# Seismic interaction of tall building and underground level

Sadiq Shamsher[1], D. Park[1], and Y.-G. Lee[3]

[1] Department of Civil and Environmental Engineering, Hanyang University, Wangsimni-ro, Sungdong-gu, Seoul, 133-791, Korea.

**ABSTRACT**

High-rise buildings are typically built in dense urban environment in cities. These tall buildings are built over underground spaces (basements) that are used for parking. The seismic response of a tall building with large underground structure can be influenced by the soil structure interaction (SSI) due to kinematic and inertial effects. Building codes recommends to only account for the kinematic interaction using substructure modeling approach and ignore the inertial interaction. This study evaluates the numerical accuracy of the substructure modeling procedures for a tall building built on shallow bedrock by comparing with the complete model. It is demonstrated that the inertial interaction further reduces the seismic response of the tall building and that considering only the kinematic interaction results in a conservative estimate of the building response.

**Keywords:** Dynamic analysis; Kinematic interaction; Inertial interaction; Substructure approaches

## 1 INTRODUCTION

Tall buildings are built over large underground spaces (basements) that are used for parking. In practice seismic analysis of such buildings is limited to analyze superstructure and underground structure separately, in this case the Soil-Structure-Interaction (SSI) interaction could not be simulated, however substructure approaches to simply this complex interaction are proposed in several studies (PEER 2010, NIST 2012, PEER 2017).

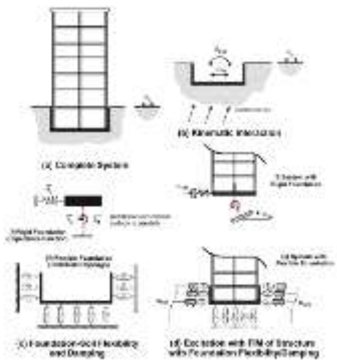

Fig. 1 Schematic illustration of substructure approach (NIST 2012)

Substructure approach as shown in Fig. 1 require 1) evaluation of free-field (FF) ground motion 2) calculation of transfer functions to convert FF motion to foundation input motion 3) calculation of spring and dashpot to represent soil stiffness and damping 4) analysis of combine spring-dashpot-structure system excited by foundation input motion. The first two steps to define the seismic demand are known as kinematic interaction Fig. 1b ignoring inertial effects. It has not been investigated that ignoring inertial interaction effect on the calculation of seismic demand for the substructure approach influence the response of tall building with underground structure.

Seismic Design Guidelines for Tall Buildings (PEER 2017) is the most recent document that recommend an alternative to procedures for the seismic design of buildings contained in ASCE 7 and IBC. In this study, we developed direct continuum 2D, RM that accounts for kinematic and inertial interaction and compared the responses with (PEER 2017) substructure modeling approaches and discusses potential implication of observed differences due to ignoring inertial interaction in design practice.

## 2 GENERAL PROCEDURES FOR TALL BUILDING UNDERGROUND SEISMIC INTERACTION

Seismic Design Guidelines for Tall Buildings (PEER 2017) provides the details to substructure modeling as shown in Fig. 2. Fig. 2.a is complete model, seismic demand is applied as rock outcrop motion. Fig. 2.b is known as fixed base model, seismic demand is applied as FF surface ground motion, $u_g$. Ignores the SSI effects biases the responses and there is no rational means to calculate the dynamic earth pressure on the basement walls. Fig. 2.c represents the rigid bathtub model which includes the spring and dashpots representing the soil stiffness and damping, the seismic demand to this model can be FF or modified foundation input motion ($U_{FIM}$) that accounts for kinematic interaction only. Fig. 2.d shows an alternative option to bathtub model in which soil-foundation interaction spring and dashpots are applied only at the foundation level. PEER (2017) refers to NIST (2012) for the most rigorous depth-invariant ground motion model, known as full substructure model (Fig. 3). PEER (2017) recommends to use ground response analysis to define the seismic demand for depth-invariant model.

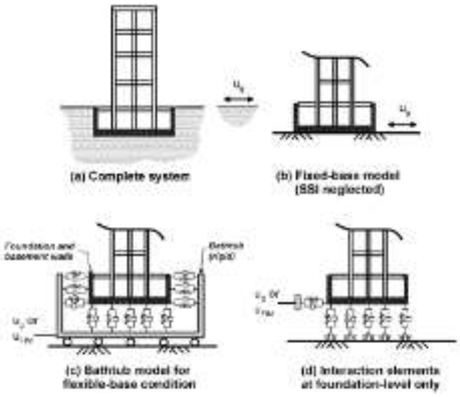


Fig. 2 Schematic illustration of alternative models of building with basements approaches (PEER 2017)

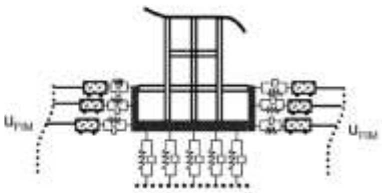

Fig. 3 Depth-invariant full substructure model (NIST 2012)

All the modeling approaches specifies the seismic demand either free-field or the modified motions that accounts for kinematic interaction ignoring the effect of inertial interaction.

