LARGE-SCALE SIMULATION OF SOIL-STRUCTURE INTERACTION ON BUILDING RESPONSE IN A REGION

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ABSTRACT :
Recent advances in the large-scale simulation of urban regions, including source and path effects, coupled with a dense spatial resolution of simulations of building response in the region of interest, provided insight into near-fault effects on building response not available from recorded data or small-scale simulations. The regional simulations to date have not included local site response effects or soil-structure interaction. These effects are addressed in refined simulations of a portion of a sub-region that includes an idealized three-dimensional, horizontally layered soil, along with a simplified model of a building and foundation on the surface. To perform simulations of a sub-region, the Domain Reduction Method (DRM) is used to define the seismic input motion and a mixed explicit-implicit (mE-I) time integration method is used because of the different physics of wave propagation in the soil and vibration of the structure. The simulations involve considerable computational challenges. New parallel computing procedures have been developed for scalable computation. Using an approximately one and one-half million element mesh for the soil region, the preliminary simulation results provide important insights into soil-structure interaction and site response effects.

KEYWORDS:
soil structure interaction, high-performance computing

1. INTRODUCTION

Estimating the seismic performance of an entire urban region presents several challenges. One is how to provide the seismic input. In many cases the approach is to perform a deconvolution of the surface ground motion to the bedrock layer and then assume vertically propagating seismic waves, or use substructuring methods combined with multiple support excitation defined by a wave field (Wolf 1985). Second, there are multiple spatial scales that characterize the geological structure of up to 100 km in length with wavelengths spanning from the order of tens of meters for the top soft soil layers to hundreds of meters, and building structural systems that have components down to an order of 0.01 m. Third, the temporal scales range from one hundredth of a second required to resolve the high frequencies of the earthquake source to tens of seconds of intense earthquake shaking. Fourth, the soil and geological structure has many geometric and material irregularities leading to a heterogeneous model. The fifth reason is that the soil materials require complex nonlinear stress-strain relationships to be incorporated in the surface ground motion, and such models have not been done on a large scale. The sixth reason is that the modeling of the coupled soil-foundation-structure interaction (SFSI) introduces computational complexities since explicit time integration no longer suffices for the solution of the equations of motion, and implicit methods do not scale computationally as well as explicit methods. Finally, the modeling of the building structural inventory has many uncertainties that must be determined through sensitivity studies and sampling methods.

This work presents preliminary results of a new parallel computational method that addresses the problem of local site effects in a subregion, using consistent boundary conditions from a regional analysis, soil-foundation structure interaction with a nonlinear model of the structure, and a mixed implicit-explicit time integration method developed for scalability. The software for scalable soil-structure interaction simulation is based on an object-oriented finite element framework OpenSees (McKenna 1997). To investigate the site response and soil-structure interaction effects a simple structural model using a generalized nonlinear single degree-of-freedom system (SDOF) is used, which is useful for preliminary investigation of these complex factors.

2. COMPUTATIONAL METHODOLOGY

Our approach to regional earthquake simulation has been to use an innovative multi-scale method. The regional ground motion simulation is uncoupled from the subregional analysis that includes the detailed models of nonlinear soils, foundations, and building inventory. A region of interest (ROI) is defined and the boundary conditions between the regional simulation and the ROI are handled consistently. To solve the simulation problem over the range of spatial and temporal scales, we are using the DRM or Domain Reduction Method (Bielak et al. 2003). The DRM allows the simulations to be done in two steps and enables an efficient handling of the multiple length scales. The first step is the regional earthquake simulation without the models of the buildings or detailed models of nonlinear surficial soil behavior. The second step is a detailed analysis of a subregion or region of interest (ROI) using the results of the regional simulation. The boundary conditions for the ROI are represented consistently via a set of equivalent exterior forces applied at the boundaries of the ROI based on the motion computed in the regional analysis (Bielak et al. 2003). The initial-boundary value problem (IBVP) within the ROI arises from the Navier equation for elastodynamics, used to model the coupled soil-foundation-structure interaction (SFSI) problem. Upon spatial discretization of an appropriate weak form of the IBVP using the finite element method, the standard system of ordinary differential equations (ODE) related to structural dynamics is produced. Approximate boundary conditions (Lysmer 1969) at the ROI prevent energy from being reflected back into the model.

