
# A framework for multi-scale seismic simulation of a city block considering site-city interaction

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## ABSTRACT

This study presents a novel approach for a multi-scale seismic analysis of a city block capable of capturing the site-city interaction (SCI) effect, which is usually disregarded in practice for buildings in dense urban areas. An automated multi-scale modeling framework is developed in which a region of interest of a city block is modeled with a finite element software, while a building of interest is modeled in detail using an independent analysis tool. The dynamic interaction between the two models is fully captured through a dynamic integration scheme and the generalized multi-platform simulation framework developed at the University of Toronto. The framework is applied to an idealized soil domain and three building structures to demonstrate its applicability. The dynamic response of one of the three buildings from the multi-scale seismic analysis is compared to the common two-step approach, where the base motion at the building location is evaluated first and then the dynamic analysis of a fixed-base building is conducted with the base motion. A verification example of the proposed framework is also presented that confirms the accuracy of the framework in capturing the dynamic responses of both the building and soil domain considering SSI. The analysis case with SCI shows 2% less base shear force compared to the case when the two-neighboring buildings are ignored in analysis.

Keywords: site-city interaction, soil-structure interaction, seismic wave propagation, multi-scale modeling.

## INTRODUCTION

The soil-structure interaction (SSI) phenomenon was initially introduced in the 1950s when Merritt and Housner [1] investigated the effect of a wide range of foundation yielding (compliance) on the fundamental period and maximum base shear of a typical multistory building model subjected to ground excitation. Luco and Contesse [2] investigated the structure-soil-structure interaction (SSSI), where the interaction of two shear walls with rigid foundations was investigated. Kato and Wang [3] reported noticeable SSSI effect on the dynamic responses of buildings.

The interest on multiple SSSI on urban environment arose after the 1985 Mexico City earthquake [4]. Studies on the seismic wave propagation and its influence on the urban environment adopts different terminology that reflects the scale of the problem. The term site-city interaction (SCI) was first introduced by Gueguen et al. [5]. Numerous studies, such as Schwan et al. [6] and Kham et al. [7] among many others, have addressed the influence of SCI on building clusters and surrounding site responses analytically, numerically, and also experimentally. Various conclusions were drawn on the SCI effect on the surface motion amid buildings, which could considerably affect the dynamic responses of the building. Bard et al. [8] stated that SCI has a beneficial effect by reducing the surface motion within the city, while others, Semblat et al. [9] showed development of high amplifications of surface motion at certain frequencies within the city.

The focus of majority of the previous studies on SCI was the size of the soil domain under investigation or the ground motion simulation in regional scale models. The models were usually generated by idealizing building structures with simple models, to decrease the complexity in developing detailed models of buildings for a regional-scale seismic analysis. For instance, Ares de Parga [10] used single mass oscillators to represent buildings, where the superstructure is modeled as single-degree-of-freedom (SDOF) systems with equivalent mass and stiffness. In the study, the basement or foundation is modeled as a frame or box of stiff structural elements. Taborda [11] conducted SCI analysis by modeling the building and its basement as homogenous hexahedral solid blocks. Lu et al. [12] examined the SCI effect on buildings by considering nonlinear multi-degree-of-freedom (MDOF) models for the buildings' superstructure. The buildings' superstructure and soil responses are coupled but without consideration of the buildings foundation.

Current rapid dense urbanization could significantly influence the seismic hazard of nearby existing buildings during an earthquake, particularly when SSSI or SCI is significant [12,13]. Current seismic design practice of tall or flexible buildings disregards SSI effects due to the expected beneficial effect of period lengthening or foundation damping. However, the trend of including SSI in analysis of buildings is growing to improve the simulation accuracy of building [14]. Therefore, this study introduces a novel multi-scale framework for the seismic simulation of a city block considering SCI effect. The framework provides a practical simplified modeling tool for assessment of buildings in densely urbanized areas. The proposed framework enables detailed modeling of a building or building cluster of interest in a city in a standalone numerical model which is common practice in design; whereas the framework facilitates an automated generation of the surrounding three-dimensional (3D) soil domain and adjacent buildings. The adjacent buildings in the city block are modeled with MDOF models, which are considered better approximation than the idealized SDOF models. Then, the dynamic analysis of the two models is performed through the University of Toronto Simulation (UT-SIM) framework, and the dynamic interaction between the two models are fully captured through a dynamic integration scheme developed by Huang [15].

