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Effects of Dynamic Soil-Structure Interaction on Performance Level of Moment Resisting Buildings Resting on Different Types of Soil

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ABSTRACT: In this study, two structural models comprising five and fifteen storey moment resisting building frames are selected in conjunction with three different soil deposits with shear wave velocity less than 600m/s. The design sections are defined after applying dynamic nonlinear time history analysis based on inelastic design procedure using elastic-perfectly plastic behaviour of structural elements. These frames are modelled and analysed employing Finite Difference approach using FLAC 2D software under two different boundary conditions namely fixed-base (no soil-structure interaction), and considering soil-structure interaction. Fully nonlinear dynamic analyses under the influence of different earthquake records are conducted and the results of inelastic behaviour of the structural models are compared. The results indicate that the inter-storey drifts of the structural models resting on soil types De and Ee (according to the Australian standard) substantially increase when soil-structure interaction is considered for the above mentioned soil types. Performance levels of the structures change from life safe to near collapse when dynamic soil-structure interaction is incorporated. Therefore, the conventional inelastic design procedure excluding SSI is no longer adequate to guarantee the structural safety for the building frames resting on soft soil deposits.

1 INTRODUCTION

The seismic response of an engineering structure is influenced by the medium on which it is founded. On solid rock, a 'fixed-base' structural response occurs which can be evaluated by subjecting the foundation to the 'free-field' ground motion occurring in the absence of the structure. On a deformable soil, however, a feedback loop exists. In the other words, the structure responds to the dynamics of the soil, while the soil also responds to the dynamics of the structure. Structural response is then governed by the interplay between the characteristics of the soil, the structure and the input motion. The process, in which the response of the soil influences the motion of the structure and vice versa, is referred to as *Soil-Structure Interaction (SSI).* Compared with the counterpart fixed-base system, SSI has four basic effects on structural response. These effects can be summarised as: (i) increase in the natural period of the system, (ii) increase in the damping of the system, (iii) increase in the lateral displacements of the structure, and (iv) change in the base shear depending on the frequency content of the input motion and dynamic characteristics of the soil and the structure (Wolf and Deeks, 2004).

The importance of SSI both for static and dynamic loads has been well established and the related literature spans at least 30 years of computational and analytical approaches to solving soil–structure interaction problems. Since 1990s, great effort has been made for substituting the classical methods of design by the new approaches based on the concept of performance-based seismic design. Several researchers (e.g. Veletsos and Meek, 1974; Kobayashi et al., 1986; Gazetas and Mylonakis, 1998; Wolf and Deeks, 2004; Galal and Naimi, 2008) studied structural behaviour of un-braced structures subjected to earthquake under the influence of soil-structure interaction. Examples are given by Gazetas and Mylonakis (1998) including evidence that some structures founded on soft soils are vulnerable to SSI. According to available literature, generally when the shear wave velocity of the supporting soil is less than 600 m/s, the effects of soil-structure interaction on the seismic response of structural systems, particularly for moment resisting building frames, are significant. Thus, for ordinary building structures, the necessity of a better insight into the physical phenomena involved in SSI problems has been recognised.

Furthermore, the necessity of estimating the vulnerability of existing structures and assessing reliable methods for their retrofit have greatly attracted the attention of engineering community in most seismic zones throughout the world. To have a better judgment on the structural performance, in this study, SSI effects are investigated on the performance level of two structural models comprising five and fifteen storey moment resisting building frames constructed on various soil types including soil types Ce, De, and Ee according to Australian Standards.

2 PERFORMANCE-BASED ENGINEERING ASSESSMENT

Practising civil engineers usually use inelastic analysis methods for the seismic evaluation and design of existing and new buildings. The main objective of inelastic seismic analysis is to estimate more precise prediction of the expected behaviour of the structure against future probable earthquakes. This has become significantly important with the emergence of performance-based engineering (PBE) as a technique for seismic evaluation and design using performance level prediction for safety and risk assessment (ATC-40, 1996). Since structural damage implies inelastic behaviour, traditional design and analysis procedures based on linear elastic techniques can only predict the performance level implicitly. By contrast, the objective of inelastic seismic analysis method is to estimate the magnitude of inelastic deformations and distortions directly and accurately (performance level).