The main computational steps are (1) generation of a mesh that represents the soil in the ROI, (2) partitioning the mesh into subdomains that are mapped to processors, (3) discretization of the governing elastic equations using finite elements, (4) apply consistent boundary conditions according to the DRM, and (4) time integration of the system of ODE. For the wave propagation problem coupled with SFSI, we use an mE-I time integration scheme based on the work of (Liu 1982), extended for nonlinear systems. Explicit time integration handles the part of the domain that models the wave propagation of the seismic waves through the soil layers and implicit time integration is used for the structural elements and the foundations, which are characterized as a vibration problem. We build on our nearly linearly scaling explicit finite element code, which uses components of the OpenSees framework. The high performance of the explicit code partially relies on the fact that the problem is well balanced in terms of the partition sizes (number of DOF) on each processing element (PE) and that the computational load in terms of element state determination is also balanced between the PEs. The mE-I integration method for mixed domains is efficient because the computational load for the implicit subpartitions is small compared to that of the explicit partitions. Runtime profiling demonstrates that the computational load imbalance is manageable and does not significantly affect the overall performance and scalability of the code.

3. PROBLEM DESCRIPTION AND MODEL

The testbed example for this work is the Great Los Angeles Basin area (GLAB). The ground motion used to generate the seismic input is for a magnitude 7.1 rupture of the Puente Hills fault. At this stage linear soil behavior is assumed. Figure 1 shows the location of the ROI. The ROI has dimensions of 1 km by 0.5 km by 0.1 km. A typical soil profile of the ROI that was used for the analyses is shown in Table 3.1.

To improve the efficacy of the absorbing boundary conditions and reduce the spurious reflections a buffer zone of size 0.4 km is used along all faces of the ROI but the surface. The entire computational domain has dimensions of 1.8 km by 1.3 km by 0.5 km and is discretized with 10 m elements uniformly. The assumption is that for a wavelength of 80 m (the softest layer considered) nine nodes per wavelength or eight elements suffice for a frequency resolution to 1 Hz. The elements used for the soil are standard eight-node isoparametric bricks, computationally optimized for linear elastic constitutive model. For the absorbing boundary conditions we use dashpots, calibrated according to the V_S and V_P of the layer and the effective area of the node. The total number of soil elements is 1.17 million with 3.63 million degrees of freedom (DOF).

The ground motion input used to generate the consistent boundary conditions according to the DRM is low frequency (f<1Hz) and mass proportional damping only is used in the soil elements. The mass proportional damping is defined according to:

$$\zeta = \begin{cases} 12.5/V_S & if \;\; V_S \le 1500 m/s \\ 2.5/V_S & otherwise \end{cases} \tag{3.1}$$

Figure 2 shows the damping ratios along the depth of the soil and how they compare against those computed by:

$$\zeta = \frac{1}{2Q_S} \tag{3.2}$$

Table 3.1 Soil properties for region of interest (ROI)

Layer	Density (t/m^3)	V_P (m/s)	Q_P	V_S (m/s)	Q_S	Thickness (m)
1	1.5	202.4	8.094	82.5	4.047	5.0
2	1.5	581.8	23.27	192.7	11.63	10.0
3	1.5	668.7	26.74	241.1	13.37	40.0
4	1.714	811.2	243.36	292.2	121.68	50.0

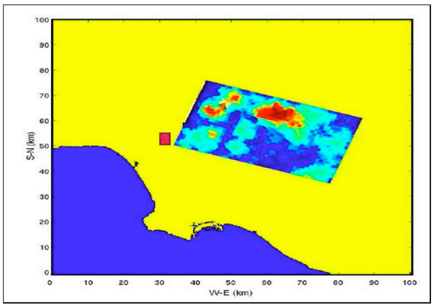

Figure 1 (a) Regional simulation domain for downtown Los Angeles (red box shows ROI)

