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IMPACT OF FOUNDATION MODELING ON THE ACCURACY OF RESPONSE ANALYSIS FOR A TALL BUILDING

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ABSTRACT

Soil-structure interaction affects the response of buildings with subterranean levels by modifying input motions relative to those in the free-field and through the added system compliance associated with relative foundation/free-field translation and rocking. We examine the importance of these effects on the seismic response of a 54 story building with four subterranean levels. We first generate a "most accurate" (MA) model of the building and foundation that accounts for kinematic interaction effects on input motions, depth-variable ground motions along basement walls, compliant structural foundation elements, and soil flexibility and damping associated with translational and rocking foundation deformation modes. With reasonable tuning of superstructure damping, the MA model accurately reproduces the observed response to the 1994 Northridge earthquake. We then remove selected components of the MA model one-by-one to test their impact on building response. Factors found to generally have a modest effect on building response above ground level include compliance of structural foundation elements, kinematic interaction effects (on translation or rocking), and depth-variable ground motions applied to the ends of horizontal soil springs/dashpots. Accounting for foundation/soil deformations insignificantly affects vibration periods for this tall building, but does impact the distribution of inter-story drifts over the height of the structure. Two approximations commonly used in practice provide poor results: (1) fixing the structure at ground line with input consisting of free-field translation and (2) modeling subterranean soil layers using a series of horizontal springs which are fixed at their far ends and subjected to free-field ground accelerations.

1. Introduction

In analyzing the seismic response of a building with a basement, various approaches for modeling the base of the building can be employed. While some of these modeling approaches are simple, others require significant effort in modeling the linear or nonlinear soil-structure interaction. What is not clear is whether these more complex and time-consuming approaches produce substantially more accurate results. We examine this issue through the example of a 54 story office building in Los Angeles that was shaken by the 1994 Northridge earthquake. The building has four subterranean levels embedded in alluvial sediments.

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We begin our analysis by developing a three-dimensional model of the building and foundation system, which we call the "most accurate" (MA) model. The MA model incorporates soil-foundation-structure interaction in the vertical and horizontal directions, including rocking, with a series of no tension springs and dampers reflecting site soil properties. Seismic demands imposed on the MA model include base translation and rocking (generally from recordings) as well as kinematic loading of basement walls (simulated by displacement histories applied to the ends of horizontal springs attached to basement walls).

Using the aforementioned specification of seismic demand, the MA model is calibrated to match the response interpreted from the recorded motions. Once the MA model successfully matches the recorded data, we replace components of the specified seismic demand and soil-foundation-structure interaction model (i.e., portions of the MA model that are below ground), one or more at a time, with various simplifications common in practice and assess the errors induced by each simplification on our estimates of various metrics of seismic response.

Many previous studies have been similar to the "MA" component of this work, in that they have developed mathematical models that replicate the recorded response of buildings (e.g., Chajes et al., 1996; Ventura et al., 2003; Kunnath et al., 2004; Liu et al., 2005). The novel aspect of the present work follows the MA model development. Those subsequent models simplify the MA model (without further calibration) so that the degree of error associated with each simplification can be evaluated. The objective is to find the simplest models which produce results of sufficient accuracy for engineering applications.

Following this introduction, we describe in Section 2 the attributes of the Los Angeles 54 story building. In Sections 3 and 4 we review a robust SFSI modeling procedure for buildings with subterranean levels and various simplifications to that procedure, respectively. Finally, Sections 5 and 6 present the results of the study and conclusions, respectively.

2. Details of the Los Angeles 54 story Building

2.1 Structural and Foundation Systems

The building is 52 stories tall above ground level with a penthouse and a four-level basement. The building is roughly rectangular in plan with base dimensions of approximately 212 ft. by 136 ft, tapering inward at the 36th and 46th floors to 196 by 121 ft and 176 by 121 ft, respectively. The vertical load carrying system consists of composite concrete slabs (2.5 inches thick) over a 3 in. steel metal deck with welded metal studs, supported by steel frames. The spans between gravity columns vary from about 10 feet to 47 feet. The lateral load resisting system consists of moment resisting perimeter steel frame (framed tube) with 10 ft. column spacing. There are Virendeel trusses and 48 inch deep transfer girders at the setbacks at the 36th and 46th floors.

