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THE NEAR-FIELD METHOD: A MODIFIED EQUIVALENT LINEAR METHOD FOR DYNAMIC SOIL-STRUCTURE INTERACTION ANALYSIS

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Abstract

In this research the problem of soil-structure interaction analysis with the direct method is studied. The direct method consists of modeling the superstructure and the underlying soil domain. Using a reduced shear modulus and an increased damping ratio resulted from an equivalent linear free-field analysis is a traditional approach for simulating behavior of the soil medium. However, this method is not accurate enough in the vicinity of foundation, or the near-field domain, where the soil experiences large strains and the behavior is highly nonlinear. This research proposes new modulus degradation and damping augmentation curves for using in the near-field zone in order to obtain more accurate results with the equivalent linear method. The mentioned values are presented as functions of dimensionless parameters controlling nonlinear behavior in the near-field zone. This paper summarizes the semi-analytical methodology and the numerical implementation and examples of the proposed modified equivalent linear procedure.

Keywords: soil-structure interaction; equivalent linear; near-field; shear modulus; damping.

1. Introduction

Investigations after some historical earthquakes have shown that the geotechnical factors can strongly affect the response of the structures and damage rate during strong ground shakings. The field of geotechnical earthquake engineering is the product of these investigations after damaging earthquakes Niigata, Japan and Alaska in 1964[1]. Considering the effect of underlying soil on the response of superstructure is the main purpose of geotechnical earthquake engineering.

The available methods to model the foundation and underlying soil can be classified in two main categories: substructure and direct methods. In the substructure method, the soil domain is completely replaced by appropriate elements in order to considering the effects of stiffness and damping of soil on the superstructure. Unlike the substructure method, the direct method includes modeling the soil domain and superstructure simultaneously and is an application of the finite element method [2]. The direct method has some serious limitations. Modeling the unbounded soil domain and its nonlinear behavior and an enormous computational effort are the most important challenges facing the direct finite element method. To overcome the unboundedness of the problem, the soil domain is usually limited to vertical artificial boundaries on the sides and rigid bedrock at the bottom of the model. Using infinite elements on the boundaries is another approach. In addition, nonlinear behavior of the soil domain can be simulated by different elastic or elastic-plastic constitutive models. Although elastic-plastic constitutive models are more accurate, but they usually have many parameters unknown for engineers and increase the computational cost. Although the soil and structure nonlinearity, contact between soil and foundation, uplift, liquefaction etc. can be considered in the direct method, the more accurate model means the more analysis cost that will be complicated and cumbersome even with modern computational tools. Therefore, efforts have been made to simplify the direct method and make it more practical.

Researchers have shown that just a limited bounded medium in the vicinity of structure undergoes large strains and considerable plastic deformations; therefore it is not reasonable to use complicated constitutive models in order to simulate the behavior of the whole soil domain [3]. Accordingly, one can divide the soil domain into two parts: a part near the foundation experiencing large strains and nonlinear behavior (the near-field zone) and a remaining part with linear behavior (the far-field zone). Different methods such as coupled BEM-FEM method [4-7] and Scaled Boundary Finite Element Method (SBFEM) [8] are available to analyze the near-field and far-field zones.

Using the Equivalent Linear Method (ELM) is an effective approach to simplify the direct method and enhance its efficiency and applicability. In this approach, the soil behavior is linear but the shear modulus and damping of each soil layer are determined in accordance with the average strain level. While the conventional ELM highly simplifies the SSI analysis, it is not accurate enough in the vicinity of foundation (the near-field zone), where the strain level is too high. On the other hand, the traditional ELM uses modified properties calculated through a free-field analysis and therefore, the effects of the large strains arising from inertial SSI are excluded. However, this fact is often ignored and the ELM is used for the total soil medium and it is the serious limitation of the ELM. Ghandil and Behnamfar [9] resolved this limitation and proposed the near-field method as a modified equivalent linear method with a further reduction of the soil shear modulus in the near-field of foundation resulting in validity of using the equivalent linear method throughout. They considered several 3D buildings resting on different soil types. A series of dynamic time-history analysis was implemented and semi-analytical relations for calculating the shear modulus modification factors as functions of the fixed-base period of structures were proposed. Results showed that the near-field method, being more accurate than traditional ELM, can considerably reduce the computational cost of the direct method.

The present study generalizes this new approach such that it can be applicable for a wide range of structures. To attain this goal, a set of dimensionless parameters representing relative properties of building structures and soil is selected and a comprehensive parametric study is carried out to capture the variation of near-field properties with respect to these parameters. Then, semi-analytical relations are proposed as functions of the dimensionless parameters to calculate the near-field properties. Finally, the validity of the near-field method is evaluated and the performance of the near-field method is compared with other modeling approaches.

2. Parametric Study

Soil-structure interaction and the effect of various parameters on this phenomenon has been the subject of many researches. Some researchers like Veletsos and Meek [10] and Aviles and Perez-Rocha [11] studied the influence of various parameters and concluded that the inertial SSI effects are more sensitive to the stiffness ratio ($\bar{s}$) and the slenderness ratio ($\bar{h}$) and sensitivity to the mass ratio ($\bar{m}$) is modest [6]. Accordingly $\bar{s}$, $\bar{h}$ and $\bar{m}$ are considered as key dimensionless parameters in this research and the effects of these parameters on the properties of the near-field region are studied. These parameters are defined in Table 1.