## 3 APPLICATION TO REFERENCE TALL BUILDING UNDERGROUND STRUCTURE INTERACTION

We first developed two-dimensional (2D), plane strain direct continuum Fig. 2.a "reference model (RM)" that accounts for kinematic and inertial SSI. We then developed the approximate substructure models a) fixed base model Fig. 2.b, b) Bathtub model Fig. 2.c, c) Depth-invariant ground motion model Fig. 3.

Seismic demand to the fixed base is calculated using one-dimensional site response analysis (1D SRA) to calculated the free-field surface response, the bathtub is excited by both FF surface and modified foundation input motion. (PEER 2017) refers to ASCE-7-16 Chapter 19 that allows 75% of the ground motion reduction computed using (NIST 2012) kinematic interaction procedure to calculate foundation input motion. Kinematic interaction comprises of two effects, base slab averaging effect (BSA) and embedment effect (EMB). As in the reference model, we utilized continuum direct approach, and the assumed horizontal spatial coherent ground motion, therefore in this study we ignored the base slab averaging effect. Foundation input motion for the bathtub model is calculated by multiplying the FF surface motion using the ASCE 7-16 embedment ratio of response spectra (RRS) function. The time history compatible to the calculated response spectra was developed using the spectral matching code RSPM (Al Atik and Abrahamson 2010). For the depth-invariant model the vertically spatial variable ground motions that account for embedment effect were calculated by running 1D SRA at the depth corresponding to each basement level.

## 3 REFERENCE BUILDING

The reference building is an idealized reinforced concrete (RC) core wall structure having 5-level of embedded basement resting on a shallow bed rock. The length and depth of the underground structure are 94.3 m and 24 m respectively. Fig. 4 shows the 3D sectional elevation and equivalent 2D sectional elevation of (50+5B) building.

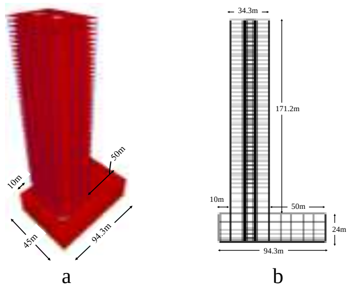


Fig. 4 Selected (50+5B) reference RCC core wall building a) 3D sectional elevation b) Equivalent 2D sectional strip

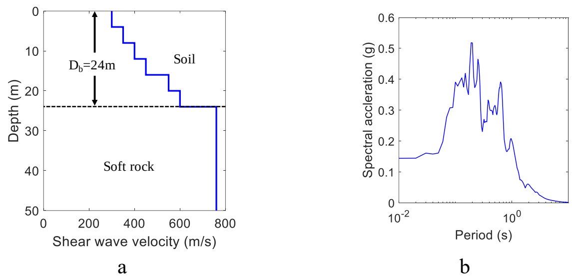


Fig. 5 a) Soil Profile and b) rock outcrop input motion acceleration response spectra for the reference model

The stiffness and inertia is distributed in core walls of 2D equivalent strip to achieve the same fundamental first mode period of 2D and 3D Eigen analysis.

Selected soil profile and rock outcrop input motion are shown in Fig. 5a & b respectively. The nonlinearity of soil in seismic excitation plays an important role in the seismic response of soil-structure interaction. The equivalent linear (EQL) properties has been derived using 1D SRA software DEEPSOIL (Hashash, Musgrove et al. 2015), effective shear strain ratio $\alpha$, which is defined as the ratio of effective strain to the maximum shear strain, 0.65 is used to determine new values for the damping and modulus by referring the backbone curves relating the damping ratio and secant modulus to the amplitude of shear strain. Calculated effective shear strain , damping ratio and modulus ratios subjected to input motion are shown in Fig. 6.

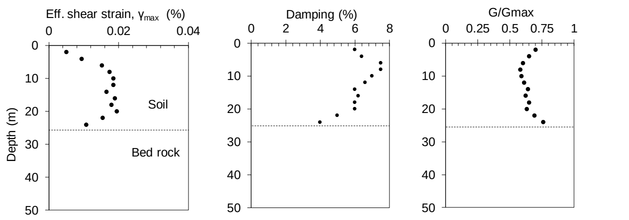


Fig. 6 Resulting effective shear strain, damping ratio and $G/G_{max}$

## 4 NUMERICAL MODELS

### 4.1 Reference model (RM)

Two dimensional (2D) plane strain finite element model shown in Fig. 7. is simulated in ABAQUS software.