The foundation system consists of a reinforced concrete mat that is 9.5 ft thick in load bearing areas and 7 ft thick in intermediate areas. Concrete basement walls surround the subterranean levels.

2.2 Geotechnical Conditions

Geotechnical conditions at the site were characterized by LCA (1981) and are summarized by Stewart and Stewart (1997). The site exploration by LCA generally encountered 65 ft of sands with variable layers of silts and clays overlying siltstone and shale bedrock, which extended to the maximum depth explored of 130 ft. The shear wave velocities shown in Fig. 1 are based on in situ downhole measurements by LCA (1981).

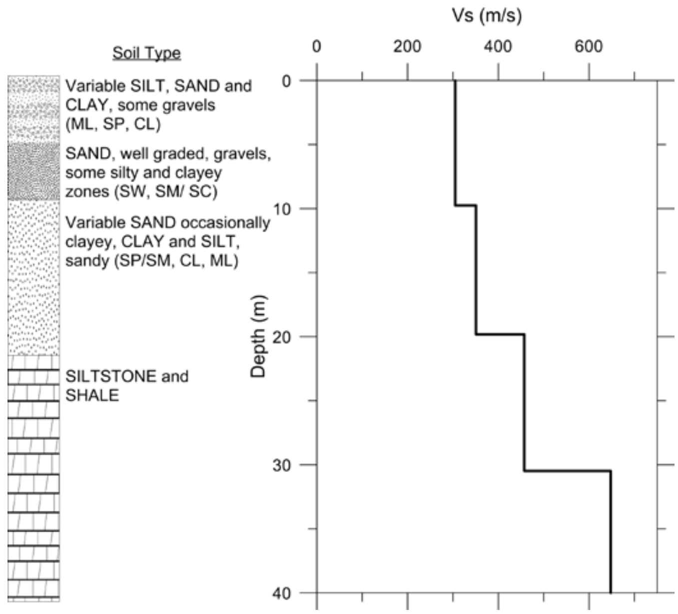

Figure 1. Geotechnical and shear wave velocity at the Los Angeles 54 Story Building

2.3 Recorded motion

The building is instrumented with 20 accelerometers. There are two sensors on the top of the mat foundation to measure vertical acceleration. Several earthquakes were recorded at this site. In this article we focus on the Northridge earthquake which produced horizontal ground motions at the foundation level of about 0.14 g.

3.0 Soil-Foundation-Structure Interaction (SFSI) Modeling for LA 54 Story Building

The general procedure for SFSI modeling of embedded structures is given in Stewart and Tileylioglu (2007). In this section, we describe the application of that procedure to the subject building.

A free-field instrument at the LA 54 story building is not present, hence free-field motion (u_g) is unknown. What is known is the horizontal translation at the base of the building and the rotation in the short (transverse) direction of the structure (because of the two vertical instruments on the base slab).

The recorded horizontal translation provides a good estimate of the “foundation input motion” (u_{FIM}), which is the theoretical base slab motion for a massless structure and foundation.

In reality, the recording is also affected by inertial soil structure interaction effects, which cause the foundation base translation to differ from u_{FIM}. However, those effects are small for buildings such as the LA 54 story building with weak inertial soil-structure interaction effects. Even when they are strong, such effects are narrow-banded at the first mode system frequency (Kim and Stewart, 2003). Hence, we take u_{FIM} as the base mat horizontal recording. Conversely, the base rotation is likely to be dominated by inertial interaction effects, so we do not rely on recordings to estimate this quantity. Instead, it is estimated based on predictions of validated theoretical models (Stewart and Tileylioglu, 2007). Those models allow the estimation of transfer functions that relate free-field motion u_g to the translational and rotational FIMs:

$$\left|H_u\right| = \frac{u_{FIM}}{u_g}, \quad \left|H_\theta\right| = \frac{\theta_{FIM}}{u_g} \tag{1}$$

where $\left|H_u\right|$ and $\left|H_\theta\right|$ are translational and rotational transfer functions (respectively) that can be evaluated as a function of frequency knowing the soil shear wave velocity and foundation dimension (expressions in Stewart and Tileylioglu, 2007). Fig. 2 presents these functions for the LA 54 building site using the aforementioned expressions. Given $\left|H_u\right|$ and $\left|H_\theta\right|$, base rotation can be estimated from u_{FIM} through manipulation of Eq. 1 to yield:

$$\theta_{FIM} = u_{FIM} \frac{\left|H_\theta\right|}{\left|H_u\right|} \tag{2}$$

To summarize, the translational motion applied at the end of the foundation spring attached to the base slab is u_{FIM} (taken from recordings). The vertical motions applied at the end of vertical springs are defined from the product of θ_{FIM} and the horizontal distance to the foundation centroid.

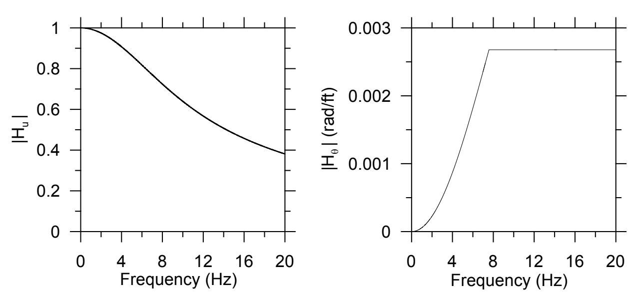

Figure 2. Theoretical transfer functions between foundation input motions and free-field motion

The remaining issue for ground motion specification is the distribution of translations over the embedment depth due to site response. This is evaluated by performing equivalent-linear ground response analysis with the input consisting of u_{FIM} at the average foundation depth of 46 ft as an outcropping motion. Those analyses were performed with SHAKE04 (Youngs, 2004), which is a modified version of SHAKE91 (Idriss and Sun, 1992). We used the velocity profile shown in Fig. 1 and nonlinear modulus reduction and damping curves as specified in EPRI (1993), Vucetic and Dobry (1991) and Seed and Idriss (1970). The variation of ground motion over the embedment depth was found to be minor in displacements but significant in accelerations (up to 35% difference was observed).

The foundation springs and dashpots are evaluated by first calculating translational (K_x, K_y) and rotational (K_{xx}, K_{yy}) stiffnesses for rectangular rigid foundations (Mylonakis et al., 2002). Dashpot coefficients (C_x, C_y, C_{xx}, C_{yy}) can be similarly evaluated using equations from Mylonakis et al. (2002). For translation, the portion of the stiffness that can be attributed to the base slab is calculated using surface foundation equations in conjunction with the seismic velocities of materials below the mat. That stiffness is applied as a spring at the elevation of the foundation mat. The total translational stiffness of the foundation is higher due to embedment, and the difference is applied as horizontal springs distributed along the basement walls. For rotation, vertical springs are distributed along the base of the foundation such that higher stiffnesses are assigned at the boundaries, but the overall rotational stiffness associated with the vertical springs matches that from the impedance function. This is accomplished by ensuring that the following equalities hold:

$$K_{xx} = \sum_i k_{z,i} \cdot y_i^2 \text{ , } K_{yy} = \sum_i k_{z,i} \cdot x_i^2 \qquad (3)$$

where K_{xx} and K_{yy} = overall rotational stiffness of foundation, $k_{z,i}$ = stiffness of vertical spring at location indexed by i, x_i=closest horizontal distance from spring i to the y-centroidal axis of foundation, and y_i=closest horizontal distance from spring i to the x-centroidal axis of foundation. Distances x and y are measured from the centroid of the foundation.