Table 1 – Definition of the considered dimensionless parameters

Parameter	Description
$\bar{s}=\omega_S h/V_S$ (or $h/V_S T$)	$\omega_S h$ and V_S quantify the stiffness of the structure and soil, respectively, and then this parameter represents the structure to soil stiffness ratio.
$\bar{h}=h/a$	The slenderness ratio (structure's height to foundation width ratio) describing the geometry of the soil-structure system.
$\bar{m}=m/\rho_S a^2 h$	$\rho_S a^2 h$ is the mass of soil in a volume extending to a depth equal to the structure height, h, below the foundation. This parameter represents the structure to soil mass ratio.

There is a specific range of dimensionless parameters for a building in its different configurations and natural modes on various soils. In addition, these parameters are related to each other in a building structure and arbitrary combinations of these parameters are not acceptable for this kind of structures. Therefore, the mathematical relations between dimensionless parameters and building structure properties were determined at the first stage and then 48 structure and soil models were chosen to conduct a comprehensive parametric study to determine the near-field zone dimensions and dynamic properties. Table 2 represents these models and their corresponding dimensionless parameters. The last mode in this table represents the last important mode that has a significant effect on the dynamic response of structure.

Table 2 – Selected models and the corresponding dimensionless parameters.

Model No.	Structure height	Mode	Structure weight	Horizontal dimension	Soil condition	V_s	ρ_s	$\bar{h}$	$\bar{s}$	$\bar{m}$
1	short	first	light	wide	soft	100	1700	0.267	0.880	0.378
2					stiff	500	2000	0.267	0.176	0.321
3				slender	soft	100	1700	1.067	0.880	0.378
4					stiff	500	2000	1.067	0.176	0.321
5			heavy	wide	soft	100	1700	0.267	0.880	0.756
6					stiff	500	2000	0.267	0.176	0.643
7				slender	soft	100	1700	1.067	0.880	0.756
8					stiff	500	2000	1.067	0.176	0.643
9		last	light	wide	soft	100	1700	0.033	0.550	0.336
10					stiff	500	2000	0.033	0.110	0.286
11				slender	soft	100	1700	0.133	0.550	0.336
12					stiff	500	2000	0.133	0.110	0.286
13			heavy	wide	soft	100	1700	0.033	0.550	0.672
14					stiff	500	2000	0.033	0.110	0.571
15				slender	soft	100	1700	0.133	0.550	0.672
16					stiff	500	2000	0.133	0.110	0.571
17	medium	first	light	wide	medium	200	1800	1.750	0.513	0.317
18					stiff	500	2000	1.750	0.205	0.286
19				slender	medium	200	1800	3.500	0.513	0.317
20					stiff	500	2000	3.500	0.205	0.286
21			heavy	wide	medium	200	1800	1.750	0.513	0.635
22					stiff	500	2000	1.750	0.205	0.571
23				slender	medium	200	1800	3.500	0.513	0.635
24					stiff	500	2000	3.500	0.205	0.571
25		last	light	wide	medium	200	1800	0.250	0.550	0.317
26					stiff	500	2000	0.250	0.220	0.286
27				slender	medium	200	1800	0.500	0.550	0.317
28					stiff	500	2000	0.5	0.220	0.286
29			heavy	wide	medium	200	1800	0.25	0.550	0.635
30					stiff	500	2000	0.25	0.220	0.571
31				slender	medium	200	1800	0.5	0.550	0.635
32					stiff	500	2000	0.5	0.220	0.571
33	tall	first	light	wide	medium	300	1900	2.625	0.342	0.301
34					stiff	500	2000	2.625	0.205	0.286
35				slender	medium	300	1900	5.250	0.342	0.301
36					stiff	500	2000	5.250	0.205	0.286
37			heavy	wide	medium	300	1900	2.625	0.342	0.602
38					stiff	500	2000	2.625	0.205	0.571
39				slender	medium	300	1900	5.250	0.342	0.602
40					stiff	500	2000	5.250	0.205	0.571
41		last	light	wide	medium	300	1900	0.375	0.367	0.301
42					stiff	500	2000	0.375	0.220	0.286
43				slender	medium	300	1900	0.750	0.367	0.301
44					stiff	500	2000	0.750	0.220	0.286

45			heavy	wide	medium	300	1900	0.375	0.367	0.602
46					stiff	500	2000	0.375	0.220	0.571
47				slender	medium	300	1900	0.750	0.367	0.602
48					stiff	500	2000	0.750	0.220	0.571

The following three sets of analyses are conducted in turn, in order to develop the mathematical relations for the near-field's mechanical and geometrical properties:

a) Analyzing the rigorous models (Plastic Models):

In the rigorous models, the soil behavior is simulated by an elastic-plastic constitutive model that is accurate enough in general loading conditions. Each one of these models is analyzed under 10 different ground motions that are selected appropriately and are imposed to the base of the models. Dimensions of a region just below the foundation, or the near-field zone, where the soil has experienced on average larger strains at a larger rate compared with the far-field zone are determined. In other words, the rate of change in shear strains of the near-field zone is considerably greater than the far-field. It is the main criterion for determining the near-field dimensions. Fig.1 shows a schematic illustration of the mentioned region. In Fig.1, *2a* is the foundation width and L_{nf} and H_{nf} represent the near-field dimensions. Average of results obtained from 10 different ground motions is considered as the response of that model.

