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EVALUATION OF SOIL-STRUCTURE INTERACTION EFFECTS USING SEISMIC CODES

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ABSTRACT

Seismic codes nowadays include design requirements in order to taking Soil-Structure Interaction (SSI) into account for realistic modelling of structures. This study is conducted to assess the behaviour of steel structure-soil systems using Standard No. 2800 and FEMA-440. Steel frame buildings are assumed to have various heights and different lateral resistant systems. The buildings are supported by shallow foundation resting on soft and also very dense soil. The strong ground motions are selected and scaled according to 2800 code. Both kinematic and inertial interaction effects are considered. SSI is investigated through the equivalent spring-dashpot method on the basis of nonlinear Winkler beam concept in the OpenSees framework. Numerical results show that period lengthening have overall agreement in both simulations and regulations. In addition, It is observed that when SSI is considered, base shear and inter-story drift demand reduces; indicating a beneficial effect of the foundation flexibility. However, the story displacement demand is observed to increase with SSI. In addition, depending on the structural building and soil type, the obtained results may differ from each other and the most significant SSI effects are related to braced frame structures on soft soil.

INTRODUCTION

The response of a structure to earthquake shaking is affected by interactions between three linked systems; the structure, the foundation, and the soil underlying and surrounding the foundation (NIST, 2012). Soil-structure interaction analysis evaluates the collective response of these systems to a specified ground motion. The dynamic response of a structure to earthquake excitation can be affected significantly by its interaction with the supporting soil. The role of SSI is usually considered beneficial to the structural system under seismic loading since it lengthens the lateral fundamental period and leads to higher damping of the system (Khalil et al., 2007). This conclusion could be misleading. Indeed, recent case studies and postseismic observations suggest that the SSI can be detrimental and neglecting its influence could lead to unsafe design for both the superstructure and the foundation especially for structures founded on soft soil (i.e. Mylonakis and Gazetas, 2000).

The development of realistic numerical models of the foundation with its supporting subgrade soil, which can reasonably capture its nonlinear rocking behaviour, has been recognized as an important and complex problem in earthquake engineering. Numerous studies have been conducted to model the behaviour of structures supported on shallow foundations. Allotey and Naggar (2007) developed a Winkler-based approach utilizing multi-linear, no-tension backbone curves. Most recently, Harden and Hutchinson (2009) developed a Winkler-based model using pile-calibrated nonlinear backbone curves to model the behaviour of shallow strip footings supporting rocking dominated shear wall buildings. This model was updated using a broad range of shallow foundation experimental database, resulting in backbone curves specifically calibrated to these tests (Raychowdhury and Hutchinson, 2009).

Recent seismic codes include design requirements in order to consider SSI for a rational modelling and dynamic response analysis of structures against earthquake. These codes describe how to estimate kinematic interaction effects, flexibility to the soil-foundation system and damping ratio of soil-structure system for a nonlinear static and dynamic analysis. For example, ATC-40 (1996) accounts for SSI by suggesting elastic–plastic Winkler springs with stiffness suggested by Gazetas (1991), whereas ASCE-7-05 (2005) account for SSI by suggesting an increased period and modified damping of the soil–structure system. The present article is going to assess the effects of SSI on the behaviour of steel structures using finite element method. In this assessment, the Iranian seismic code of practice; Standard No. 2800 (2012) and Federal Emergency Management Agency; FEMA (2005) have been used. Steel frame buildings are assumed to have three, six, and twelve-story. Two different structural systems including moment resistant frame (MRF) and braced frame (BrF) are also considered. The buildings are supported by shallow foundations rested on the two different soft and stiff soils; soil type II and IV according to the classification of 2800 code. The strong ground motions are selected and scaled according to 2800 code for nonlinear time history analyses. In this article, a numerical model based on the Beam-on-Nonlinear-Winkler-Foundation (BNWF) approach of Harden and Hutchinson (2009) is selected due to its relative simplicity and acceptance in engineering practice. The BNWF model is utilized to assess the effect of nonlinear SSI on the seismic response of steel structural buildings and also compare the building results with those from fixed-base.