Both the horizontal and vertical springs are specified as “compression-only,” meaning that no tension is allowed to develop. This allows a gap to form, although the implementation does not track gap width.

4.0 Simplifications to SFSI Modeling

Naeim et al. (2008) consider a number of simplifications to the MA model. Here, for brevity we focus on only two, both of which are commonly used by structural engineers in practice. Following the nomenclature of Naeim et al. (2008), they are referred to as Models 3b and 3d.

In model 3b, the soil flexibility is entirely neglected at the level of the base slab (i.e., the base slab is fixed vertically and horizontally), but soil flexibility is simulated along the basement walls using horizontal springs with ends fixed to match the free-field ground motion. Seismic demand consists only of horizontal motions (equivalent free-field condition) at the base slab level and at the ends of foundation springs. This simulates a condition commonly used in structural engineering practice.

In model 3d, the below ground portion of the building is ignored and the superstructure is assumed to be fixed at the ground level. Seismic demand consists only of horizontal motions (equivalent free-field condition) applied at ground level.

5.0 Results

5.1 Results for the MA Model

The best match of motions computed using the MA model to recordings was obtained with all modal damping values set to 1.0% of critical except for modes 1 and 4 where the damping values were set to 1.8%. The same damping values were used for all approximations. A summary of 50 Ritz vectors provided a level of accuracy that did not improve by inclusion of more vectors (up to 300 Ritz vectors were utilized to see if there is any significant difference in the results). For the first two modes, computed periods for the MA model in the E-W, N-S and torsional directions were close to those identified from recorded data using the CSMIP-3DV software (Naeim et al. 2005; 2006).

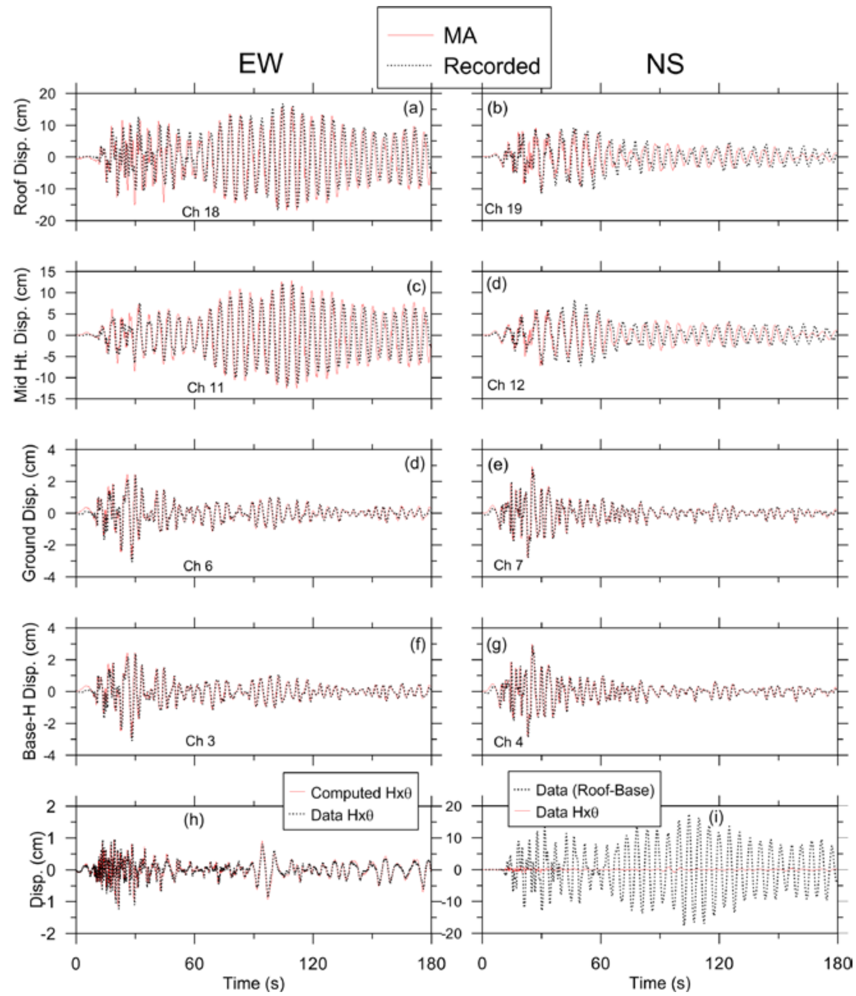

Figure 3. Comparison of recorded displacements with those computed for the MA model

