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Nonlinear time-domain soil–structure interaction analysis of embedded reactor structures subjected to earthquake loads

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HIGHLIGHTS

- Derived modified version of Bielak's SSI method for nonlinear time-domain analysis.
- Utilized a Ramberg–Osgood material with parameters that can be fit to EPRI data.
- Matched vertically propagating shear wave results from CARES.
- Applied this technique to a representative SMR, compared well with SASSI.
- The technique is extensible to other material models and nonlinear effects.

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ABSTRACT

A generalized time-domain method for soil–structure interaction analysis is developed, based upon an extension of the work of the domain reduction method of Bielak et al. The methodology is combined with the use of a simple hysteretic soil model based upon the Ramberg–Osgood formulation and applied to a notional Small Modular Reactor. These benchmark results compare well (with some caveats) with those obtained by using the industry-standard frequency-domain code SASSI. The methodology provides a path forward for investigation of other sources of nonlinearity, including those associated with the use of more physically-realistic material models incorporating pore-pressure effects, gap opening/closing, the effect of nonlinear structural elements, and 3D seismic inputs.

1. Introduction

For over 30 years, modeling of nuclear power reactors for seismic safety has been conducted using a simplified soil-structure interaction (SSI) analysis approach that has proven remarkably powerful given the then available knowledge of the response of structures, soils, and their interactions under the cyclical loading of seismic shaking. This analysis approach is exemplified by the computer program SASSI, which has been subject to continuous improvement since its introduction in the early 1980s, documented in Ostadan (2007). However, many of the inherent limitations of the overall approach remain.

Technology related to earthquake rupture, seismic wave propagation, structural mechanics, and soil models have all advanced enormously since the early eighties, grounded substantially on the rapid advance in computing power. Much more robust models are now available to address each part of power reactor seismic response (source to site) and to address all of the relevant physics including nonlinear features of site and structure response. Given recent events in which nuclear power reactors have been subjected to beyond-design seismic shaking, as well as the emergence of advanced reactor designs, an important and urgent question is whether a coherent new approach incorporating advanced nonlinear models and modeling techniques using high performance computing can predict nuclear reactor response to earthquakes with higher fidelity than standard techniques in current use.

Given this motivation, this work develops a generalized time-domain method for soil-structure interaction, based upon an extension of the domain reduction method originally developed by Bielak and coworkers, with more details in Bielak et al. (2003). The methodology was combined with a simple hysteretic model based on the 1-D Ramberg–Osgood formulation and utilized to model the response of a notional Small Modular Reactor (SMR)

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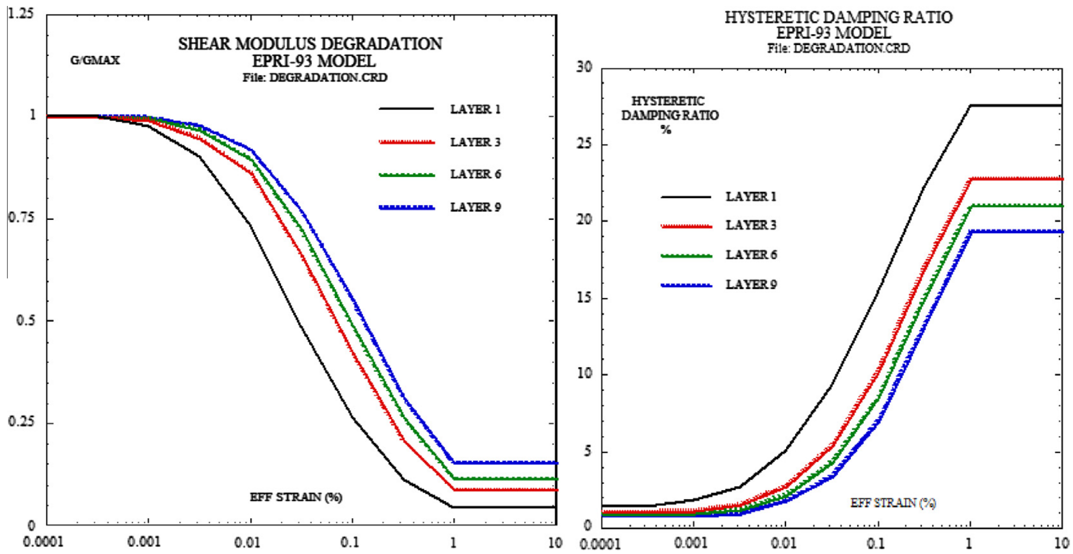

Fig. 1. Typical shear modulus degradation and damping curves.