SOIL-STRUCTURE MODEL

Steel frame buildings with three, six and twelve stories and three spans were considered, as typically shown in Fig. 1. Both gravity and seismic loads were imposed on the frames according to the Iranian national building codes. All frames were designed as MRF and BrF based on AISC-360 (2005).

The numerical modelling of the frames is carried out with the finite element method using the software OpenSees (2013). The structural members are modelled to behave nonlinearly (Fig. 2). The beams and columns are modelled as nonlinear beam-column elements allowing the spread of plasticity along the member length. A Rayleigh damping of 3% is assumed for the two modes of each frame.

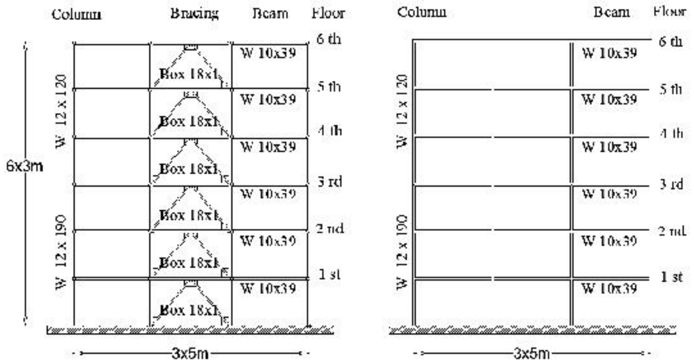


Figure 1. Typical six story BrF and MRF with nomenclature

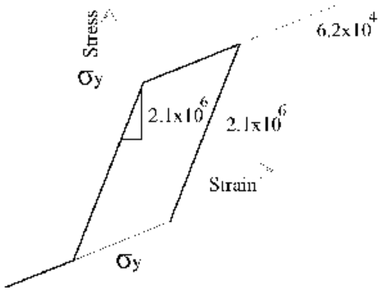


Figure 2. Hardening steel material (at Kg/cm^2)

In order to evaluate the effect of nonlinear SSI on the structural response, two different base conditions are considered at the soil-foundation interface. The first case is the fixed-base case, in which the foundation is assumed to be fixed against all the movements. The second case is the nonlinear SSI case, in which the soil-foundation interface is modelled as nonlinear Winkler springs (Fig. 3). The stiffnesses and bearing capacity of the springs are calculated following the method in Gazetas (1991), Terzaghi and Mohr-Coulomb failure criteria. The corresponding model has been implemented within the framework of OpenSees. This model can reasonably predict experimentally measured footing response in terms of moment, shear, settlement and rotational demands (Raychowdhury, 2011).

The investigated buildings are supported by two different soil conditions according to the classification of Standard 2800; soil type II and IV. With specified category and shear wave velocity for site classes, satisfactory values were estimated to represent their design parameters according to well-known geotechnical references. Selected values from the recommended ranges are presented in Table 1.