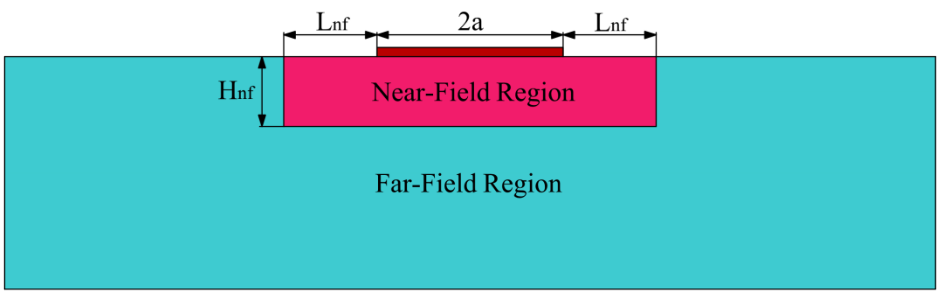


Fig. 1 – Schematic illustration of the near and far-field regions.

b) Analyzing models with the near-field approach

In this case, the soil is assumed to have an equivalent linear behavior. Properties of the soil is first obtained by free-field analysis of the site and kept unchanged for the soil in the far-field region in the rest of analysis. Then, characteristics (shear modulus and damping) of the near-field soil are modified through a trial and error process in order to achieve the same maximum structural responses obtained in the rigorous analyses.

c) Regression analysis to develop mathematical relations

After obtaining the near-field properties for all of the models, regression analyses will be performed to develop mathematical relations for the near-field properties based on the dimensionless parameters of the SSI system, as introduced in Section 2.

3. Modeling Details

The open source software framework OpenSees (*Open System for Earthquake Engineering Simulation*) [12, 13] has been used to create and analyze the three dimensional FE models of this. The structure is idealized as an SDF stick model with modal properties of the building structure resting on a shallow square rigid foundation and both the structure and its foundation are supposed to have a linear elastic behavior during analysis. The PDMY elastic-plastic constitutive model developed by Yang et al.[14] is used to simulate soil behavior in the rigorous models. The soil domain is semi-infinite in dimension and just a bounded cut of it can be modeled in the FE analysis. The boundary condition developed by Lysmer and Kulhmeyer [15] is used as the absorbing boundary to simulate the radiation damping. An example of the 3D FE mesh of the soil-foundation-structure (SFS) system of this study is illustrated in Fig.2.

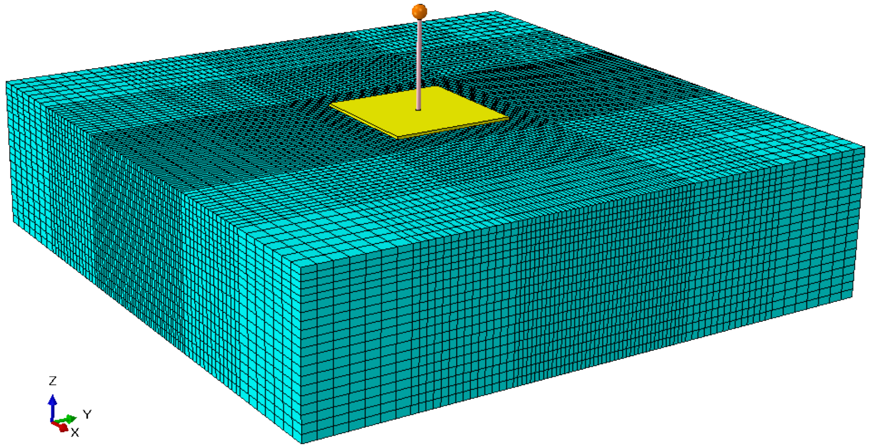


Fig. 2 – 3D FE model of the SFS system.

As shown in Table 2, four different soil types are considered for this research. A set of 10 ground motions are selected from the PEER Strong Motion Database [16] and the European Strong Motion Database [17] for each site. The selected earthquake records are scaled to be strong enough to excite the structure more or less similarly. The ASCE7-10 [18] criteria and design spectrum are used for this purpose. In addition, a deconvolution analysis is performed beforehand to calculate the ground motion at the base level.

4. Deriving Semi-Analytical Relations

As mentioned in Section 2, 48 different SFS models are created for performing the parametric study and each model is subjected to 10 ground motions. The near-field properties consist of the near-field dimensions, which are obtained from the rigorous analysis, and the shear modulus and damping ratio from the modified equivalent linear models. Nonlinear regression analysis should now be performed for deriving semi-analytical relations for calculating the near-field properties based on the SSI characteristics including $\bar{s}$, $\bar{h}$ and $\bar{m}$. After performing this analysis in a sample statistical software to obtain a preliminary estimation of the coefficients and powers, a manual adjustment is also necessary to arrive at smoothed values. Derived relations for the shear modulus reduction factor and damping ratio of the near-field region are presented in Eqs. (1) and (2) respectively.