Performance levels describe the state of structures after being subjected to a certain hazard level and are classified as: fully operational, operational, life safe, near collapse, or collapse (Vision 2000, 1995; FEMA 273/274, 1997). Overall lateral deflection, ductility demand, and inter-storey drifts are the most commonly used damage parameters. The above mentioned five qualitative performance levels are related to the corresponding quantitative maximum inter-storey drifts of: <0·2%, <0·5%, <1·5%, <2·5%, and >2·5%, respectively.

The generic process of inelastic analysis is similar to conventional elastic linear procedures in which engineers develop a model of the building or structure, which is then subjected to a representative, anticipated seismic ground motion. The primary difference with the linear elastic design procedure is that the structural elements are allowed to deform plastically when the plastic moment is reached in the element.

In many instances, it is important to include the structural and geotechnical components of the foundation in the simulation. Inelastic bending is simulated in structural elements by specifying a limiting plastic moment. If the member is composed of a material that behaves in an elastic-perfectly plastic manner (Figure 1), the plastic resisting moments M^p for a rectangular section can be computed as follows:

$$M^p = \sigma_y \left(\frac{bh^2}{4}\right) \tag{1}$$

Where, b is the section width, h is the section height, σ_y is yield stress of the structural material.

It should be noted that the present formulation assumes that structural elements behave elastically until reaching the defined plastic moment. The section at which the plastic moment occurs can continue to deform, without inducing additional resistance, when M^p is reached.

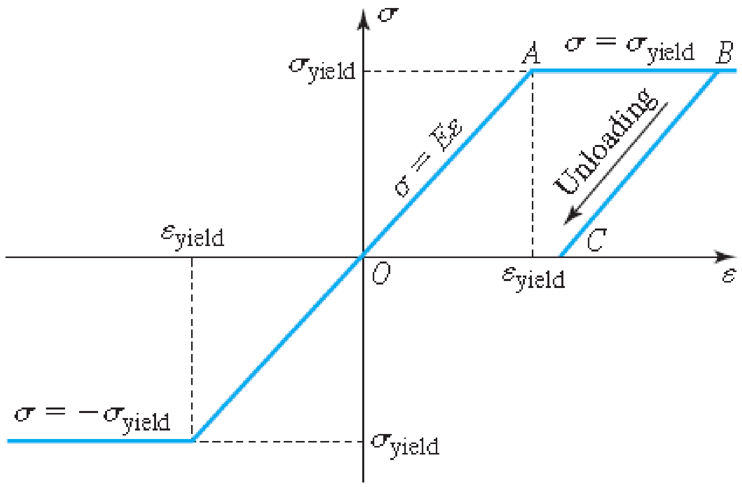

Figure1. Elastic-perfectly plastic behaviour of structural elements (ATC-40, 1996)

3 STRUCTURAL AND GEOTECHNICAL CHARACTERISTICS OF THE MODELS

3.1 Structural Characteristics of Models

In this study, two structural models, consisting of 5 and 15 storey frames, representing the conventional types of buildings in a relatively high risk earthquake prone zone, as per specifications mentioned in Table 1, are selected in conjunction with three soil types with the shear wave velocity less that 600m/s comprising one cohesionless and two cohesive deposits, representing classes Ce, De and Ee, according to AS 1170.4 (Earthquake action in Australia).

Table 1. Characteristics of the studied concrete frames

Model Name	Number of Storey	Storey Height (m)	Bay Width (m)	Total Height (m)	Total Width (m)
S5	5	3	3	15	12
S15	15	3	3	45	12

Structural sections are designed according to AS3600:2001 (Australian Standard for Concrete Structures) after undertaking inelastic dynamic analysis under influence of four different earthquake ground motions, as a fixed base model resting on soil class Ee (most adverse condition) considering cracked reinforced concrete sections according to ACI318.2002. The characteristics of the earthquake ground motions are tabulated in Table 2. Performance level of the structural model is considered as life safe level in this design indicating that the maximum inter-storey drifts of the model are less than 1.5%.