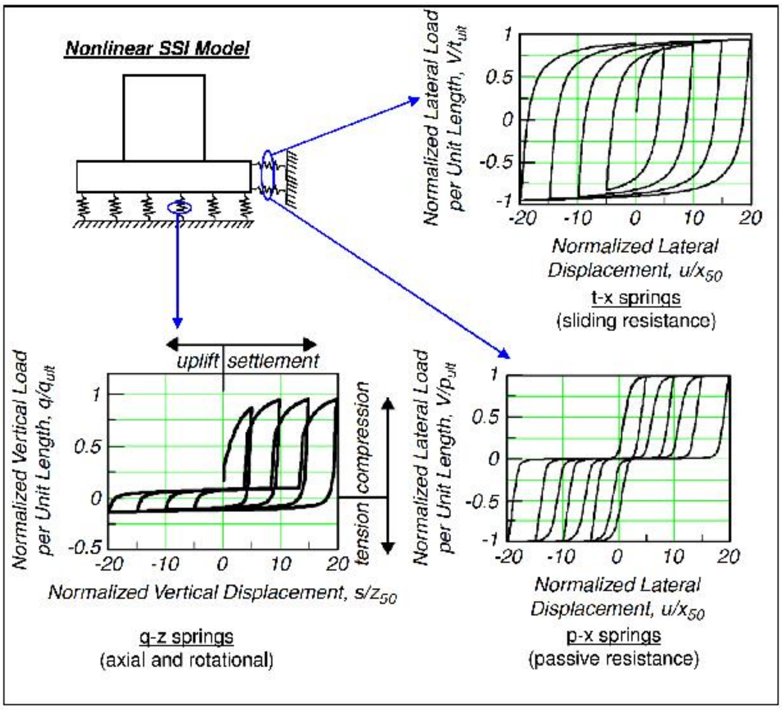


Figure 3. Nonlinear Winkler-based SSI model considered in the study (Raychowdhury, 2011)

Table 1. Selected characteristics for soil type II and IV

Soil type	Site Class Definitions	Shear wave velocity, V_s (m/s)	Density ($Kg.s^2/m^4$)	Shear modulus (Kg/cm^2)	Poisson's ratio
II	Very dense soil	500	220	32315	0.3
IV	Soft clay	150	170	390	0.4

ANALYSIS OF SOIL-STRUCTURE SYSTEM

In order to understand the behaviour of the nonlinear structure incorporating the nonlinear SSI, an eigen value analysis is performed, followed by a dynamic time history analysis. Four different ground acceleration records have been used for dynamic analysis of the systems. Table 2 provides some relevant information for the records. The seismic signals have been recorded on the ground surface in site classes with shear wave velocity complies with the soil type considered in Table 1. Thus, there is no need to site response analysis for the selected acceleration records.

The earthquake records have been scaled according to the Iranian Standard 2800. Kinematic interaction is applied to records through FEMA-440 and then the ground motions are applied to the models. The analyses results are discussed in the following sections.

Table 2. Scaled ground motions considered in the present study

Earthquake	Station	Moment magnitude	PGA (cm/s^2)
Chi-Chi, Taiwan, 1999	ILA004	7.62	611.7
Loma Prieta, 1989	Foster City-Menhaden Court	6.93	635.4
San Fernando, 1971	Cholame-Shandon Array#8	6.61	633.2
Borrego Mtn., 1968	LA- Hollywood Stor FF	6.63	622.1

KINEMATIC INTERACTION

Kinematic interaction results from the presence of stiff foundation elements on or in soil, which causes foundation motions to deviate from free-field motions as a result of base slab averaging and embedment effects. The Ratio of Response Spectra (RRS) factor is used to represent kinematic interaction effects in FEMA-440. An RRS is simply the ratio of the response spectral ordinates imposed on the foundation (i.e., the foundation input motion, FIM) to the free-field spectral ordinates. Elsabee and Morray (1977) developed analytical transfer functions relating base-slab translational motions to free-field translations for an incident wave field consisting of vertically propagating, coherent shear waves. Base-slab averaging does not occur within this wave field, but foundation translations are reduced relative to the free-field due to ground motion reductions with depth and wave scattering effects. Elsabee's analyses were for a finite soil layer. The following approximate transfer function amplitude model developed by Elsabee:

$$\left|H_u(\mu)\right| = \cos\left(\frac{e}{r}a_0\right) \geq 0.454 \tag{1}$$

where $a_0 = \omega r/V_s$, e is foundation embedment and r is the foundation equal radius.

Fig. 4 presents the foundation input motions derived from the free-field motion of the selected Chi-Chi earthquake for the two mentioned procedures. The kinematic interaction effect in Fig. 4 is accounted for BrF three-story building on soil type IV. It can be observed that high frequency motions decreases in Elsabee's transfer function more than FEMA-440. As seen, FEMA-440 underestimates the kinematic interaction effect in high frequency portion of the selected earthquake record. It should be noted that only a few ground motion time histories were used in these analyses, and additional research is needed to evaluate the relationship between RRS and transfer function ordinates as a function of ground motion characteristics and damping ratio.