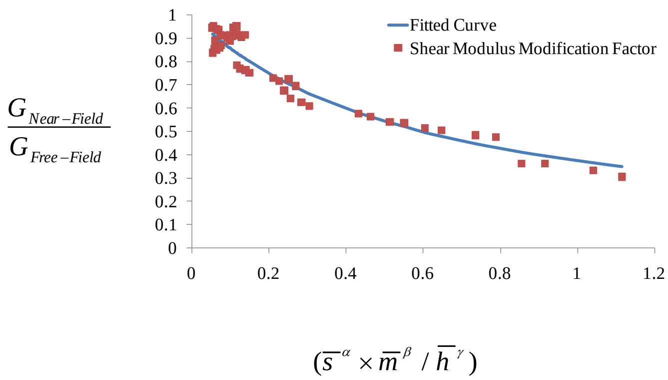
$$(1)\ \frac{G_{Near-Field}}{G_{Free-Field}} = \frac{0.6}{\left(\frac{\bar{s}^{1.5} \times \bar{m}^{0.10}}{\bar{h}^{0.25}}\right) + 0.6}$$

$$(2)\ \xi = 18\left(\frac{\bar{s}^{1.5} \times \bar{m}^{0.10}}{\bar{h}^{0.25}}\right) + 3$$

where $G_{Near-Field}$ is the final shear modulus of the near-field zone and $G_{Free-Field}$ is the effective shear modulus for the top layer of soil obtained from ELM analysis of the free-field and ξ is the damping ratio of the near-field zone in percent. Figs.3 and 4 demonstrate the curve fitting for the shear modulus reduction factor and damping ratio of the near-field zone.

Part of the horizontal dimension (length) of the near-field protruding from each side of the foundation (see Fig. 1), L_{NF}, normalized to the foundation dimension is estimated by Eq. (3).

$$(3)\ \frac{L_{N.F.}}{2a} = \frac{3.25\left(\frac{\bar{s}^{1.5} \times \bar{m}^{0.10}}{\bar{h}^{0.25}}\right)}{6\left(\frac{\bar{s}^{1.5} \times \bar{m}^{0.10}}{\bar{h}^{0.25}}\right) + 0.5}$$



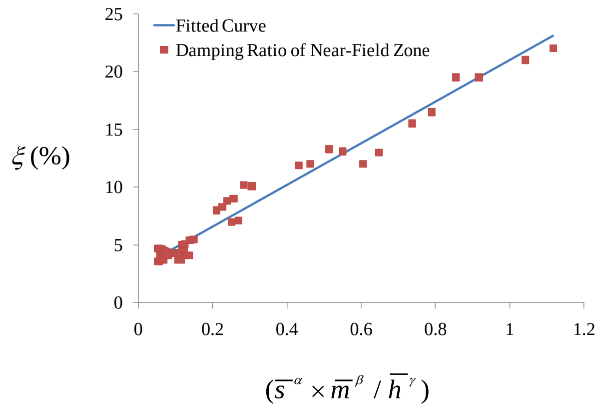


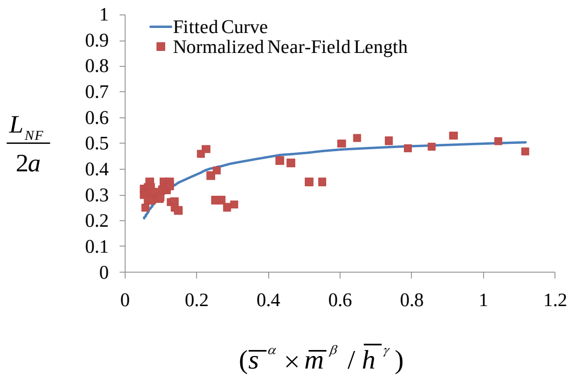
Fig. 3. Curve fitting for the shear modulus reduction factor

Fig. 4. Curve fitting for the damping ratio of the near-field zone

Finally, the depth of the near-field zone is calculated as:

$$H_{N.F.} = 0.25(2a) = 0.5a \quad (4)$$

where $2a$ is the foundation width. Figs.5 and 6 illustrate the proposed equations for the near-field dimensions of all of the analyzed models.



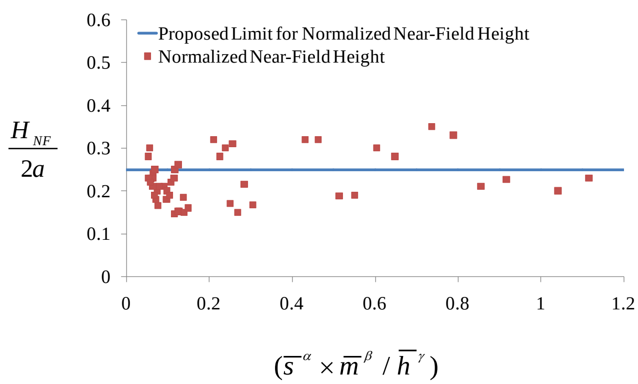


Fig. 5. Curve fitting for the normalized near-field partial length.

Fig. 6. Curve fitting for the depth of the near-field zone.