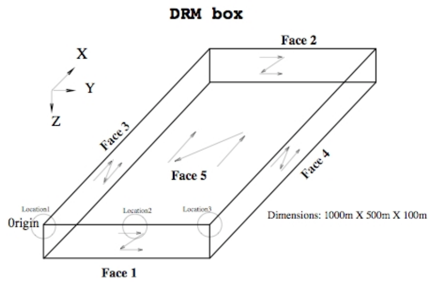

Figure 1 (b) DRM box for ROI

The first step was to simulate the free-field response within the ROI using the DRM. Figure 3 shows the free-field wave field along the two centerlines of the surface of the ROI. Significant spatial variability is observed especially along the Y direction.

With an understanding of the free-field surface response, soil-structure interaction can be investigated using a simplified nonlinear structural model for a preliminary investigation of the effects and testing of the computational procedure. For a preliminary understanding of the fundamental interaction effects, two separate single degree of freedom systems (SDOF) were considered and their properties are shown in Table 3.2. The yield displacement is u_y, the elastic displacement is u_o, the foundation width is w_f,. For each case, the SDOF system was placed at the center of the ROI. The mass of the structures is computed as a function of their height (H) according to $m = 0.08*H*w_f^2*\rho$, where ρ is the mass density equal to 2.5 (t/m^3); w_f has been kept constant in both cases and equal to 20 m. The ratio of structural to foundation mass is kept constant at 5.

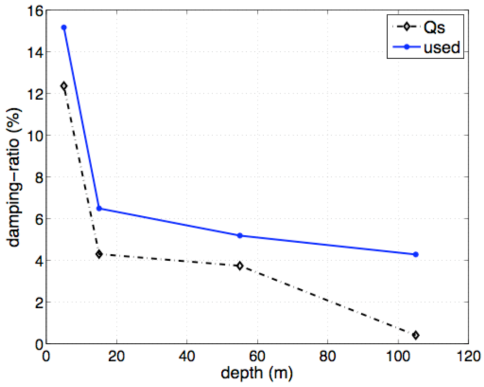

Figure 2 Damping ratios of soil layers.