## PROPOSED FRAMEWORK FOR MULTI-SCALE MODELING APPROACH

The proposed multi-scale SCI framework comprises of several modeling tools that are integrated to investigate the seismic performance of a target building in a city considering SCI as shown in Figure 1. A generic SCI framework utilizing collected borehole data and building information is developed to automatically generate a 3D linear elastic city model of the region of interest (ROI), including the soil lithology and material properties. The automated procedure for generating the city model through the SCI framework is described in three phases. Phase 1 represents the generation of the soil domain of the ROI. It includes the preparation of the borehole data, which consists of assigning the borehole coordinates, the various soil layers depth, and material properties of the soil layers: shear wave velocity $V_s$, mass density $\rho$, and Poisson ratio $\nu$. Then, SCI framework employs Rockworks [16] to generate the geometry of the soil layers, within the domain of ROI, through the interpolation and extrapolation process of the available borehole data. Simultaneously, Phase 2 generates the idealized MDOF models of the existing structures within the ROI, which requires limited information from the user such as: number of buildings, building locations, building types, total height, storey heights, and underground basement levels. Subsequently, SCI framework implements the generated MDOF models into the established soil domain in Phase 3, and the framework assigns the input ground motion, boundary conditions, and damping model.

The outcome of these modeling phases is named as Substructure 1. The detailed model of the target building is generated separately and named as Substructure 2. This substructure modeling method enables multi-scale modeling because Substructure 1 is prepresetned with idealized and coarse models of soil domain and many buildings in the ROI while, while the building model in Substructure 2 includes details such as shear walls, columns, beams, etc. The dynamic interaction analysis of the generated city model (Substructure 1) and the target building (Substructure 2) is performed through UT-SIM framework and is described in the next section. Finally, the results are post-processed and visualized for both the surrounding city block (Substructure 1) and the target building (Substructure 2).

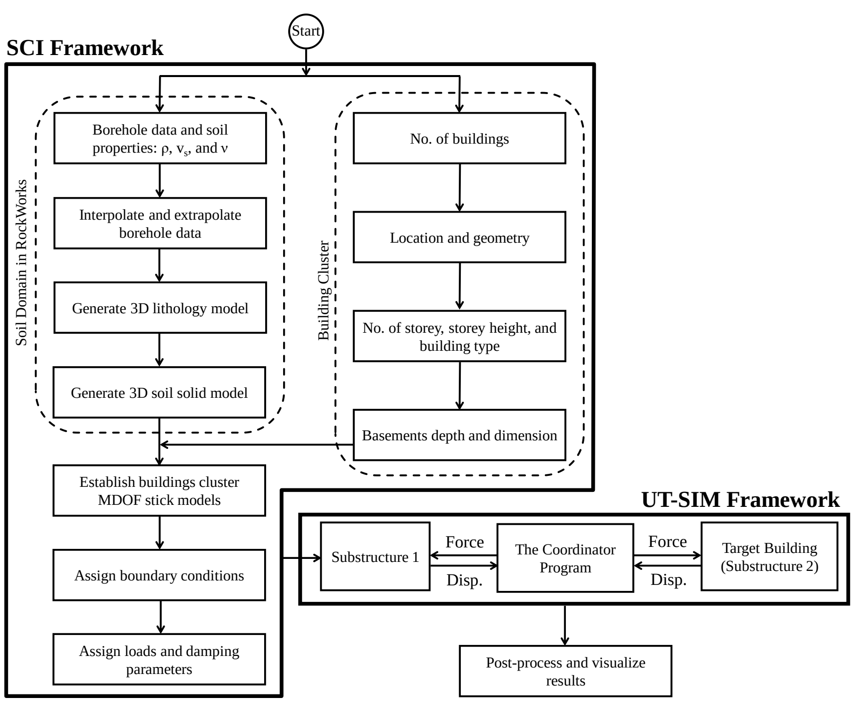



*Figure 1. Procedure of the development of the multi-scale SCI framework.*

### Dynamic Integration of Substructures

The dynamic integration of substructures is achieved through the University of Toronto Simulation (UT-SIM) framework. The framework allows a system to be decomposed into a *primary* substructure and several *secondary* substructures. The communication and data exchange between the *primary* and the *secondary* substructures are performed through the University of Toronto Network Protocol (UTNP) at the interface nodes.

