AN EFFICIENT APPROACH FOR TWO SCALE MODELING OF SEISMIC SOIL STRUCTURE INTERACTION

S. Madhavan$^1$ and M.N. Guddati$^2$

ABSTRACT

An efficient approach to model seismic soil structure interaction has been developed. For a horizontally stratified basin located in the far field, the approach involves (a) obtaining the free-field solution using deconvolution consistent with the local domain to get incident wave field, (b) global to local information transfer via a scattering formalism that incorporates absorbing boundaries and (c) increasing computational efficiency by utilizing Complex-length Finite Element Method (CFEM) along the depth for soil layers that do not contain the structure of interest. The key idea lies in the fact that for a multi-layered soil, the large computational cost associated with modeling multiple layers with finite elements (FE) can be significantly reduced since we do not need the solution inside the soil layers, but only need to capture the effect of these layers on the building response. The proposed approach has been implemented for the cases of anti-plane shear and plane strain. A deconvolution methodology based on Crank-Nicolson method with semi-discretization consistent with the CFEM in the vertical direction has been proposed. The correct way to prescribe the tractions at the boundaries consistent with CFEM has also been developed. In the scattering formalism, utilization of PMDL (Perfectly Matched Discrete Layers) for absorbing boundaries, further aids in reducing the computational cost due to relatively few elements required to mimic the half-space. The proposed approach requires minimal modification to existing FE code, and the computational cost reduction is expected to be significant for a large 3-D soil-structure interaction problem.

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An efficient approach for two scale modeling of seismic soil structure interaction

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An efficient approach to model seismic soil structure interaction has been developed. For a horizontally stratified basin located in the far field, the approach involves (a) obtaining the free-field solution using deconvolution consistent with the local domain to get incident wave field, (b) global to local information transfer via a scattering formalism that incorporates absorbing boundaries and (c) increasing computational efficiency by utilizing Complex-length Finite Element Method (CFEM) along the depth for soil layers that do not contain the structure of interest. The key idea lies in the fact that for a multi-layered soil, the large computational cost associated with modeling multiple layers with finite elements (FE) can be significantly reduced since we do not need the solution inside the soil layers, but only need to capture the effect of these layers on the building response. The proposed approach has been implemented for the cases of anti-plane shear and plane strain. A deconvolution methodology based on Crank-Nicolson method with semi-discretization consistent with the CFEM in the vertical direction has been proposed. The correct way to prescribe the tractions at the boundaries consistent with CFEM has also been developed. In the scattering formalism, utilization of PMDL (Perfectly Matched Discrete Layers) for absorbing boundaries, further aids in reducing the computational cost due to relatively few elements required to mimic the half-space. The proposed approach requires minimal modification to existing FE code, and the computational cost reduction is expected to be significant for a large 3-D soil-structure interaction problem.

Introduction

In seismic analysis of structures, soil layers exhibit strong influence on the structural response [1]. Soil-structure interaction (SSI) provides not only a greater understanding and accuracy of the expected performance of structure but can also help realize reductions in foundation costs. To rigorously capture the SSI effects requires a full-scale simulation of the soil domain which is vastly different in size and scale compared to the structure of interest. In the framework of finite elements this difference in scale acts as a bottleneck in terms of the computational cost associated with modeling a large basin containing multitude of soil layers. In this short note, we outline an efficient way to solve the SSI problem, in the frequency domain of a 2D/3D soil-structure system set far

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away from the source, subjected to vertically propagating shear waves. Given the frequency domain computation, we assume either linear or equivalent linear formulation, where the surrounding global domain is horizontally stratified.

**Methodology**

For seismic ground motion, far away from the source, scattering formalism based on sub-structuring approach provides the input displacements and tractions along the boundary of a reduced region of the soil-structure system (“the local domain”), see e.g. [2]. Two formulations aid in the reduction of the number ‘conventional’ finite elements required to model the SSI effects. The first is the Perfectly Matched Discrete Layers (PMDL) [3] which uses few layers of modified finite elements to capture the scattered waves in the unbounded global domain. This reduces the computational domain to encompass only the substructure and soil within in the horizontal directions and till the bedrock in the vertical direction. The second recently-developed formulation, namely Complex-length Finite Element Method (CFEM, see [4]) can be used to model the large number of soil layers from the region of interest down to the bedrock. Both these formulations are combined into the scattering formalism along with Crank-Nicolson deconvolution for consistent input, to provide a significant reduction in computational cost. In the remainder of the note, we outline the methodology and present representative results. Further details can be found in [5].

1) **Perfectly Matched Discrete Layers (PMDL)**

PMDL is an absorbing boundary condition that approximates the stiffness of the unbounded exterior surrounding the computational boundary. The exterior includes the bedrock in the vertical direction and the unbounded soil layers in the other directions. PMDL elements are mid-point integrated finite elements whose lengths are, in general, complex valued and frequency dependent. Real-length PMDL elements absorb evanescent waves while imaginary-length PMDL elements absorb propagating waves. To model an infinite system with a finite system, truncation is employed after a certain number of elements. The lengths of the elements are chosen to minimize this error due to truncation. The key advantage of PMDL over other methods is that relatively few element layers are required to accurately capture the radiation boundary condition without introducing artificial reflections.

2) **Complex-length Finite Elements (CFEM)**

Complex-length Finite Element Method (CFEM) is a method introduced recently [4] to obtain the response at select localized regions, whereby the discretization along with nature of integration is modified to have exponential convergence at preselected points. In the case of layered subdomains, usage of CFE (Complex-length Finite Elements) inside the layer results in exponential convergence at the layer boundaries. The key features of the method are:

1) The solution at layer boundaries is obtained accurately with just few Complex-length finite elements compared to large number of conventional finite elements.
2) The lengths of the CFE elements scale with the length of the layer being modeled and are independent of the domain properties or the frequency (as in contrast with PMDL).
3) The elements are mid-point integrated along the direction of complex-length mesh bending.
3) **Crank-Nicolson method of deconvolution**

The input motion into the system via the scattering formalism requires obtaining the input displacement and stress fields on the computational boundary. However, due to the introduction of Complex Finite Elements (CFE), the boundary coordinates are complex valued, requiring the stress fields at these non-physical (complex) coordinates. To address this, the Crank-Nicolson method is chosen whereby the deconvolution through depth is performed using element lengths that are *consistent* with FE and CFE regions of the interior. In other words, the lengths used in the stepping, are real valued in the region of FE and complex valued where CFE is used. The Crank-Nicolson method provides this consistency due to the unique link of mid-point integration which lends itself into a propagator form of the stiffness of the layered soil profile.

**Results and discussion**

Fig. 1 illustrates a representative SSI problem where a structure (tunnel) rests on multilayered soil. Regular FE is used around the tunnel, PMDL is utilized for the unbounded exterior and CFE for the interior soil layers.

![Figure 1. Schematic SSI problem](image)

Fig. 2 illustrates the drastic reduction in the number of elements (8 CFE in contrast with 400 FE) required to achieve a target 1% relative error.
Conclusions

As has been illustrated using a representative example, the proposed approach clearly provides a significant reduction in computational cost. For practical error tolerance requirements, there is an order of magnitude reduction in number of elements used. We emphasize that (a) the approach requires minimal modification to existing finite element code, (b) the extension to a 3D model is straightforward where the reduction in computational cost is expected to be significant and (c) while time-domain simulation requires the implementation in complex arithmetic, the proposed approach can be used immediately in current frequency domain analysis procedures for SSI with horizontally layered soil profiles (since it already contains complex arithmetic due to material and radiation damping).

References