5. Employing The Near-Field Method

In the previous sections details of the near-field method proposed in this study were explained. As mentioned before, this method is based on decomposition of the soil domain into near-field and far-field regions and proposes modified properties for modeling of the soil in the near-field zone. This section presents a step-by-step methodology for employing the near-field method in direct SSI analysis. The main steps of the near-field method can be summarized as follows: 1) modal analysis of the fixed-base structure; 2) determining the important modes based on modal participation factors; 3) calculating $\bar{s}$, $\bar{h}$ and $\bar{m}$ values for important modes (see Table 1); 4) using Eqs.1 and 2 to calculate the shear modulus modification factor and damping ratio of the near-field region for important modes, 5) computing weighted average of the shear modulus modification factor and damping ratio using the modal mass participation factor as the weight; 6) using Eqs.3 and 4 to determine the near-field region dimensions; 7) performing free-field analysis to calculate effective soil properties under the considered earthquake and assigning effective properties to the far-field zone; 8) modifying the effective properties of the near-field zone using the modification factors obtained in step 5 and the characteristics calculated in step 7.

6. Verification and Example Application

Evaluating the validity and performance of the near-field method, and comparing the performance of the near-field method with other modeling approaches are the main objectives of this section. To attain this goal, two sets of 3D examples are considered. The first set of examples is selected from ATC-83 [19] report and includes applying certain SSI models to an existing building and comparing with actual observed responses. In the second set of examples, a parametric study is performed with evaluating the nonlinear seismic response of five, ten, fifteen and twenty story moment-resisting frame steel buildings. Two site conditions corresponding to site classes C and E based on the ASCE 7-10 [18] criteria along with different SSI modeling techniques are considered for this part of study. It should be noted that a nonlinear Winkler model developed by El Ganainy and El Naggar [20] is also applied for both sets of examples to compare performance of the near-field method with another new SSI modeling technique. This model is an efficient 3D nonlinear Winkler model for simulating shallow foundations and represents the foundation in a compact assembly of three structural elements. This assembly consists of a rotation hinge, a shear hinge and an elastic frame element.

6.1. Sherman Oaks commercial building

ATC-83 [19] has presented two example applications analyzed with conventional soil-structure interaction modeling techniques. In this paper, one of the two, called the Sherman oaks commercial building, has been selected to investigate the ability of the near-field method. Sherman Oaks building is a 13-story reinforced concrete moment frame structure with two basement levels, located in Sherman Oaks, California. The average shear wave velocity for the top 30m of the soil profile and for the soil near the foundation are equal to 320m/s and 200m/s, respectively [19]. This building was instrumented in 1977 and six earthquake events have been recorded until now among which Northridge event was chosen in this study.

A full and a stick model have been utilized by ATC-83 for the Sherman Oaks building. Since no enough details have been provided to model the full structure, here the structure is idealized as a stick model. The stick model of the building is illustrated in Fig.7. Stiffness properties of each floor above ground surface are calculated by an equivalent nonlinear link element having an idealized force-displacement behavior obtained from pushover analysis of that floor in the full model. For instance, Fig.8 shows the idealized force-displacement curve for floor 11 in East-West (EW) direction as presented in ATC-83 report [19]. More details about the stick model including its lumped masses, stiffness, etc. can be found in ATC-83 [19].

Table 3 summarizes the near-field zone properties calculated after employing the steps mentioned in Section 5.

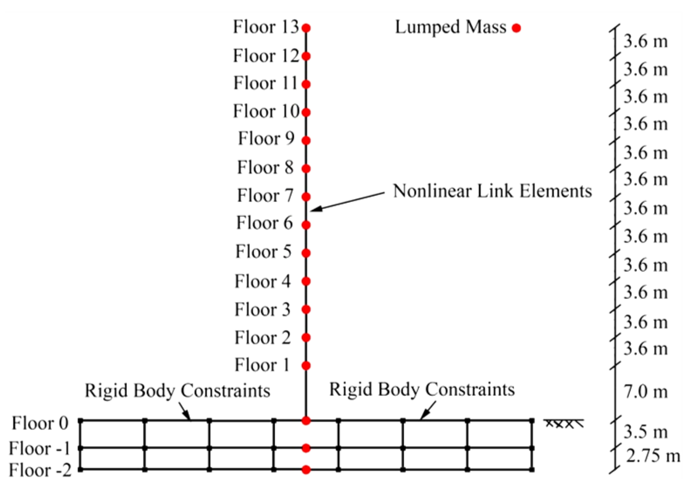


Fig. 7 – Elevation view of the stick model of the Sherman Oaks building.

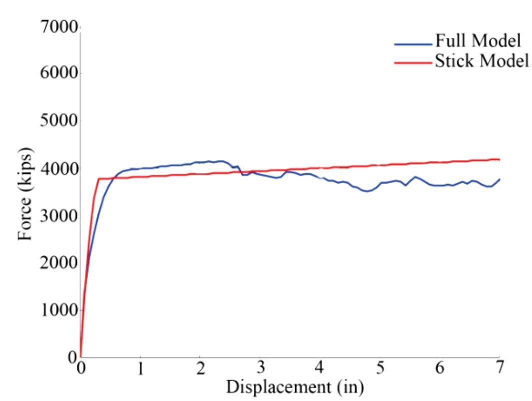


Fig. 8 – Idealized force-displacement curve for floor 11 in EW direction

Table 3 – Near-field properties for the Sherman Oaks building

Direction	$G/G_{Free-Field}$	$\xi(\%)$	Partial length $(L_{N.F.}/2a)$	Total length $(2L_{N.F.}+2a)$ (m)	Depth $(H_{N.F.})$ (m)
Longitudinal (E-W)	0.68	7.7	0.415	95	8.89
Transverse (N-S)	0.76	6.0	0.371	38	8.89

Comparison between the results of El Ganainy's model, the near-field method and the observed responses of the building is presented in the following. Results of the analyses show that application of the near-field method to the Sherman Oaks building example has led to results with very good accuracy and in most cases the accuracy is superior to the El Ganainy's method.