In this study, a pilot small city block in downtown Toronto is decomposed into three substructures: (1) the building of interest, which is modeled as a *secondary* substructure and referred to as Substructure 2 hereafter, (2) the adjacent buildings and soil domain, which are generated through the SCI framework and are defined as another *secondary* substructure and named as Substructure 1 hereafter, (3) the interface elements between Substructure 1 and 2, which are modeled as the *primary* substructure. The *primary* substructure is modeled in the Coordinator program while the two *secondary* substructures are modeled with OpenSees [17].

After establishing the three substructure models, the dynamic analysis of the substructures is conducted in loops at each dynamic time step. At the first dynamic step, the Coordinator program predicts the forces at the interface nodes, and then sends them to the two *secondary* substructures through UTNP. Subsequently, each of the two *secondary* substructures receives the predicted forces and conducts a dynamic analysis using the Alpha-OS integration scheme [18], to extract the displacements at the interface nodes. The displacements are sent back to the Coordinator program to predict the interface forces for the next dynamic time step. These steps are repeated until the end of the dynamic analysis. For more details pertaining to the integrated simulation method, see Huang and Kwon [19] and Huang [15].

## REGION OF INTEREST

### Building Inventory and Geotechnical Boreholes

A relatively small ROI of a city block that consists of three buildings, located in downtown Toronto area, is investigated to demonstrate the potential of the framework. Two of the three buildings (denoted as B1 and B2) exist in the ROI, while the third building (denoted as B3) is proposed for future construction. This pilot study provides a practical small-scale example on the effects of neighboring buildings on a building of interest. The seismic responses of B3 will be investigated in three cases: fixed-base without SSI, with SSI but no neighboring buildings (namely, B1 and B2), and with SSI and neighboring buildings which is referred to as SCI. Table 1 summarizes the configuration and building information. B1 and B2 have no basement levels with a foundation depth of 2 m below ground surface; whereas, B3 has five basement levels with total depth of 14 m below ground surface. Information pertaining to five borehole data were available (BH1 to BH5) within the ROI. The available borehole data is considered in modeling the 3D soil domain with dimensions 140 m × 180 m × 32 m in the next section. The locations of the boreholes and buildings in the ROI are depicted in Figure 2.

*Table 1. Inventory of buildings in the region of interest.*

| Building No. | Floor Area ($m^2$) | Length (m) | Width (m) | Height (m) | Storey | Interstory Height (m) | Basement Levels | Period (sec) |
|---|---|---|---|---|---|---|---|---|
| B1 | 336 | 12 | 28 | 18.9 | 6 | 3.15 | 0 | 0.36 |
| B2 | 768 | 24 | 32 | 24.4 | 8 | 3.05 | 0 | 0.46 |
| B3 | 640 | 16 | 40 | 131.5 | 43 | varies | 5 | 3.34 |

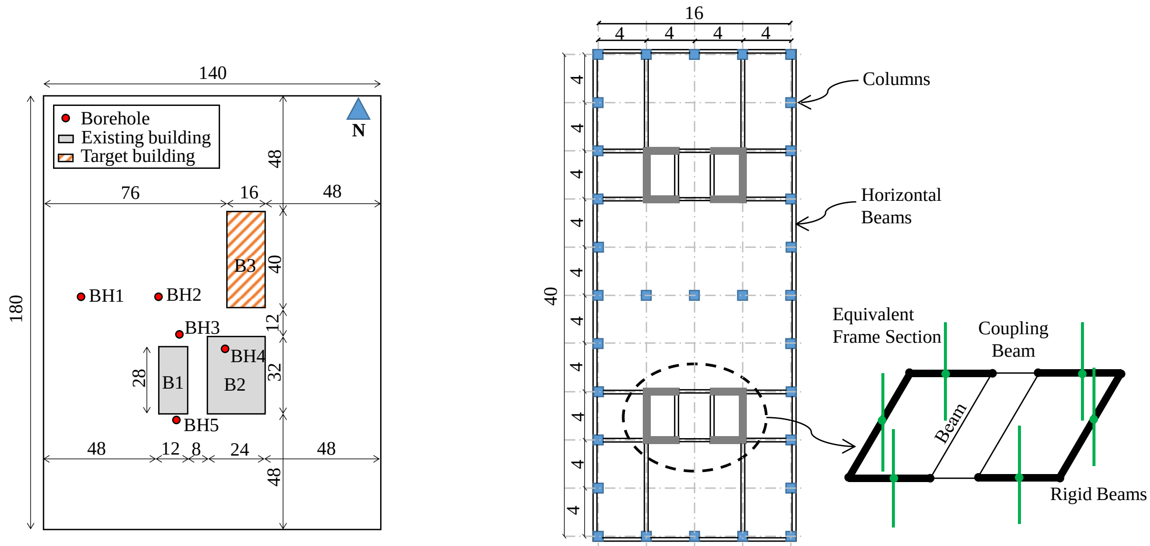
### Building of Interest (B3)

