT) < 0.1$, relative distributions of moments and shear forces in a building can be modified relative to the fixed-base condition, particularly in dual systems, structures with significant higher-mode responses, and subterranean levels of structures.

Variations in foundation/free-field ground motion are not particularly sensitive to the structural stiffness but are controlled by the foundation size (footprint area and depth). SSI analyses may identify significant short-period reductions of free-field ground motions for foundations having large footprint dimensions and embedment.

SSI Applications and State of Practice

The application of SSI phenomena are discussed within the framework of analysis procedures used by structural engineers to assess seismic demand in building structures, including equivalent lateral force procedures, pushover-type procedures, and response history analysis procedures. In the case of equivalent lateral force procedures, SSI affects the base shear as a result of period lengthening and a change in damping. In pushover-type procedures, SSI affects nonlinear force-displacement (pushover) curves for the structure (through flexibility at the foundation level) and demand in the form of the displacement spectrum.

The application of SSI to response history analyses was a principal motivation for developing the technical recommendations in this project, and was emphasized in focused studies on two sample buildings. The effects of different SSI modeling approaches, ranging in complexity from ignoring SSI to full incorporation of the techniques presented in the NIST report. Two modeling procedures recommended in the recently published *Guidelines for Performance-Based Seismic Design of Tall Buildings* [2] are found to be reasonably effective at capturing above-ground response. One procedure ignores the effects of soil but extends the structural system through the subterranean levels to the foundation level of the structure, where it is fixed against rotation or displacement resulting from soil flexibility. The other procedure includes foundation/soil spring and dashpot elements but ignores ground motion variations over the height of basement walls, thus avoiding the practical difficulty of multi-support excitation in structural modeling over the height of the subgrade structure.

Relative to the superstructure, the response of subterranean levels is more sensitive to details of the foundation modeling, including ground motion variations over the height of basement walls, flexibility in structural foundation elements, and other factors. It is within the subgrade portion of the structural system that the modeling of SSI produces the largest impact on predicted engineering demand parameters such as story shears and inter-story drifts.

The recommendations for SSI modeling in the NIST report are made with some understanding of the uneven state of practice. Through extensive discussions with geotechnical and structural engineering practitioners, it was found that although SSI effects are still often ignored in practice (foundation damping effects are most often ignored), there is tangible momentum within the profession towards more frequent consideration of flexible foundation support and foundation/free-field ground motion variations. This is particularly true for analyses of existing buildings, where the impact of SSI modeling can be substantial. Unfortunately, the manner by which springs are included and ground motions are applied to structural models varies widely, with some approaches providing grossly inaccurate results. The technical recommendations in the NIST report, if widely implemented, should provide a major step forward towards improved implementation of SSI in structural design.

Role of Geotechnical-Structural Engineer Interactions

Perhaps the greatest challenge that must be overcome to tangibly affect the SSI state of practice is the often inadequate communication between Structural and Geotechnical Engineers. Structural Engineers are often not providing to Geotechnical Engineers the information needed for a proper SSI analysis. For example vibrational characteristics from a fixed-base structural analysis of the superstructure are necessary for assessing the importance of SSI phenomena.

Likewise, Geotechnical Engineers are sometimes providing results that reflect a lack of understanding of the Structural Engineer’s needs. For example, foundation springs for seismic analysis should not be based on a coefficient of subgrade reaction for long-term settlement problems. Limiting spring forces for seismic applications should not be based on settlement considerations nor should they be capacity-based limits adjusted by a factor of safety.

To help overcome these problems, standardized checklists are recommended in the NIST report that summarize concisely: (1) information for Structural Engineers to provide Geotechnical Engineers early in a design project; and (2) results that should be provided in geotechnical reports to enable proper consideration of SSI in seismic demand characterization for buildings.

Acknowledgments

The work forming the basis for this paper was conducted pursuant to a contract with the NEHRP Consultants Joint Venture (a partnership of the Applied Technology Council and Consortium of Universities for Research in Earthquake Engineering), under Contract SB134107CQ0019, Earthquake Structural and Engineering Research, issued by the National Institute of Standards and Technology.

The authors of this report are members of the Project Technical Committee, or in two cases, members of supporting committees (MG and GM). We wish to acknowledge the contributions of other Working Group members (Curt Haselton, Fortunato Enriquez, Silva Mazzoni, Erik Olstad, and Andreas Schellenberg) and Review Panel members (Craig Comartin, Youssef Hashash, Annie Kammerer, Gyimah Kasali, and Graham Powell). The success of the project depended to a great extent on their efforts.

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