Displacement histories obtained from the calibrated MA model are compared to recordings in Fig. 3. The match in both horizontal directions at the ground level is excellent (Figs. 3f-g). Elsewhere over the height of the building, the quality of the match is generally better in the E-W direction than N-S. However, the matching of both maximum amplitudes and phasing are very good in both directions. At the foundation level, Fig. 3(h) shows that the base rocking produced by the model matches very well with observation, suggesting that the rotational foundation impedance is well represented by the MA model. However, this base rocking is a small contributor to the roof translation, as shown in Fig. 3(i).

5.2 Results for Selected Approximations

Our analyses of Models 3d and 3b are presented relative to the MA results instead of the recordings. This allows for direct comparison of the impact of changes in model attributes.

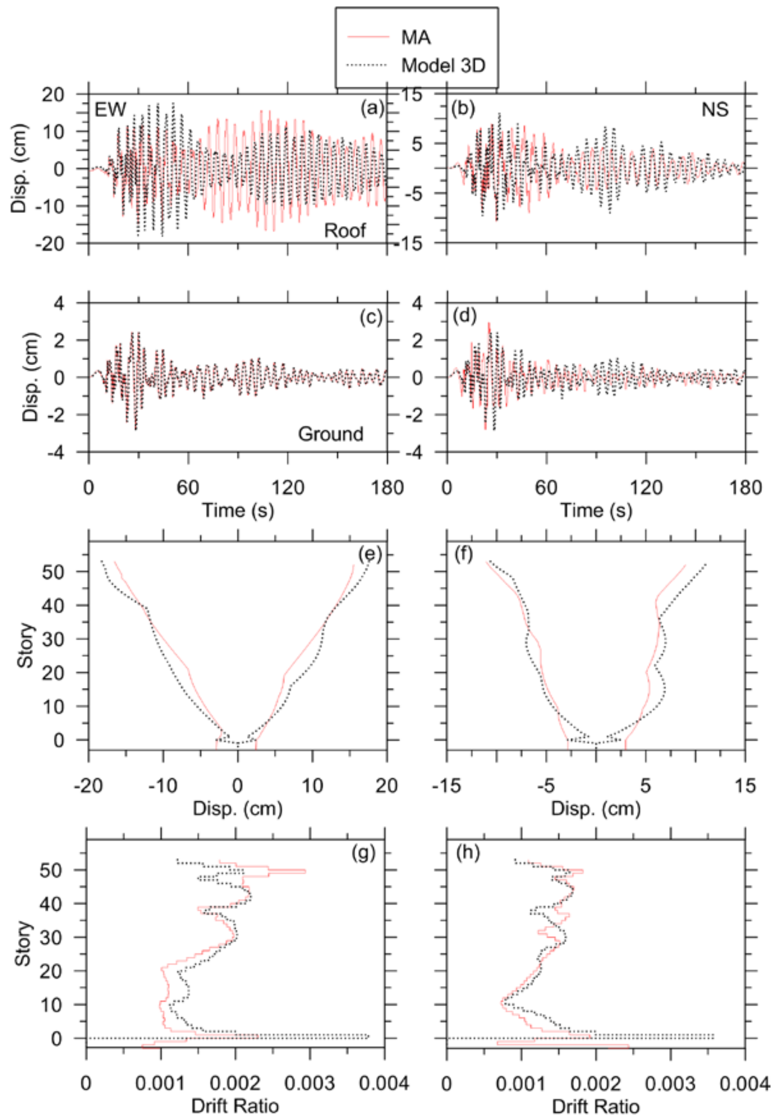

Figure 4. Comparison of displacement histories, maximum displacement and drift ratios obtained from the MA and 3d models