A 43-storey reinforced concrete high-rise building (Building B3) with a total height of 131.5 m is assumed to be a building of interest, which requires detailed modeling. Some information, such as overall height, number of floors, and depth of underground levels is available. However, because the detailed design of the building is not available and the actual structural dimensions are not important to demonstrate the potential of the framework, several design information pertaining to the building are assumed. The building is assumed to have reinforced concrete shear walls at the core, and perimeter columns as shown in Figure 2. The dimensions of the columns and shear walls decrease by 0.1 m every 10-storey (i.e., the square columns have a dimension of 0.8 m × 0.8 m at the base and 0.5 m × 0.5 m at the top, while the shear wall has a thickness of 0.6 m at the base and 0.3 m at the top). The width and depth of the horizontal and coupling beams are kept constant, having dimensions of 0.25 m × 0.6 m and 0.3 m × 0.5 m, respectively. The thickness of the floor slab is assumed to be 0.2 m.

A refined linear elastic model of building B3 is developed in OpenSees. The U-shape shear walls are modeled with the equivalent frame elements as shown in Figure 2. Rigid beams are included at each floor level to connect the equivalent frame elements. For verification, a sophisticated model of the building was developed in SAP2000 [20], where the coupled shear walls are modeled as shell elements, to confirm the accuracy of the equivalent frame modeling approach in capturing the dynamic characteristics of the building. The eigenvalue analysis of the fixed-base case of the building is conducted for the two modeling approaches, and the dynamic characteristics are shown in Table 2. The results of the equivalent frame modeling approach and the SAP2000 model show comparable results. In Table 2, $U_X$ and $U_Y$ describe a translational mode shape in X- and Y-direction, respectively, while $R_Z$ describes a torsional mode shape.

*Table 2. Time periods and mode shape directions of the first six modes of building B3.*

| | **Equivalent frame model** | | **Shell element model (SAP2000)** | | **Difference (%)** |
|---|---|---|---|---|---|
| | **Period (sec)** | **Direction** | **Period (sec)** | **Direction** | |
| Mode 1 | 3.344 | $U_y$ | 3.454 | $U_y$ | 3.29 |
| Mode 2 | 3.165 | $U_x$ | 3.398 | $U_x$ | 7.36 |
| Mode 3 | 2.614 | $R_z$ | 2.697 | $R_z$ | 3.18 |




(a) Region of interest

(b) Plan of the target building B3

*Figure 2. Region of interest and the target building (all units are in m).*

## SITE-CITY INTERACTION MODELING

### Free-field Soil Domain

A free-field soil domain of size 140 m × 180 m × 32 m is first generated in OpenSees. The finite elements are selected to have dimensions of width 4 m, length 4 m, and thickness 2 m. The discretization of the model yields 28,152 nodes and 25,200 elements. The elements size is selected to accommodate a maximum frequency of 5 Hz to propagate in the soil domain as [21]:

$$t_{max} = \frac{V_{s_{min}}}{n f_{max}} \quad (1)$$

where, $t_{max}$ is the maximum dimensions of the finite elements, $V_{s_{min}}$ is the minimum shear wave velocity in the soil domain taken as 170 m/s, $f_{max}$ is the maximum frequency of interest, and $n$ is the desired number of soil elements to capture the wavelength, which is commonly recommended between 5-10, and is taken as 8 in this study. The relatively small dimensions of the soil domain, width of 140 m and length of 180 m, are chosen to reduce the computational time. Energy absorbing boundaries of the soil domain are required to capture the free-field response away from the location of the buildings. The relatively small dimensions for the soil domain in this study with a reasonable offset away from the city block location (48 m from all directions) are selected while implementing adequate absorbing boundaries to dissipate the radiated waves before reaching lateral boundaries.