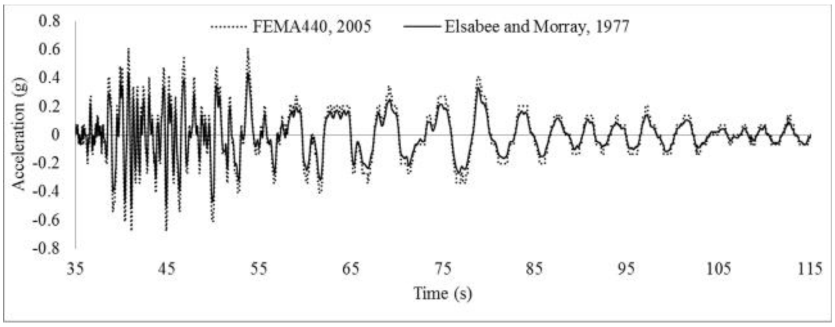


Figure 4. Foundation input motions derived from the scaled Chi-Chi, 1999 earthquake; a comparison between the FEMA-440 and Elsabee and Morray, 1977 transfer functions

PERIOD LENGTHENING

In order to understand the behaviour of the nonlinear structure incorporating the nonlinear SSI, an eigenvalue analysis is performed to determine the fixed-base and flexible-base periods. On the basis of FEMA-440, the flexible-base first mode period, $\tilde{T}$, shall be determined as follows

$$\frac{\tilde{T}}{T} = \sqrt{1 + \frac{K_{fixed}}{k_x} + \frac{K_{fixed}\, h^2}{k_\theta}} \qquad (2)$$

where T is the fixed-base first mode period, K_{fixed} is the stiffness of the fixed-base structure, k_x represents the horizontal stiffness of the foundation system, k_θ is effective rotational stiffness of the foundation and h is the effective structure height.

On the other hand, the effective period of the structure supported by mat foundations may be determined from equation 3 (Standard 2800, 2012):

$$\tilde{T} = T\sqrt{1 + \frac{25\alpha .r_a .\bar{h}}{V_s^2 .T^2}\left(1 + \frac{1.12\, r_a\, \bar{h}^2}{\alpha_\theta .r_\theta^3}\right)} \qquad (3)$$

where α is relative weight density of the structure and the soil, r_a and r_θ are characteristic foundation lengths and α_θ is dynamic foundation stiffness modifier for rocking. For detail information refer to Standard 2800.

Fig. 5 illustrates the period ratio of flexible to fixed-base averaged for all the examined buildings. As shown, the SSI effect implies an increase in the building fundamental period compared with the fixed-base reference model, especially when the BrFs are located on soil type IV. In fact, by decreasing the rigidity of soil, the difference between period of vibrations in two cases (structures modelled on flexible soils and structures modelled as fixed-base) will be increased. Consequently, the effect of SSI for soil type IV is considerable while for relatively rigid ground, it is negligible. It can be also seen that the period elongations of BrF structures are greater than the MRFs. In addition, the simulated results are in agreement with those obtained from the design codes, except from BrF structure on soil type IV where the regulations underestimate the period lengthening.