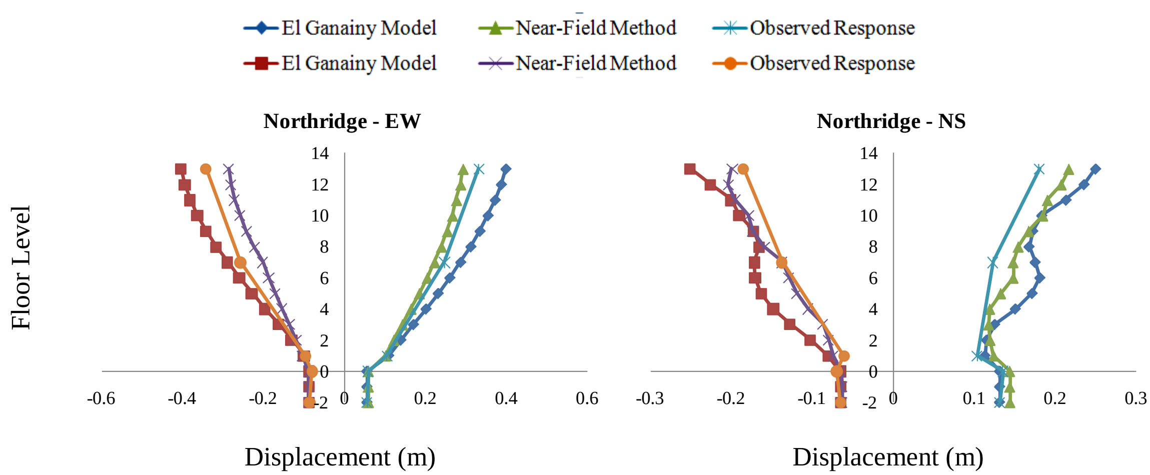


Fig. 9 – Comparison of near-field and El Ganainy's results with the recorded peak displacements, Northridge event

6.2. Steel moment resisting frame buildings

6.2.1. Models description

As the second set of examples, 3D nonlinear time history analyses are performed for several moment-resisting steel structures. The buildings have similar plans with 6×5 bays spanning 6 m unanimously in each bay and a constant story height of 3.5 m. Two-way steel moment-resisting frames are considered as the lateral resisting system of the buildings. Preliminary analysis and design of the buildings is performed using SAP2000 software. Two types of site conditions are considered, including the site classes C and E according to the site classification of ASCE/SEI 7-10 [18]. The seismic loading is determined using the regulations of ASCE/SEI 7-10 [18]. The structural members are designed according to ANSI/AISC 360-10 [21] and ANSI/AISC 341-10 [22]. The fundamental periods of the designed buildings turn out to be 0.79, 1.55, 2.25, and 2.70 sec for the 5, 10, 15, and 20-story buildings, respectively. Concentrated plastic hinges are used to model nonlinear behavior of the structural members. The moment-rotation behavior of plastic hinges is introduced according to ASCE 41-13 [23]. Fig.10 illustrates an example of the plastic hinges.

The following four different base conditions were assumed in this part of study for evaluating performance of the near-field method:

I. Building model with no SSI (the fixed-base model);
II. Soil-structure interaction model utilizing the nonlinear Winkler model proposed by El Ganainy and El Naggar [20] (El Ganainy's model);
III. Soil-structure interaction model using the near-field method presented in this study (the near-field model). The near-field properties are calculated through Section 5 steps;

IV. Soil-structure interaction model using Pressure Dependent Multi-Yield (PDMY) elastic-plastic constitutive model developed by Yang et al. [14] (the plastic model).

The plastic model is considered as a rigorous model and used as a basis of comparison of results of different models.

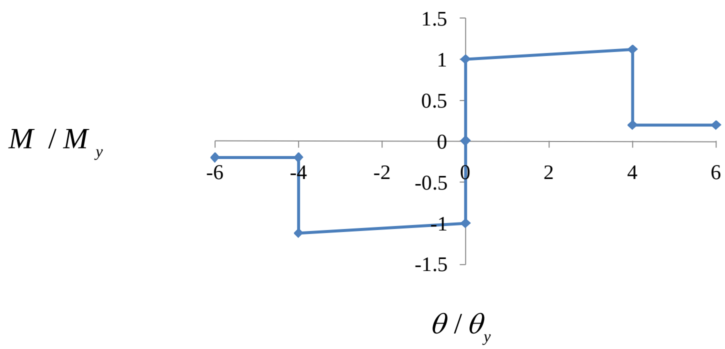


Fig. 10. An example of the plastic hinges [23].