The adequate seismic wave propagation and SCI modeling require attention in selecting the soil domain boundary conditions. The base of the 3D soil model is fixed in the X- and Z-directions, while Ricker wavelet is imposed as a displacement history in the Y-direction at the base. The input motion has a peak displacement of 0.01 m and central frequency of 3.5 Hz that matches the fundamental frequency of the soil domain for the sake of site resonance. Absorbing boundaries with 3 series of Lysmer and Kuhlemeyer [22] dashpots, as shown in Figure 3, are assigned at the boundary of the soil model to model seismic wave propagating outward, which is effectively energy dissipation through radiation damping. Two tangential and one normal dashpots are connected at each of the outer nodes of the soil domain, while fixing the other end of the dashpots as illustrated in Figure 3. The dashpots coefficients in tangential and normal directions are defined as:

$$C_T = b\rho AV_s \tag{2}$$
$$C_N = a\rho AV_p \tag{3}$$

where, $C_T$ and $C_N$ are the tangential and normal dashpots coefficient, respectively; $A$ is the tributary surface area of the soil elements at the model boundaries used by the dashpots; $V_s$ and $V_p$ are the soil shear wave and compressional wave velocity, respectively. The parameters, $a$ and $b$, are effective parameters suggested by White et al. [23] to enhance the overall performance of the absorbing boundaries to decrease the spurious reflection of the waves at the model boundaries. Parameters $a$ and $b$ are calculated at each dashpot as [23]:

$$a = \frac{8}{15\pi}(5 + 2S - 2S^2) \tag{4}$$
$$b = \frac{8}{15\pi}(3 + 2S) \tag{5}$$
$$S = \sqrt{\frac{(1-2\upsilon)}{2(1-\upsilon)}} \tag{6}$$

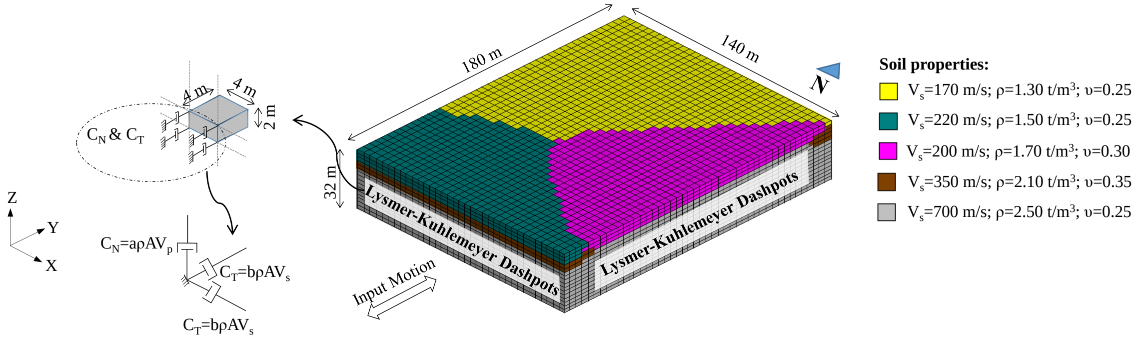



*Figure 3. Discretization of the soil domain and dashpots coefficients at the absorbing boundaries.*

where, $\upsilon$ is the Poisson ratio of the soil. Since the analysis is linear, Rayleigh damping is introduced to the linear time domain analysis to simulate the material damping of the different regions of the model. The regions of the model can be identified as: soil elements, basement elements, and structural elements of the buildings. The damping ratios for the soil, basements, and structural elements are assumed as 0.02, 0.02, and 0.05, respectively. The mass and stiffness proportional Rayleigh damping coefficients are calculated and assigned separately for the different regions of the model based on the two reference vibration modes selected for each region. The 1st and 3rd modes are assigned for soil, basement elements, and structural elements of B1 and B2, while 1st and 10th modes are defined for B3. The dynamic analysis is conducted for the free-field soil domain, and the distribution of the peak surface ground displacement in both X- and Y-directions are plotted in Figure 4. The results show high displacement amplification at the ground surface in Y-direction with a peak value of 0.06 m compared with the input displacement of 0.01 m. In the X-direction, high amplification is seen in the regions of soft soil deposits with a peak displacement value of 0.02 m, while the remaining surface of the domain shows negligible amplifications.

