Soil Dynamics and Earthquake Engineering 107 (2018) 218–233

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Linear and nonlinear soil-structure interaction analysis of buildings and safety-related nuclear structures

Chandrakanth Bolisetti[a,*], Andrew S. Whittaker[b], Justin L. Coleman[a]

[a] Idaho National Laboratory, 2525 Fremont Avenue, Idaho Falls, ID 83415, USA
[b] University at Buffalo, The State University of New York, North Campus, 230 Ketter Hall, Amherst, NY 14260, USA

ARTICLE INFO

Keywords:
Soil-structure interaction
Nonlinear soil-structure interaction analysis
Earthquake engineering
Finite-element analysis

ABSTRACT

Soil-structure interaction (SSI) analysis is generally a required step in the calculation of seismic demands in nuclear structures, and is currently performed using linear methods in the frequency domain. Such methods should result in accurate predictions of response for low-intensity shaking, but their adequacy for extreme shaking that results in highly nonlinear soil, structure or foundation response is unproven. Nonlinear (time-domain) SSI analysis can be employed for these cases, but is rarely performed due to a lack of experience on the part of analysts, engineers and regulators. A nonlinear, time-domain SSI analysis procedure using a commercial finite-element code is described in the paper. It is benchmarked against the frequency-domain code, SASSI, for linear SSI analysis and low intensity earthquake shaking. Nonlinear analysis using the time-domain finite-element code, LS-DYNA, is described and results are compared with those from equivalent-linear analysis in SASSI for high intensity shaking. The equivalent-linear and nonlinear responses are significantly different. For intense shaking, the nonlinear effects, including gapping, sliding and uplift, are greatest in the immediate vicinity of the soil-structure boundary, and these cannot be captured using equivalent-linear techniques.

1. Introduction

Soil-structure-interaction (SSI) analysis is routinely performed on safety-related nuclear structures, including nuclear power plants, in the United States, in support of both design and seismic probabilistic risk assessment. The use of such analysis for the seismic design of buildings is becoming more common but it is not used in mainstream practice because the effects of soil-structure-interaction analysis are assumed to be beneficial, measured here in terms of reduced demands on structural components and floor and wall-mounted equipment.

This paper studies equivalent-linear and nonlinear SSI analysis, with an emphasis on safety-related nuclear structures. Emphasis is placed on nuclear structures because SSI analysis is by-and-large always required by the regulatory authorities to support a design. However, many buildings have construction types and dynamic properties similar to those of nuclear structures, and so conclusions drawn regarding the latter can be directly applied to the former.

The state of practice in SSI analysis in the US nuclear industry involves the use of frequency-domain codes, such as SASSI [23], with equivalent-linear, strain-compatible properties used to represent the soil. These methods should accurately predict responses for low intensity ground shaking that produces near linear response in the soil. For intense earthquake shaking involving large soil strains and possible gapping and sliding at the foundation-soil interface, nonlinear analysis is theoretically more appropriate because the inelastic effects are captured explicitly. Nonlinear SSI analysis is only possible in the time domain and the numerical tools and codes required to perform these analyses have been developed only recently. Analysts, engineers and regulators will have to gain more experience with nonlinear SSI analysis before the method is broadly accepted for design and risk assessment. A first step is to compare predictions of equivalent linear and nonlinear codes for low intensity shaking, where results should be similar.

A few studies have compared results of frequency-domain and time-domain SSI analysis [46]. compared predictions made using SASSI and LS-DYNA [21] from SSI analyses of deeply embedded nuclear structures. They observed that results calculated using SASSI and LS-DYNA differed considerably for both linear and nonlinear analyses, with differences in results of linear analyses stemming from differences in the damping formulations. Similar studies by Anderson et al. [1] and Coronado et al. [13] showed that the linear SSI analyses of deeply embedded nuclear structures using time-domain and frequency-domain codes produced very similar structural responses. In these studies, Anderson et al. compared results from SAP2000 [12] to those from

---

* Corresponding author.

E-mail addresses: chandrakanth.bolisetti@inl.gov (C. Bolisetti), awhittak@buffalo.edu (A.S. Whittaker), justin.coleman@inl.gov (J.L. Coleman).

https://doi.org/10.1016/j.soildyn.2018.01.026
Received 27 January 2016; Received in revised form 2 October 2017; Accepted 8 January 2018

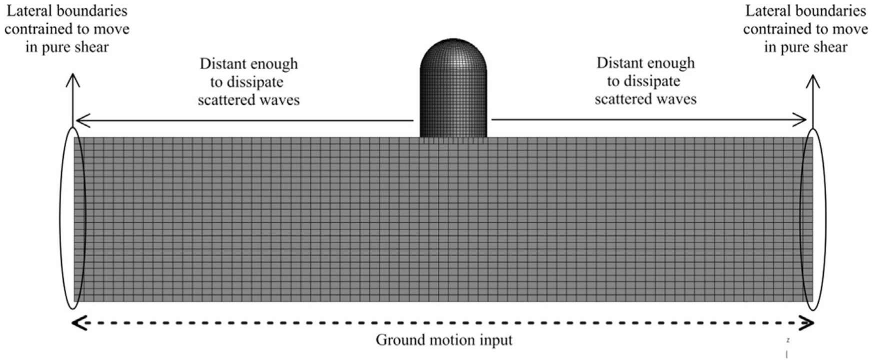

Fig. 1. Finite-element model for soil-structure interaction analysis using the direct method [8].