Ten consistent ground motions are selected from the PEER Strong Motion Database [16] and the European Strong Motion Database [17] for each of the site classes. These ground motions are first scaled and deconvoluted and then applied to the building models.

6.2.2. Nonlinear time history analyses results

As mentioned above, four buildings, two site classes and four modeling procedures are considered herein. Each one of these 32 computational cases is excited by 10 different ground motions and the average of maximum responses is considered as the representative response of the case. Because of the extensive amount of results obtained from this part of study, only some representative results are presented here. The dynamic responses of the structures are presented as maximum drift ratio and story shear profiles. In addition, the Root-Mean-Square Error (RMSE) is calculated for each case to evaluate the accuracy of the modeling technique. The RMSE can be calculated using Eq. (5):

$$(5)\; RMSE\;(\%) = 100 \times \sqrt{\frac{\sum_{i=1}^{n} \left(\frac{X_{Ri} - X_{Ai}}{X_{Ri}}\right)^2}{n}}$$

where X_R is the maximum response by the rigorous model, X_A is the maximum response of one another model, both averaged between ten earthquakes, and n is the number of stories.

Fig.11 illustrates the averaged maximum drift ratio profiles of the 10-story building. The trend of inter-story drift is almost the same for all of the employed SSI models. These figure indicate that SSI can increase inter-story drifts in the lower to middle stories. Increase in the inter-story drift is more pronounced for the site class E. The drift ratios for upper floors of the buildings are almost the same among the cases and in other words, the effect of SSI on the drifts of the upper floors is negligible. Results of the near-field analysis have a better similarity to the rigorous model in most cases. This fact is numerically discussed in the following.

The RMSE's for the maximum drift ratio of 10-story building are calculated using Eq. (5). Fig.12 shows the RMSE diagrams for various SSI modeling techniques. It is clear from this figure that ignoring SSI in the selected cases result in considerable errors. On the other hand, the near-field method is proved to be the most accurate one among the others.

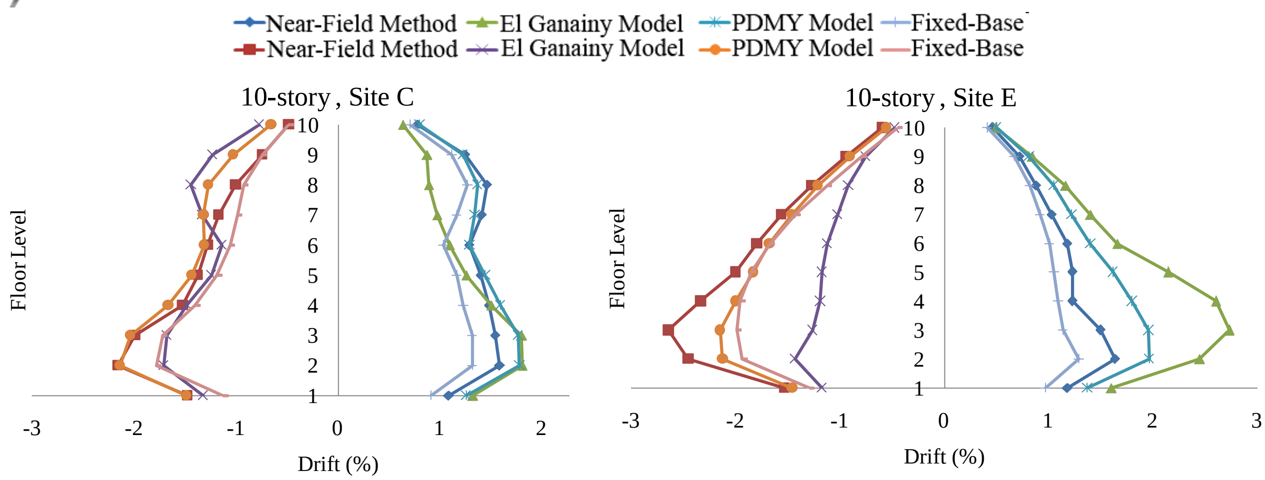


Fig. 11 – Averaged maximum drift ratio profiles for 10-story building.

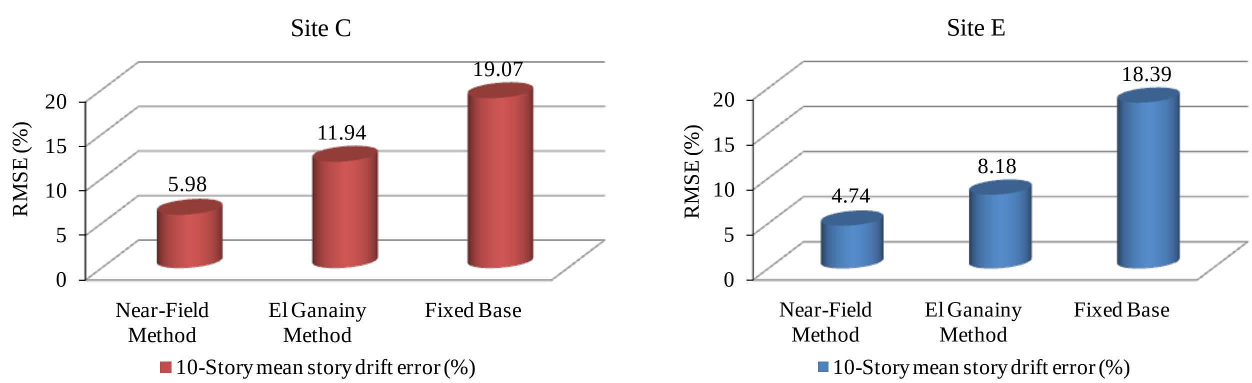


Fig. 12 – RMSE's for the averaged maximum drift ratio of 10-story building.