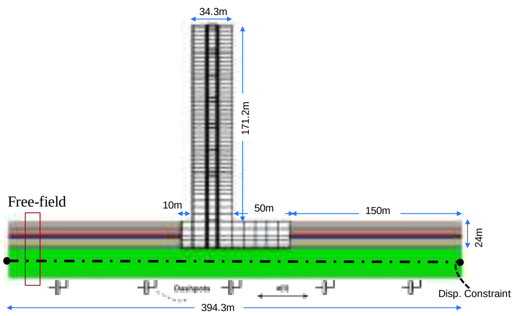


Fig. 7 Computational domain of reference building (50+5B)

Structure is simulated using linear elastic constitutive behavior whereas linear elastic with EQL properties. The lateral boundaries of the computational domain are tied together with kinematic constraint to simulate the simple shear condition using multi-point constraints (MPCs). Viscous dashpot Lysmer at the soil domain base is applied in horizontal direction to simulate an elastic half-space. Surface to node soil structure interface is applied, separation is simulated using normal behavior option of hard, whereas slip and sliding is simulated using tangential plenty with value of 0.5.

### 4.2 Development of EQL spring and dashpot coefficient for substructure models

NIST (2012) recommendations are referred to develop and distribute the EQL springs and dashpot coeffieients for the translation models of vibration. The required input for the calculations of these coefficients are fixed mode fundamental peroid of structure, embedded basement dimensions and strain compatible shear modulus. These spring and dashpot coefficients were implemented using SPRING and DASHPOT element available in ABAQUS shown in Fig. 8.

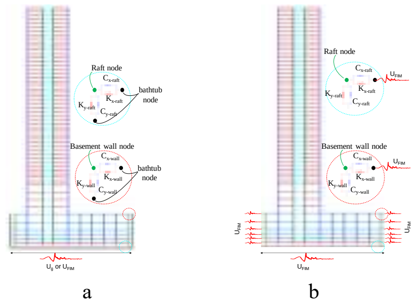


Fig. 8 a) Rigid bathtub model b) Depth-invariant multi-support excitation model

### 4.3 Seismic demand for substructure models

Fixed base model was excited by the FF surface motion Fig. 9.b calculated using 1D SRA. Bathtub model was excited by both FF surface as well as $U_{FIM}$ which was calculated by multiplying the FF surface response spectra to kinematic embedment function shown Fig. 9a. Depth in-variant model was excited by multi-support vertically incoherent ground motions at depths in FF corresponding to basement levels calculated using 1D SRA shown in Fig. 9.

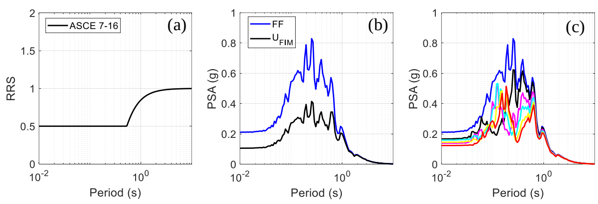


Fig. 9 a) Kinematic interaction, embedment RRS function b) seismic demand for fixed base and bathtub model c) Vertically incoherent ground motion for depth-invariant model

## 5 RESULTS AND DISCUSSIONS

The comparison of FF acceleration response spectra with RM extracted at each basement levels are shown in Fig. 10, the FF response is significantly reduced in period range 0.01-1s. Fig. 11 shows the spectral ratios, structure to FF at each basement level, maximum response is de-amplified at the first basement level, whereas magnitude of de-amplification decreases as embedment depth increases, superstructure core inertial effect is maximum at the first floor basement level and it attenuate with increase in depth.

Performance of substructure approaches are evaluated by comparing the inter-story drift ratios (IDRs) and residuals of IDRs. Dimensionless IDRs residual are calculated as

$$\text{Residual IDR} = \log\left(\frac{IDR_{RM}}{IDR_{Substructure}}\right)$$

Residual IDR>0 shows an underestimation and IDR<0 shows an overestimation of response. Fixed base, ignoring SSI effect subjected to surface FF ground motion, overestimate the response 20% and 10% for basement and superstructure respectively shown in Fig. 12. Bathtub model excited by uniform FF surface motion overestimate response 40% and 20% for the basement and superstructure respectively, inclusion of UFIM (Kinematic interaction) reduces the error, and observed differences are 20% for basement, 10% for superstructure story range (1-20), remaining superstructure response is predicted well shown in Fig. 12.

Depth-invariant model excited by multi-support exicitation accounted for kinematic interaction (embedement depth) overestimate response of basement maximum 30% at first basement level and minimum 5% at the last basement level, as shown in spectral ratio Fig. 11 maximum inertial de-amplification effect is observed at the first basement level and inertial de-amplification effect attenuates as embedment depth increases. Observed error for the superstructure is 20%.