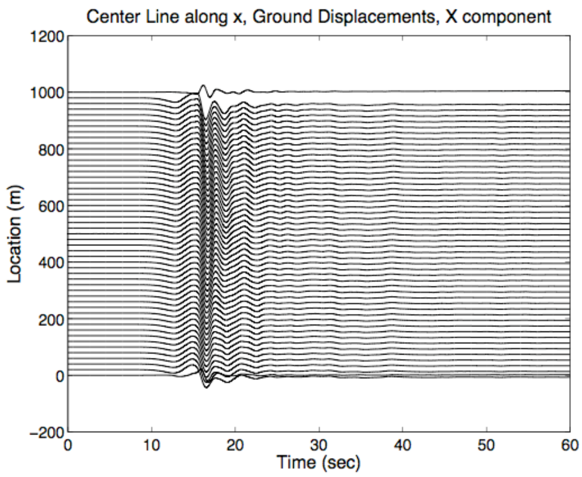

Figure 3 (a) Free field wave field along X centerline of ROI

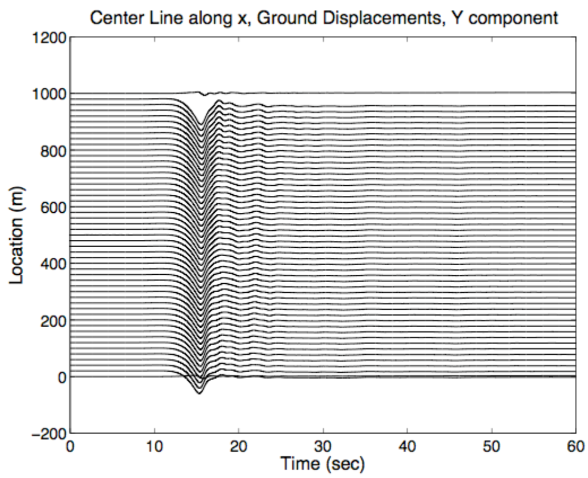

Figure 3 (b) Free field wave field along X centerline of ROI

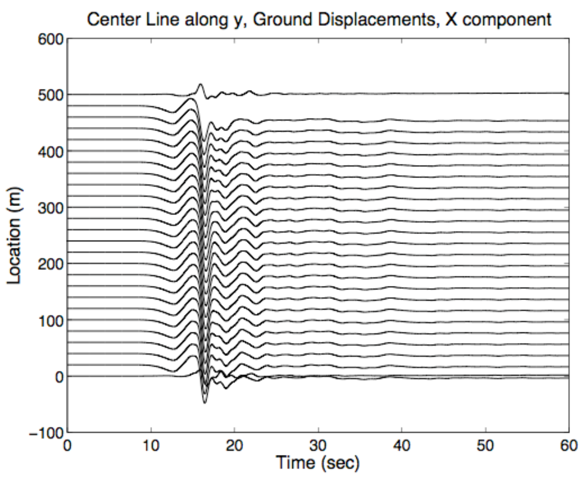

Figure 3 (c) Free field wave field along Y centerline of ROI

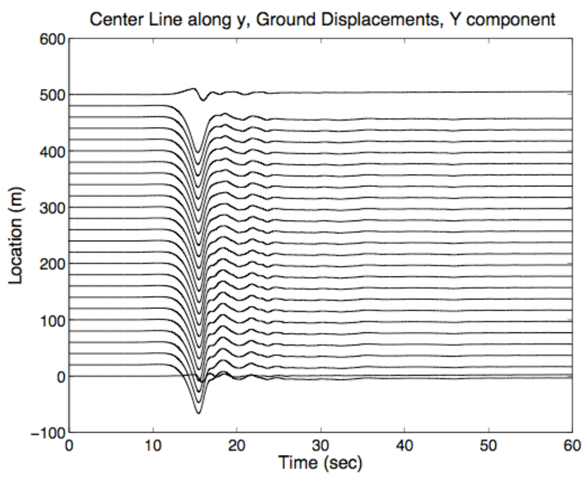

Figure 3 (d) Free field wave field along Y centerline or ROI

Table 3.2 Properties of SDOF systems

SDOF	T (sec)	ζ	u_y (m)	u_o (m)	H/w_f	μ (dir)	H (m)	R
1	1.0	0.05	0.044	0.088	2	3.9 (y)	40	2.0
2	2.0	0.05	0.195	0.414	4	1.9 (x)	80	2.4

The SDOF systems are modeled using the nonlinear beam column element (Neuenhofer 1998) with a fiber section. The constitutive model is a hardening material with α=0.001. The two SDOF systems have been designed using standard pushover and non-linear time history analyses for the free-field ground motion at the center location of the ROI. The constitutive material properties of the fiber section have been selected to achieve a good fit with the dynamic response of an elastic-perfectly plastic SDOF system subject to the free-field ground motion at the center of the ROI.

For the SFSI interaction analysis, the beam element with 6 degrees of freedom (DOF) per node must be connected with a foundation element to the soil elements with 3 DOF per node. In order to connect the beam element to the foundation, it was mounted on top of a rigid beam element, which is embedded in the common nodes of four brick elements that model the concrete foundation at the location of the excavated soil. The translational DOFs are constrained to be equal to those of the brick nodes. The rotation about the longitudinal axis of the beam element is fixed. The SDOF models are placed at the center of the ROI.