Table 2. Earthquake ground motions used in this study

Earthquake	Country	Year	PGA (g)	Mw (R)
Northridge	USA	1994	0.843	6.7
Kobe	Japan	1995	0.833	6.8
El Centro	USA	1940	0.349	6.9
Hachinohe	Japan	1968	0.229	7.5

3.2 Geotechnical Characteristics of Subsoil

Characteristics of the utilised soils are summarised in Table 3. The shear wave velocity values shown in Table 3 are called G_{max} which their corresponding cyclic shear strains are about 10^{-4} percent. In the event of an earthquake, the cyclic shear strain amplitude increases and the shear strain modulus and damping ratio, which both vary with the cyclic shear strain amplitude, change relatively. Vucetic and Dobry (1991), for cohesive soils, and Seed and Idriss (1986), for cohesionless soils, developed ready to use charts indicating the variations of the shear modulus ratio (G/G_{max}) with the cyclic shear strain(γ_c) in nonlinear dynamic analysis as well as material damping ratio(λ) versus cyclic shear strain(γ_c), which have been adopted in this study.

Table 3. Geotechnical characteristics of the utilised soils in this study

Soil Type (AS1170)	Shear Wave Velocity Vs (m/s)	Unified Classification	Shear Modulus G_{max} (kPa)	Poisson Ratio (υ)	SPT	Plasticity Index (PI)	Cohesion C' (kPa)	Friction Angle ϕ' (Degree)
Ce	600	GM	623,409	0.28	N>50	-	5	40
De	320	CL	177,304	0.39	30	20	20	19
Ee	150	CL	33,100	0.40	6	15	20	12

4 DYNAMIC ANALYSIS OF SOIL-STRUCTURE INTERACTION

The governing equations of motion for the structure incorporating foundation interaction and the method of solving these equations are relatively complex. Therefore, Direct Method, the method which by using that entire soil-structure system is modelled in one step, is employed in this study and Finite Difference software, FLAC2D, is utilised to model the soil-structure system and to solve the equations for the complex geometries. FLAC (Fast Lagrangian Analysis of Continua) is a two-dimensional explicit finite difference program for engineering mechanics computations. This program simulates the behaviour of different kinds of structures. Materials are represented by elements which can be adjusted to fit the geometry of the model. Each element behaves according to a prescribed linear or nonlinear stress/strain law in response to the applied forces or boundary restraints. The program offers a wide range of capabilities to solve complex problems in mechanics such as inelastic analysis including plastic moment and simulation of hinges for structural systems.

Several efforts have been made in recent years in the development of analytical methods for assessing the response of structures and supporting soil media under seismic loading conditions. There are two main analytical procedures for dynamic analysis of soil-structure systems under seismic loads, equivalent-linear and fully nonlinear methods. Byrne et al. (2006) and Beaty and Byrne (2001) provided an overview of the above mentioned methods and discussed the benefits of the nonlinear numerical method over the equivalent-linear method for different practical applications. The equivalent-linear method is not appropriate to be used in dynamic soil-structure interaction analysis as it does not capture directly any nonlinear effects because it assumes linearity during the solution process. In addition, strain-dependent modulus and damping functions are only taken into account in an average sense, in order to approximate some effects of nonlinearity (e.g. damping and material softening). Byrne et al. (2006) concluded that the most appropriate method for dynamic analysis of soil-structure system is the fully nonlinear method. The method correctly represents the physics associated with the problem and can accommodate any stress-strain relation in a realistic way. Considering the mentioned priorities and capabilities of the fully nonlinear method for dynamic analysis of soil-structure systems, this method is used in this study in order to attain rigorous and more reliable results. Using fully nonlinear method for dynamic analysis, enables us to apply Vucetic & Dobry (1991) and Seed and Idriss (1986) charts directly to the model and take soil nonlinearity into account in an accurate and realistic way.

On the other hand, inelastic seismic analysis and design method is employed in this study to directly estimate the performance level of the structural system. This method provides a rational approach for the analysis of the structure as well as reasonable economy in the structural design as the structural sections required by this method are smaller in size than those required by the method of elastic analysis. The plastic moment is used to determine the plastic limit behaviour of the column–beam element.