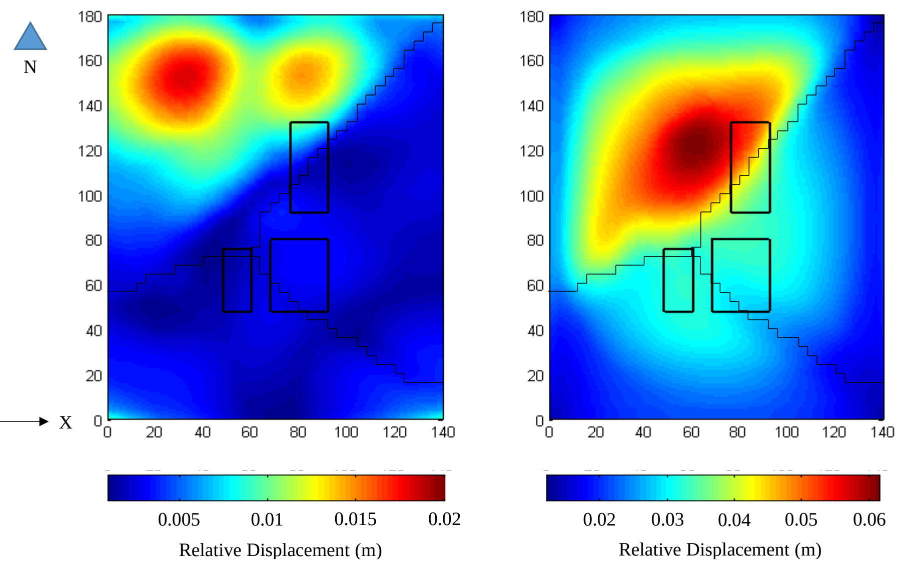
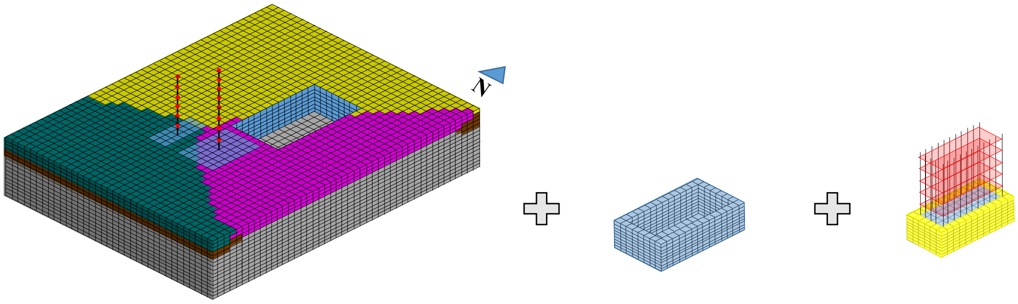



*Figure 4. Distribution of the free-field peak ground displacement, at surface, along the X-direction (left) and the Y-direction (right) (the black boxes indicate the location of the buildings).*

## DYNAMIC INTEGRATION SCHEME

As previously described in the dynamic integration scheme, the city block model is decomposed into three models to conduct the dynamic integration analysis considering the multi-scale modeling of different buildings and incorporating the SCI effect. The three models are: Substructure 1, Substructure 2, and Coordinator, as shown in Figure 5. Both Substructure 1 and Substructure 2 are modeled separately in OpenSees. Substructure 1 consists of the free-field soil model excluding a soil block with dimensions of 32 m × 56 m × 18 m. The excluded soil block represents the soil replaced by the building of interest, B3. The two other buildings, B1 and B2 are idealized with lumped mass stick models, and their foundations are modeled as 8-node brick elements with assigning parameters extracted from Kato and Wang [3].