Ignoring the subterranean levels by assuming a rigid base at ground level (Model 3d) significantly alters the vibration periods of the building. As a result, it was found that many of the displacement history responses are out of phase with those of obtained for the MA model (Fig. 4

a, b and d). The roof peak displacement in the E-W direction for the MA and 3d models have similar amplitudes but they occur at very different times. The error in peak roof displacement is less than 20%. Interestingly, the distributions of inter-story drift over the height of the structure are significantly affected, with drifts increasing at lower levels and decreasing at higher levels of the building for Model 3d relative to MA (Fig. 4 g and h).

Fixing the far ends of horizontal soil springs, and subjecting these fixed ends to free-field ground accelerations (Model 3b) is one of the two common methods used by engineering offices to bound the SFSI problem. This approximation also significantly affects the dynamic characteristics of the model by shortening its period because the fixed-end springs provide more resistance to the below-ground structure. Fig. 5a and Fig 5b show that the displacement histories at roof level are very different from those obtained from MA model. Note that the peak roof displacement in the N-S direction happens to be close to that twice that of the MA model. This is reflected in the maximum displacement and drift charts presented in Fig. 6 where the results in the E-W direction look deceptively close to that of MA model while the results in the N-S direction vary sharply from those obtained from the MA model. As shown in Fig. 5c-d, the ground level displacements reported by this approximation are negligible compared to those reported by the MA model. Note that in this model the ground accelerations are used as input and the structural engineering program used to perform the analysis (ETABS) does not calculate the displacements at the fixed ends of the horizontal springs. Therefore, the displacements reported at the ground line consist only of the in-plane displacements of the ground floor diaphragm which are very small.