4. SIMULATION RESULTS AND INTERPRETATION

The simulations for the region of interest are carried at NCSA's Abe (NCSA), using 8-dual quad core nodes (64 PEs) for a total of 21.2 hours at 17 μsec per element per time step. The structural response including soil-structure interaction is compared with the fixed base analysis using bidirectional input. Figure 4 shows the x and y components of the displacement time history of the center node of the ROI for the free field compared with the kinematic interaction case (massless foundation). Kinematic interaction is insignificant in this case, which is expected since the input is relatively low frequency and the foundation size is small compared to the wavelengths.

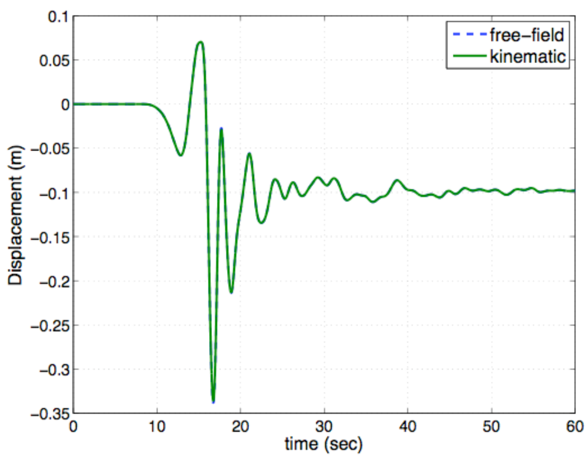

Figure 4 (a) Soil center node displacement X component

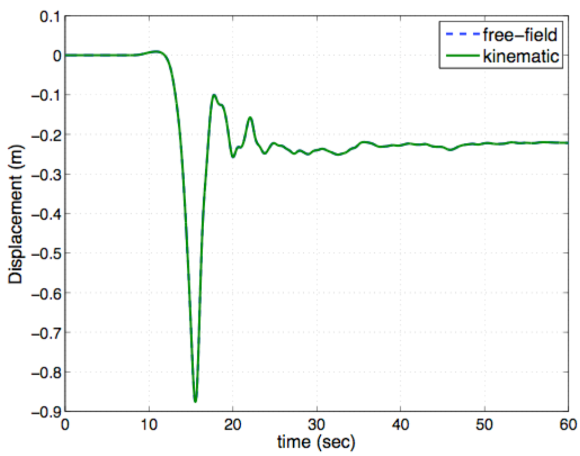

Figure 4 (b) Soil center node displacement Y component

Figures 5 and 6 plot the displacement at the soil node for the kinematic interaction case against the SFSI case for the two SDOF cases x and y directions. The effect of SFSI on the displacement field is also small. Figures 7 and 8 show the x and y components of the deformation time history of the tip of the SDOF system and compare the fixed base analysis results to those of the SFSI analysis. Soil-structure interaction effects result in increasing the residual displacements in the T=1sec case. The max ductility requirement is for the T=1sec case when compared against the max unidirectional response. Table 4.1 summarizes certain results from the analyses.