Substructure 2 comprises the three-dimensional detailed model of building B3 and its 14 m depth basement. Similarly, the basement is modeled with 8-node brick elements. It is worth mentioning that Substructure 2 includes an offset of one layer of soil elements that surround the basement as depicted with yellow color in Figure 5. The offset soil row is added to illustrate the flexibility of the proposed framework in handling existing building models without contributing any modifications to the models. The representative block of Substructure 2 has a total width of 24 m, length of 48 m, and depth of 16 m. The Coordinator is modeled separately as an interface layer between the two substructures with 8-node soil brick elements as shown in Figure 5. The coordinator is discretized into 910 nodes and 432 elements. The Coordinator handles the interface data for Substructure 1 at 531 interface nodes and at 379 interface nodes for Substructure 2, with a total of 910 interface nodes and 2730 transferred degree-of-freedom.




Substructure 1
Soil Domain and Adjacent Buildings

Coordinator

Substructure 2
Building B3

*Figure 5. Dynamic integration models considering SCI effect.*

### Dynamic Integration Verification

A verification example of the proposed dynamic integration of substructures scheme against a standalone model is presented prior to implementing the SCI analysis of the city block. The verification example is detailed herein to demonstrate the accuracy of the proposed framework in capturing the dynamic responses of both the soil domain and buildings under investigation. The standalone analysis is performed by modeling both the soil domain and building B3 in OpenSees in one model, and the displacement Ricker wavelet is applied in the Y-direction at the base of the model. On the other hand, in the dynamic integration analysis, the soil domain and building B3 are modeled as two separate models in OpenSees. The Coordinator integrates the two models, and the dynamic analysis is performed considering that the displacement Ricker wavelet is applied in Y-direction at the base of the soil domain model. The displacement response at three various locations is investigated in Y-direction as shown in Figure 6. The three locations are: the ground surface displacement away from the building (Point A), the displacement at the base of the building (Point B), and the displacement at the top of the building (Point C). The results show similar time history responses from the standalone analysis and the proposed dynamic integration analysis at the three locations; thus, indicating the accuracy and adequacy of the proposed framework in capturing the dynamic responses of both the building and the soil domain considering SSI.

### Two-step Analysis Approach

Prior to conducting the dynamic analysis of the designated city block to examine its influence on the target building B3, a two-step seismic analysis approach is performed only for building B3. The two-step analysis approach is a common practice modeling approach when investigating the seismic analysis of a tall building fixed to the ground, while neglecting the SSI or SCI effects. The two-step analysis procedure is stated by NEHRP [14] among several modeling approaches used in seismic analysis and design of tall buildings. In the first step, a one-dimensional free-field site response analysis at the base of the target building is performed in DEEPSOIL [24] to extract the surface free-field base motion. Then, the seismic analysis of the fixed-base building is conducted with the extracted base motion.

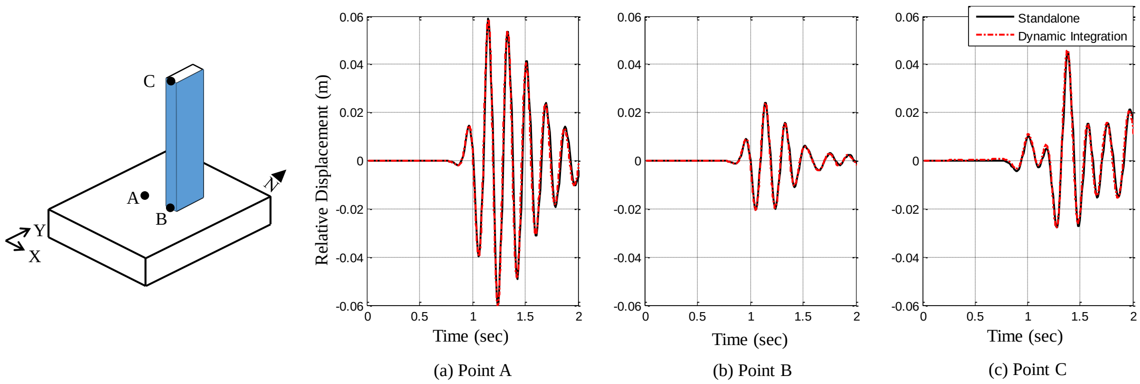



*Figure 6. Verification of the proposed dynamic integration framework against the standalone analysis at three points.*