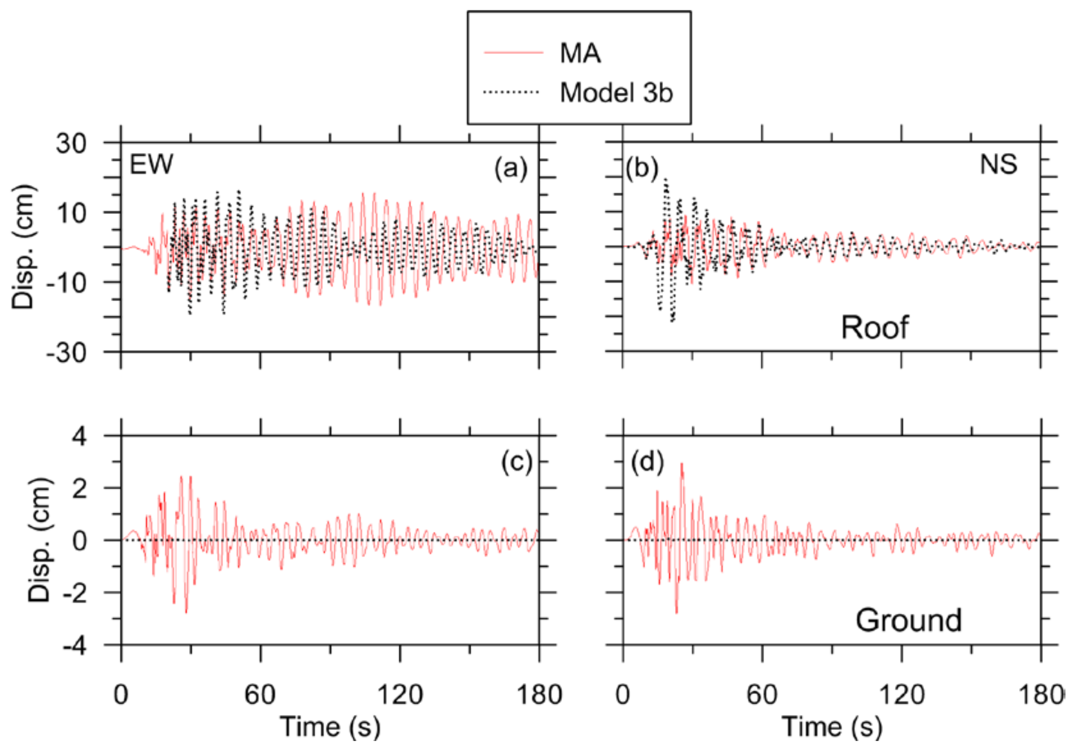

Figure 5. Comparison of displacement histories obtained from the MA and 3b models

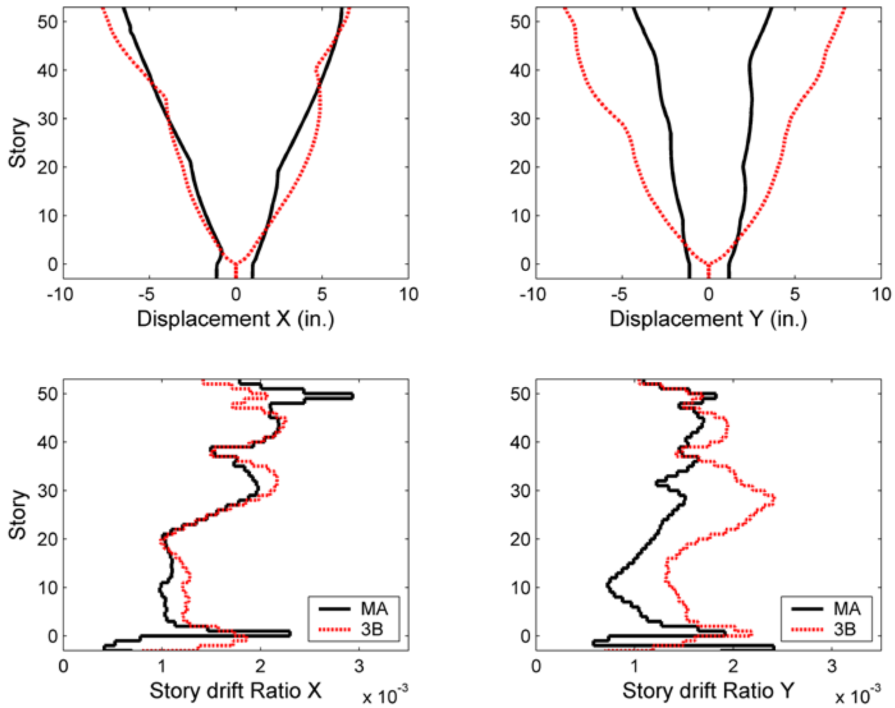

Figure 6. Comparison of maximum displacements and drift ratios obtained from the MA and 3b models

6.0 Summary and Conclusions

Soil-structure interaction can affect the response of buildings with subterranean levels by modifying the characteristics of input motions relative to those in the free-field and through the added system compliance associated with relative foundation/free-field translation and rocking. While procedures are available to account for these effects, they are seldom utilized in engineering practice. Our objective is to examine the importance of these effects on the seismic response of a 54 story building with four subterranean levels. We first generate a "most accurate" (MA) model that accounts for kinematic interaction effects on input motions, depth-variable ground motions along basement walls, compliant structural foundation elements, and soil flexibility and damping associated with translational and rocking foundation deformation modes.

With reasonable tuning of superstructure damping, the MA model accurately reproduces the observed response to the 1994 Northridge earthquake. Two approximations commonly used in practice are shown to introduce errors in story drifts: (1) fixing the structure at ground line with input consisting of free-field translation and (2) fixing the structure at the base level, applying free-field motions as input at the base level, and using horizontal foundation springs along basement walls with their end condition fixed to the free-field ground motion.

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