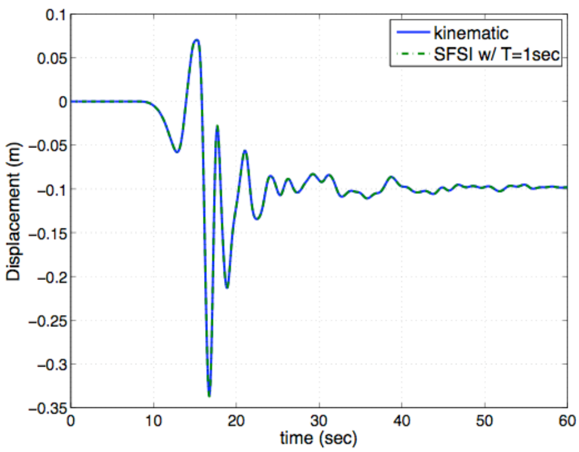

Figure 5 (a) Soil center node displacement X component

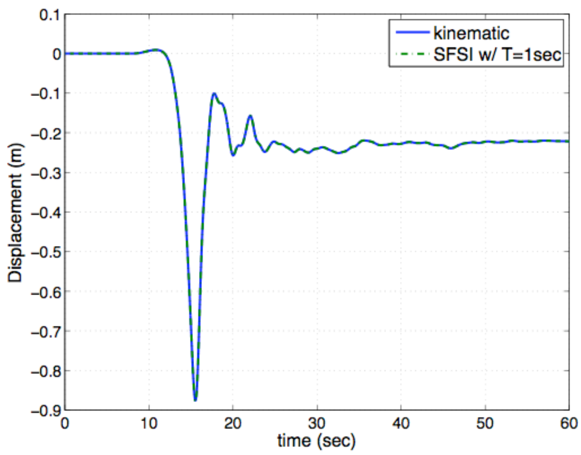

Figure 5 (b) Soil center node displacement Y component

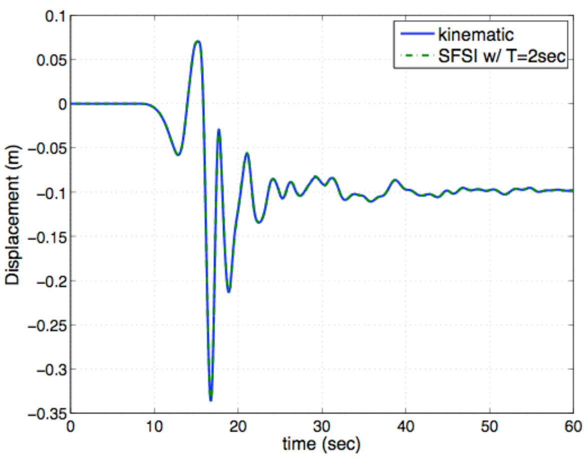

Figure 6 (a) Soil center node displacement X component

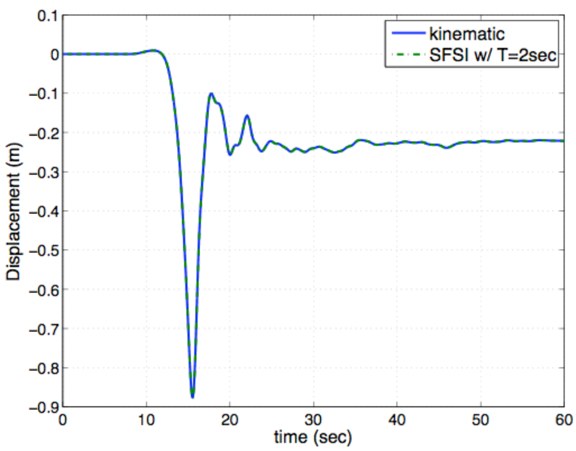

Figure 6 (b) Soil center node displacement Y component

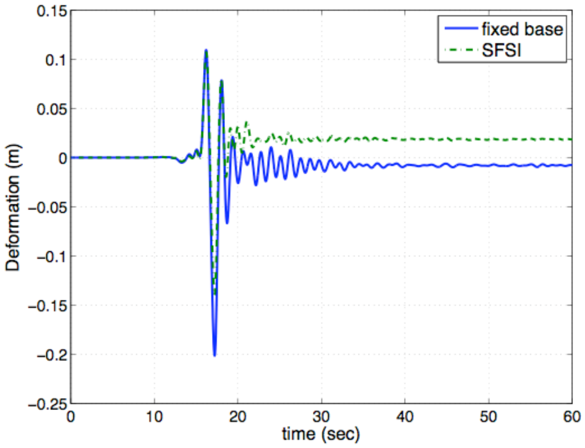

Figure 7 (a) Comparison of fixed base analysis and SFSI analysis. X component of deformation of SDOF system with T = 1 sec