5 NUMERICAL SIMULATION OF SOIL - STRUCTURE SYSTEM

In this study, fully nonlinear time history dynamic analysis has been employed using FLAC 2D to define inelastic seismic response of the concrete moment resisting frames incorporating SSI. Dynamic analysis is carried out for two different systems: (i) fixed-base structure on the rigid ground (Figure 2), and (ii) structure considering subsoil and strip foundation using direct method of SSI analysis as the flexible base model (Figure 3). The following aspects have been considered in the dynamic time history analysis of the study:

- Fully nonlinear behaviour of the subsoil including material nonlinearity (relationship between soil stiffness and material damping ratio versus cyclic shear strain) and geometric nonlinearity (large strains)
- Inelastic behaviour of the structural system and geometric nonlinearity of the structure (large displacements)
- Cracked sections for the reinforced concrete sections according to ACI318.2002

The soil-structure model (Figure 3) comprises beam elements to model beams, columns, and strip foundation, two dimensional plane strain grid elements to model soil medium, fixed boundaries to model the bed rock, absorbent boundaries (viscous boundaries) to avoid reflective waves produced by soil lateral boundaries, and interface elements to simulate frictional contact and probable slip due to seismic excitation. According to Rayhani and Naggar (2008), horizontal distance between soil boundaries is assumed to be five times the structure width, and the bedrock depth is assumed to be 30 m.

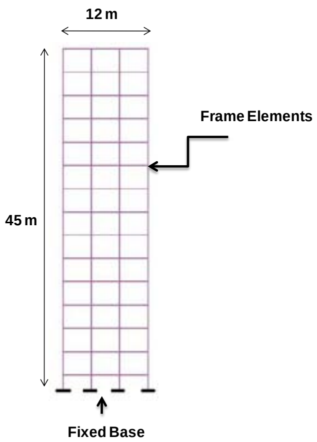

Figure 2. Fixed-base model

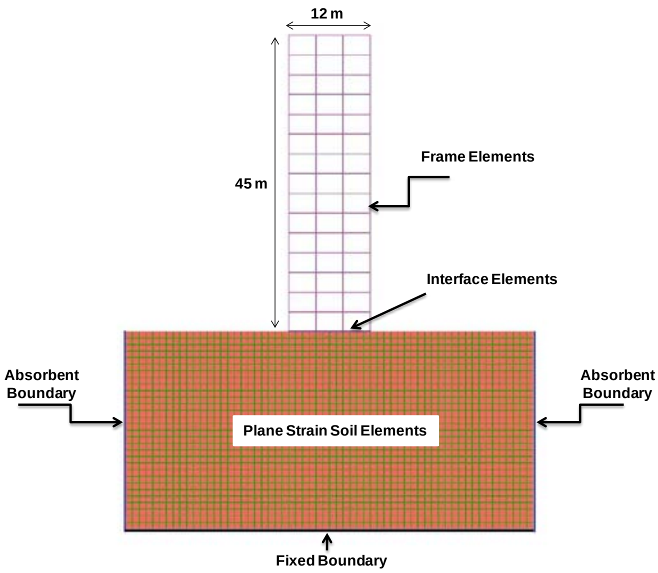

Figure3. Components of the Soil-Structure model in FLAC

Four different earthquake ground motions (Table 2) are applied to both systems in two different ways. In the case of modelling soil and structure simultaneously using direct method (flexible base), the earthquake records are applied to the combination of soil and structure directly at the bed rock level, while for modelling the structure as the fixed base (without soil), the earthquake records are applied to the base of the structural models.

6 RESULTS AND DISCUSSIONS

The results of the inelastic analyses including the base shear and the inter-storey drifts for both 5 and 15 storey models are determined and compared for the fixed-base and flexible-based cases resting on the three different types of soil, so as to clarify the effects of subsoil rigidity on inelastic seismic response of moment resisting frames and their performance levels. According to the results summarised in Table 4, the ratios of the base shear of the flexible-base models ($\tilde{V}$) to that of fixed-base (V) in all models are less than one. These results have good conformity to NEHRP-2003 regulations. In addition, by decreasing the shear wave velocity of the subsoil, the base shear ratios decrease relatively. These reductions in the base shear ratios are more substantial for the 15 storey structural model (S15) in comparison with the 5 storey model (S5).