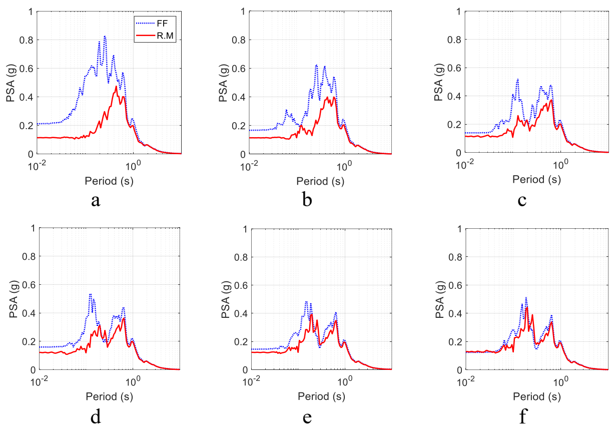


Fig. 10 Comparison of FF acceleration response spectra to RM spectra at a) first floor 0m, b) 7m, c) 13m, d) 17m, e) 21m and d) 24m raft

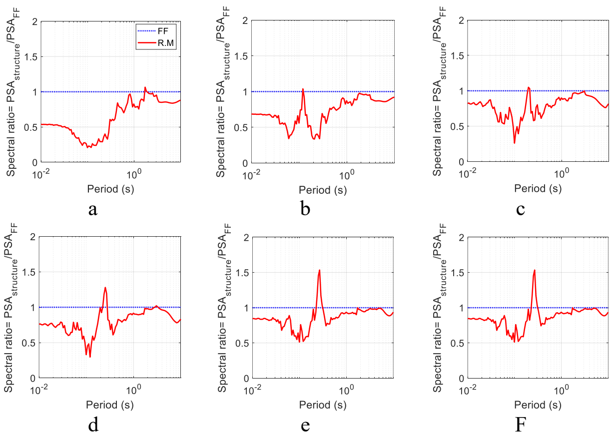


Fig. 11 Spectral ratio of basement to FF at each level of basement a) first floor 0m, b) 7m, c) 13m, d) 17m, e) 21m and d) 24m raft

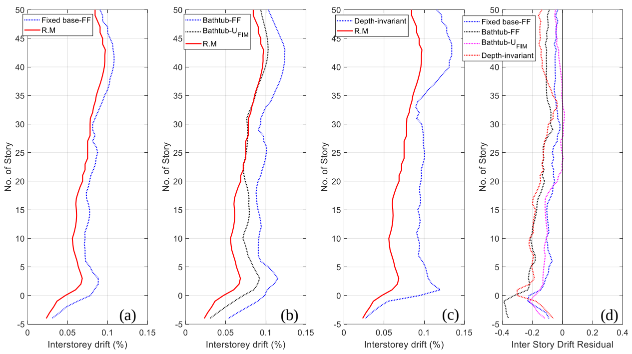


Fig. 12 Comparison of substructure and RM a-c) inter-story drift ratio d) residuals of inter-story drift ratio

## 6 CONCLUSION

We evaluated the numerical performances of substructure modeling approaches used for seismic interaction of tall building with underground soil structure interaction (SSI) resting on shallow bed rock. We first developed two-dimensional (2D), plane strain direct continuum "reference model (RM)" that accounts for kinematic and inertial SSI. We then developed the approximate substructure models recommended in building codes. This study compares the responses of RM with building code-based substructure approaches and it is inferred that ignoring inertial effect significantly overestimate the responses, therefore for design purposes inertial and kinematic coupled interaction must be accounted for, and only accounting for kinematic interaction assumption is conservative. It should be noted that the conclusion of this study is limited to one building and ground motion. Further study is warranted for verification of the conclusions of this paper.

## ACKNOWLEDGEMENTS

This work was supported by the National Research Council of Science & Technology (NST) grant by the Korean government (MSIP) (No. CRC-16-02-KICT).

## REFERENCES

Al Atik, L. and N. J. E. S. Abrahamson (2010). "An improved method for nonstationary spectral matching." 26(3): 601-617.

Hashash, Y., M. Musgrove, J. Harmon, D. Groholski, C. Phillips and D. Park (2015). "DEEPSOIL 6.1, user manual." Board of Trustees of University of Illinois at Urbana-Champaign, Urbana.

NIST (2012). "Soil-structure interaction for building structures." 12-917.

PEER (2010). Guidelines for performance-based seismic design of tall buildings, Pacific Earthquake Engineering Research Center, College of Engineering.

PEER (2017). Guidelines for performance-based seismic design of tall buildings, Pacific Earthquake Engineering Research Center.