SASSI2010 [33], and Coronado et al. compared results from the extended subtraction method in SASSI2010 to those calculated using the commercial finite-element code ANSYS [2]. Spears and Coleman [38], in a comprehensive study, developed a methodology for performing nonlinear SSI analysis in the time domain, compared the SSI responses calculated using this methodology with those from SASSI, and identified some issues regarding the usage of these codes.

More benchmarking studies are required to support the implementation of nonlinear SSI analyses. These studies should examine cases involving material nonlinearities in the soil and the structure, and geometric nonlinearities, such as gapping and sliding of the foundation, neither of which, can be explicitly simulated in the frequency domain. This paper presents an assessment of the frequency-domain code, SASSI, and the time-domain code, LS-DYNA, for such cases. Analysis using these codes is described in Section 2. A benchmarking study comparing SASSI and LS-DYNA responses of simple, linear structures and soil profiles is presented in Section 3. The benchmarked time-domain analysis procedure is used for nonlinear SSI analyses of two surface-founded structures and the results are compared with those from SASSI. The SASSI analyses are performed using equivalent-linear soil properties and ignoring gapping and sliding at the foundation: the state-of-the-art approach of the US nuclear industry. The results of these analyses and observations regarding the differences between equivalent-linear and nonlinear responses at various ground motion intensities are presented in Section 4.

To maximize the utility of the paper, LS-DYNA keywords are identified where appropriate. This will enable the interested reader to build an understanding of the associated numerical model a) via material that is available at the LSTC website, and b) via reference to Spears and Coleman [8]. Such models are not described in detail here. Importantly, reference to LS-DYNA and its keywords is not an endorsement, and a user of another commercial finite element code (e.g., ABAQUS and ANSYS) can map the LS-DYNA keywords to models and algorithms in that code.

2. Numerical codes

2.1. SASSI

The System for Analysis of Soil-Structure Interaction (SASSI) is the most widely used code for SSI analysis in the nuclear industry. Originally developed by a team at the University of California at Berkeley, several versions of the code are now available. The version distributed by University of California, Berkeley and Ostadan [32], SASSI2000, is used for the frequency-domain analysis described in this paper.

SASSI uses a sub-structuring method to perform SSI analysis and is capable of two- and three-dimensional analysis of any foundation shape or superstructure [30,31]. The sub-structuring method is based on the principle of superposition and is therefore limited to linear analysis. A soil profile in SASSI is composed of infinitely horizontal layers. The soil and structural materials are modeled as linear viscoelastic. Each layer in the soil profile is defined by a layer thickness and a set of material properties; the structure is modeled using finite elements. The sub-structuring method allows the soil-structure model to be solved in parts: 1) calculation of free-field soil response (site-response analysis), 2) calculation of impedance functions at the foundation (impedance analysis), and 3) calculation of structural response (structural analysis). Equivalent-linear, strain compatible properties are used for the soil, which are calculated for each ground motion input using an equivalent-linear site-response code such as SHAKE2000 [35].

2.2. LS-DYNA

LS-DYNA is a commercial finite-element code capable of three-dimensional nonlinear analyses. It is equipped with a large number of material models that can be used for soil and structure and several contact models suitable for a soil-foundation interface. LS-DYNA has been used for nonlinear site-response and SSI analyses of buildings and petrochemical structures [43]. Soil-structure interaction analysis in LS-DYNA can be performed using either the direct method or the Domain Reduction Method[1] [DRM; [7]].

The direct method involves analysis of the entire soil-structure system in a single step, thus circumventing the use of superposition, which is restricted to linear analyses. This enables simulation using nonlinear material models for the soil and structure, and contact models that allow separation and sliding at the soil-foundation interface. Soil-structure interaction analysis using the direct method can also be performed using other commercial finite-element codes such as ABAQUS [14], ANSYS, or the open source codes, OpenSees [29] and MOOSE [16].

Fig. 1 describes a finite-element model for SSI analysis using the direct method. In this method, an infinite soil domain is simulated by a finite soil domain that 1) effectively damps the scattered waves radiating away from the structure, and 2) provides free-field stress equilibrium at the lateral boundaries. The former can be achieved using absorbing boundaries such as the viscous boundary model by Lysmer and Kuhlemeyer [22] and the Perfectly Matched Layer (PML) model [3], both of which, have been implemented in LS-DYNA, and infinite element implemented in ABAQUS. However, these boundary models are 1) limited to linear materials and 2) do not simulate the free-field stress condition required at the lateral boundaries. No absorbing boundary models have yet been developed for nonlinear materials to the knowledge of the authors. A reasonable approach to simulating an infinite domain at this time is to build a large soil domain with sufficient plan dimensions to dissipate the radiating waves, and constraining the lateral boundaries to move in pure shear, thus simulating a free-field condition. In this approach, the radiating waves dissipate through

---

[1] This method is referred to as the Effective Seismic Input method in the LS-DYNA keyword manual [21]. The Effective Seismic Input method, proposed by [6], is a predecessor to the DRM, but is practically equivalent [5].