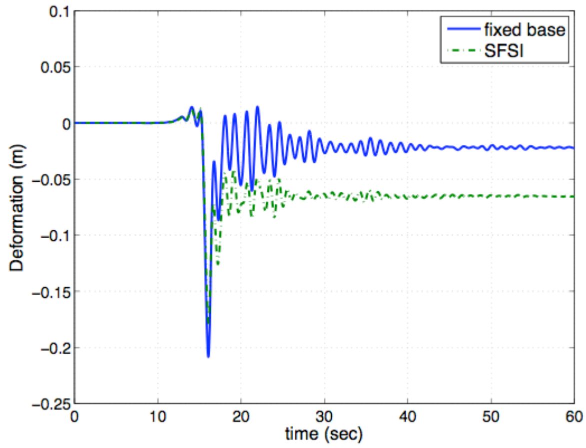

Figure 7 (b) Comparison of fixed base analysis and SFSI analysis. Y component of deformation of SDOF system with T = 1 sec

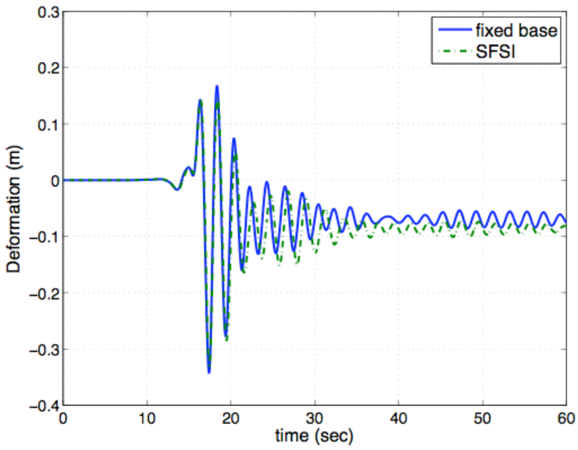

Figure 8 (a) Comparison of fixed base analysis and SFSI analysis. X component of deformation of SDOF system with T = 2 sec

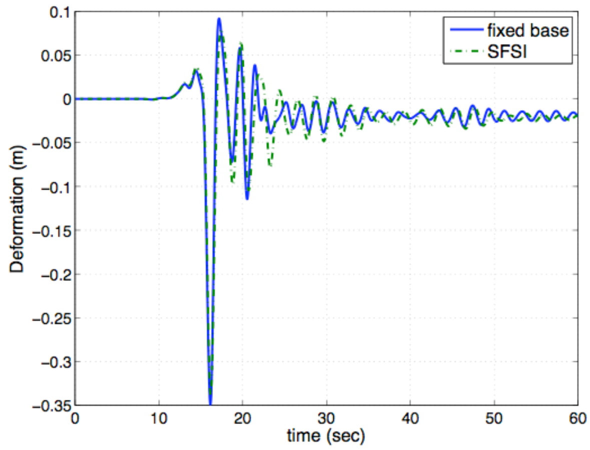

Figure 8 (b) Comparison of fixed base analysis and SFSI analysis. Y component of deformation of SDOF system with T = 2 sec

Table 4.1 Results from SFSI analysis of SDOF systems

SDOF	u_{max} (m)	μ_{max}	C_{smax}
1	0.199	4.52	0.20
2	0.359	1.84	0.20

5. CONCLUSIONS

The multi-scale simulation method using the Domain Reduction Method provides an efficient approach for the simulation of site response and soil-structure interaction effects. The preliminary simulations using a nonlinear SDOF system demonstrate the effects of kinematic and inertial interaction.

A new implementation of implicit-explicit time integration provides a scalable computational procedure for soil-structure interaction simulation using parallel computers. The computational cost is identical or almost identical to that for large-scale explicit computations, for small enough implicit subdomains. Such simulations provide important insight into the complex phenomena of interaction, but they can rarely be used as part of regular engineering design and analysis procedures. However, progress in multicore processor technology as well as the increasing availability of parallel computing services such as Amazon Web Services and IBM Grid, render such solutions increasingly attractive for performing large-scale SFSI simulations.

6. ACKNOWLEDGEMENTS

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