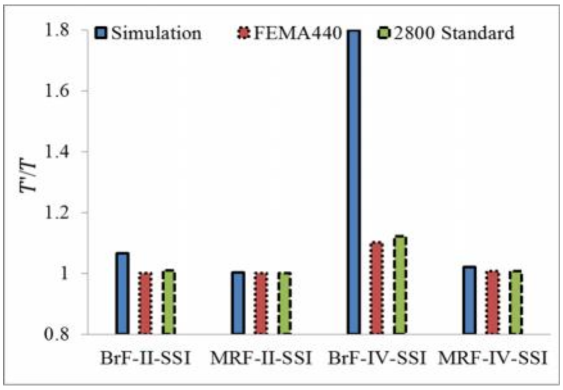
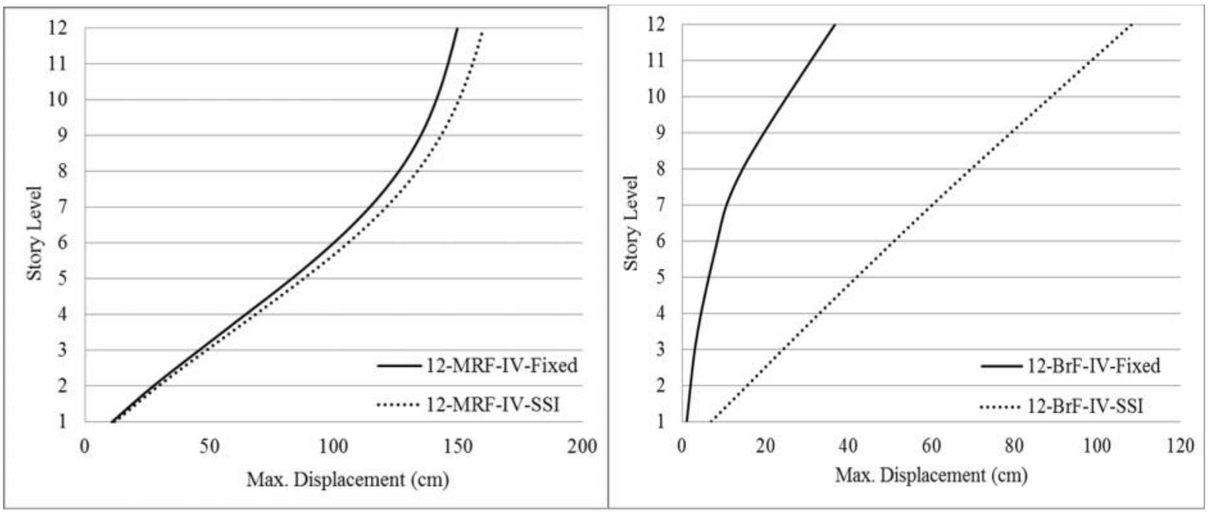


Figure 5. Average period lengthening for all the examined MRF and BrF buildings

DISPLACEMENT DEMAND

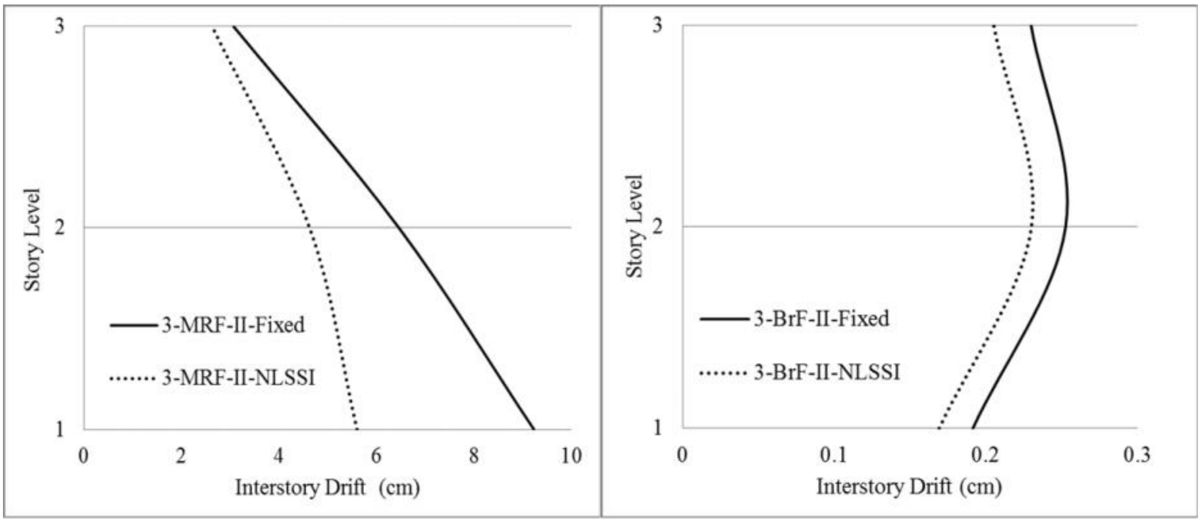
Displacement demands at roof level in tall buildings are strongly affected by foundation displacements and rotations. So, the SSI turns out to be significant where the second order effects are important as well. Steel structures usually have high deformation capacity, but this capacity is limited because of service requirements. Fig. 6 shows the peak absolute displacement at the floor level in the direction of applied acceleration for representative twelve-story building on soil type IV. It is observed that the story displacement increases as the base condition changes from fixed to flexible. The increase is siginificantly largest for the BrF case because of its higher soil-structure relative rigidity. The increase in story displacement is occurring due to the overall reduction in the global stiffness resulting from the induced foundation movements.