## SSI and SCI Effects

The seismic response of building B3 is investigated for three analysis cases, i.e., No-SSI, SSI, and SCI. The No-SSI case describes the two-step analysis of the fixed-base building; the SSI case represents the aforementioned verification example of the building and the soil domain using the proposed dynamic integration scheme, while the SCI case represents the condition where all buildings are considered in analysis utilizing the proposed dynamic integration scheme. The distribution of peak lateral displacement and base shear force along the height of building B3 in Y-direction for the three analysis cases are depicted in Figure 7. SSI and SCI developed less peak lateral displacement and higher peak base shear compared to No-SSI case along the building height, which may be attributed, but not limited, to: (1) utilizing a one-dimensional free-field surface motion in No-SSI analysis while the actual depth of the building basement suggests that the basement directly rests on the bedrock; (2) the fixed-base idealization ignoring the soil-undergournd basement interaction which is considered a less appropriate modeling technique for shear wall buildings, while modeling the basement with idealized soil springs is required for more accurate comparison. On the other hand, SCI is favorable developing an average 98% of the peak base shear of SSI case along the building height. Moreover, further investigation is required, by conducting parametric studies, for selecting proper and realistic equivalent properties for basements modeling in the proposed framework considering SCI.

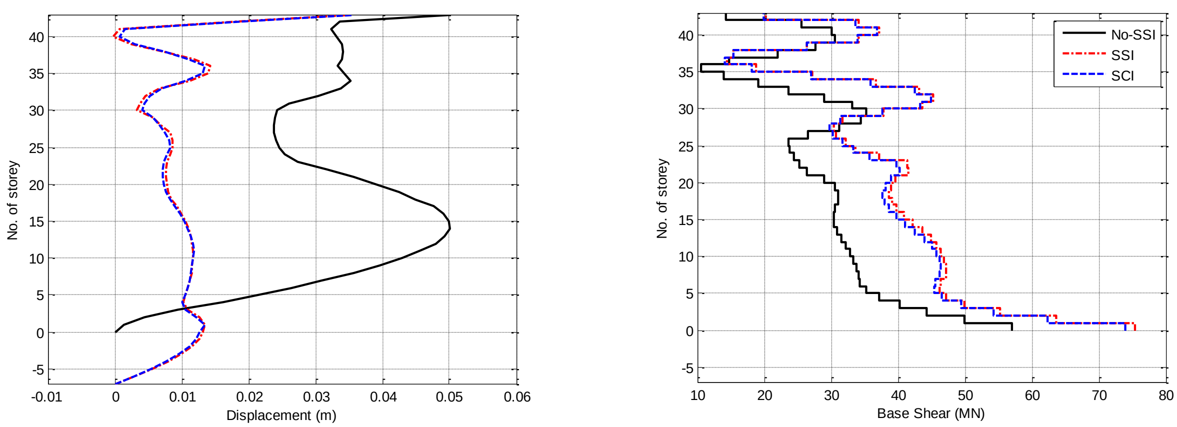



*Figure 7. Peak lateral displacement and base shear force distribution along the height of building B3.*

## CONCLUSIONS

This study presents a novel multi-scale framework that generates a macro-level city model and a detailed standalone building model in the city. These two models are integrated through a dynamic integration scheme. A pilot study of small city block was conducted to demonstrate the potential of the proposed framework in capturing the SCI effect on a target building. Potential applications of the proposed framework ranges from investigating the seismic response of a complex building or an underground structure in a small city block to the analysis of a regional scale city model considering SCI. The framework was developed to reduce the complexity associated with implementing detailed models of certain buildings in a city when the building interaction with surrounding urban area and soil domain is considered. The framework allows integration of models that are generated in various software such as Abaqus [25] and OpenSees. Therefore, it can integrate existing models of buildings that were used for design purposes or SSI analysis in a soil domain with minimal effort. The research is in-progress to extend the application of the proposed framework to allow the dynamic integration of a city block model in a supercomputer and a target building model in a personal computer.

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