Story shear envelopes of 10-story building are illustrated in Fig.13. The envelopes show that SSI reduces the story shears. The reduction in story shear is larger for lower stories and softer soil conditions and is negligible for upper stories.

Diagrams of the story shear RSME's are presented in Fig.14. Again the near-field method shows the maximum accuracy with RMSE's less than 10% for all of the cases and neglecting SSI leads to considerable errors.

7. Conclusions

The near-field method, as a procedure for simplifying the direct analysis of SSI problems taking into account soil nonlinearity especially in the vicinity of foundations, was introduced in this paper. This method proposes semi-analytical equations for modifying properties of the linear soil in the near field of foundations as well as the near-field dimensions.

An existing building (Sherman Oaks Building) was selected as the first example and its recorded maximum responses during recent earthquakes were utilized as the basis of comparison. In the second example, four buildings having 5, 10, 15, and 20 stories with 3D steel moment-resisting frames were designed for the purposes of this study. Two site conditions corresponding to the site classes C and E were considered. Accuracy of the near-field method to estimate different responses of nonlinear buildings resting on nonlinear soils was compared in the above examples with another nonlinear Winkler method [20]. It was shown that almost in all of the cases the near-field method possesses a superior accuracy.

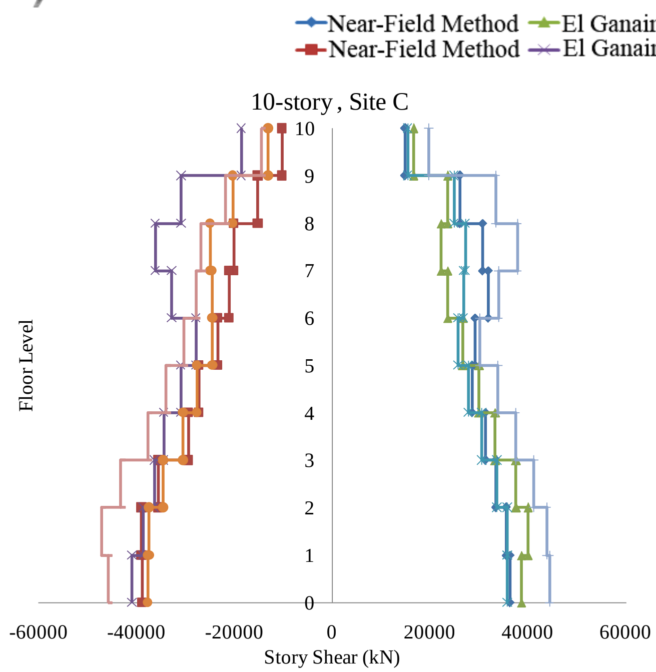


Fig. 13 – Story shear envelopes for 10-story building.

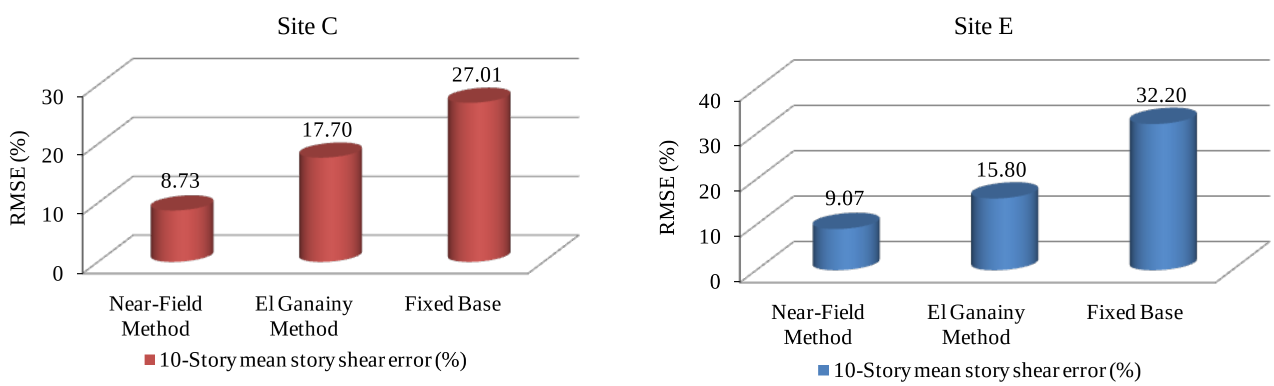


Fig. 14 – RMSE's for the story shears of 10-story building.

Regarding the time of computation, when for a sample case dynamic analysis of the SSI system with a nonlinear structure and a plastic soil takes about 4 hours, analyzing the same system with the near-field method, including the time needed for calculation of the modified parameters, takes only 20 minutes. Therefore, the near-field method can be an efficient alternative for dynamic analysis of nonlinear soil-structure systems.

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