Although the absolute displacements at story levels are greater in the case of flexible-base conditions, the relative displacements show a decreasing trend when base nonlinearity is introduced, as indicated in Fig. 7. It is observed that the relative story drift, which is generally known as the interstory drift ratio, reduces significantly when nonlinear SSI is incorporated. Since the interstory drift demand is an important parameter for the design of structural members, it is very likely that the members are designed over-conservatively in the absence of incorporation of nonlinear SSI.



(a) (b)

Figure 6. Average peak story displacements of twelve-story on soil type IV subjected to assumed earthquake records with and w/o SSI effect (a) MRF building (b) BrF building

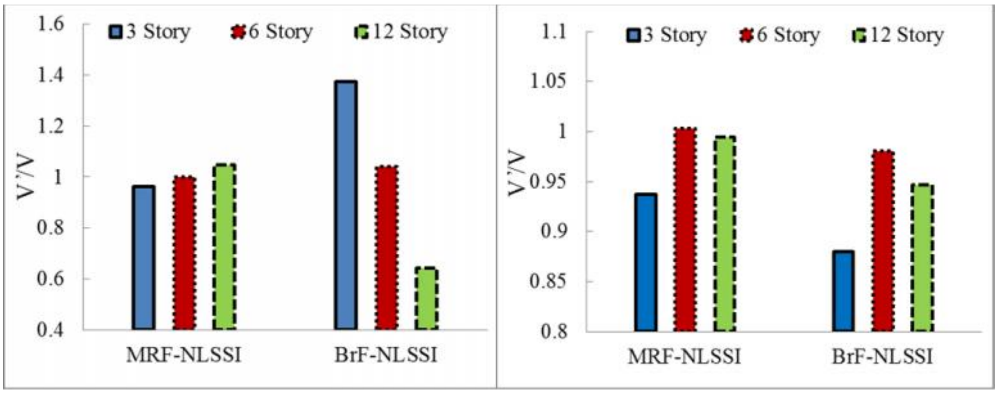


(a) (b)

Figure 7. Average peak interstory drift of three-story on soil type II subjected to assumed earthquake records with and w/o SSI effect (a) MRF building (b) BrF building

BASE SHEAR

The base shear created by the inertial forces is the main parameters to be checked in order to understand how the soil-structure interaction works. Fig. 8 presents the structural response in terms of the peak base shear demand for the selected ground motions. The obtained results indicate that the soil-structure interaction plays a significant role in base shear demands. This effect is more pronounced in buildings resting on softer soil. It can be observed that modelling the soil–foundation interface as fixed would lead to an over-conservative estimation of the base shear. The effect of structural system is also evident here, indicating that BrF models have the potential for greater reduction in structural force demands due to the higher relative rigidity at the soil-structure interface.



(a) (b)

Figure 8. Average ratio of peak absolute base shear for flexible-base to fixed-base buildings on soil (a) type II (b) type IV

CONCLUSIONS

The numerical results obtained in this study show that SSI effect reduces the base shear and inter-story drift demand; indicating a beneficial effect of the foundation flexibility. However, the story displacement demand increased with SSI. Thus, modelling the SSI may play an important role in altering the force and displacement demand, indicating the necessity for consideration of foundation flexibility behaviour in the seismic structural design. It is noted that for the selected structures and soil types, the results may differ from each other and the most significant effects are related to BrF cases on soil type IV. The results also show that the SSI effect may strongly be influenced by the frequency content of the earthquake ground motion. Therefore, this study still needs to be verified for additional structures with a wide range of natural periods, different soil conditions and earthquake records before the findings could be generalized and used for design recommendations. This discussion will appear in future publications.

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