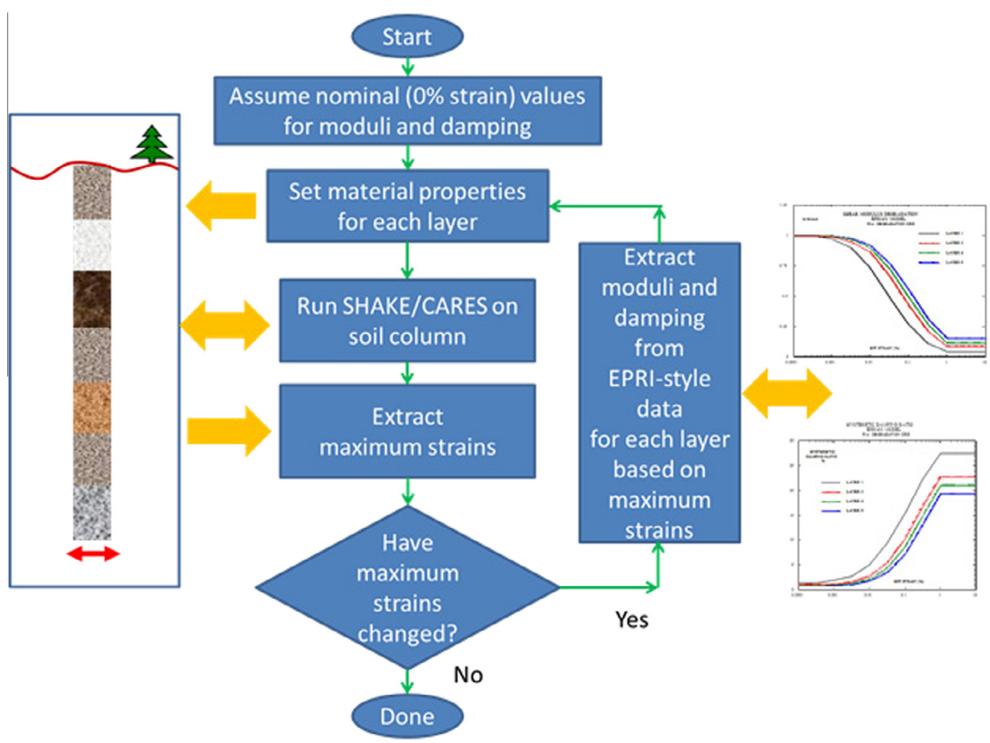

Fig. 2. Calculation of equivalent-linear properties.

and incorporated into the parallel implicit multiphysics finite element code DIABLO, documented in Solberg et al. (2014). DIABLO was then used to simulate synthesized earthquakes with nominal magnitudes from 0.2 g to 0.9 g applied to the structure. The results expressed in terms of response spectra at selected points on the structure compare favorably with those produced by SASSI. Because of the use of a general nonlinear time-domain formulation, the methodology provides a path forward for investigation of other sources of nonlinearity, including those associated with more physically-realistic material models incorporating pore-pressure effects, gap opening/closing, the effect of nonlinear structural elements, and 3D seismic inputs. This paper is a summary of work which is covered more comprehensively in a report authored by Solberg et al. (2013) which is accessible through the LLNL library with reference number LLNL-TR-635762.

2. The need for non-linear time domain analyses

The current approach as represented by the computer code SASSI solves the equations of motion in the frequency-domain. Such an approach is inherently limited to linear representation of soil properties as it relies on the principle of superposition. Soils are strongly nonlinear even at small strains, featuring both strain-dependent stiffness and strain-dependent damping characteristics, as documented for example in the EPRI report on