Table 4. Base shear ratio of flexible-base to fixed-base models

Model Name	Earthquake	Fixed-base model	Soil Type Ce		Soil Type De		Soil Type Ee	
		V (kN)	$\tilde{V}$ (kN)	$\tilde{V}/V$	$\tilde{V}$ (kN)	$\tilde{V}/V$	$\tilde{V}$ (kN)	$\tilde{V}/V$
S5	Northridge	89	88	0.988	73	0.820	59	0.663
	Kobe	130	128	0.984	106	0.815	85	0.653
	Hachinohe	39	38	0.974	30	0.769	24	0.615
	El Centro	47	46	0.978	36	0.766	29	0.617
S15	Northridge	441	432	0.979	316	0.716	203	0.461
	Kobe	550	533	0.969	391	0.710	258	0.469
	Hachinohe	167	158	0.946	123	0.736	63	0.377
	El Centro	194	178	0.917	133	0.686	72	0.371

Comparing the inter-storey drifts of fixed-base and flexible-base models resting on soil classes Ce, De, and Ee for model S5 (Figures 4-7) and model S15 (Figures 8-11), it is observed that the inter-storey drifts of the flexible base models resting on soil class Ce do not differ much from that of the fixed-base models for both structural models. As a result, the performance level of the model resting on soil class Ce remains in life safe level. For model S5, inter-storey drifts of the flexible base model resting on soil class De under influence of earthquake records with high PGA (Northridge and Kobe) increase to more than 1.5% by incorporating dynamic SSI (Figures 4 and 5) while for model S15 resting on the same soil the inter-storey drifts exceeded 1.5% life safe criterion under influence of all the earthquake records.

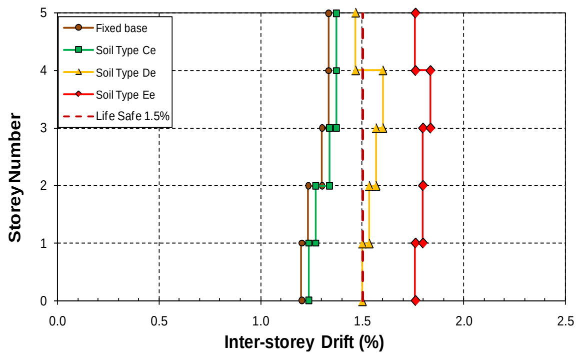

Figure 4. Inter-story drifts for 5 storey fixed base and flexible base models (Northridge earthquake, 1994)

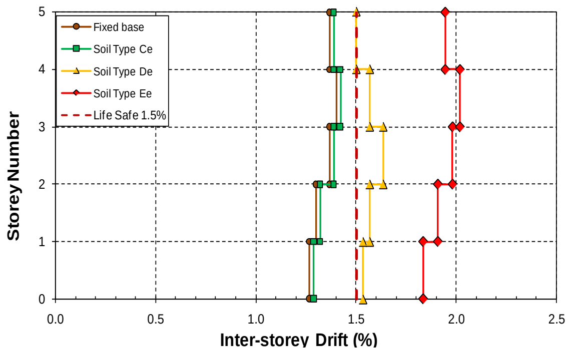

Figure 5. Inter-story drifts for 5 storey fixed base and flexible base models (Kobe earthquake, 1995)

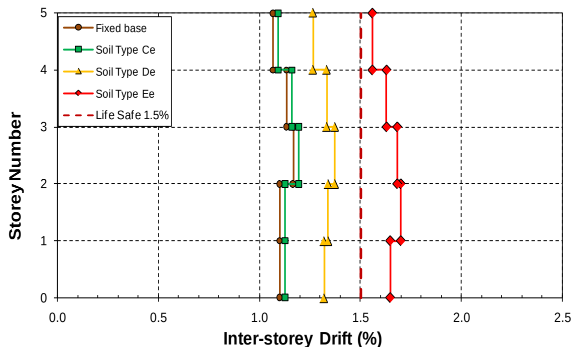

Figure 6. Inter-story drifts for 5 storey fixed base and flexible base models (El Centro earthquake, 1940)

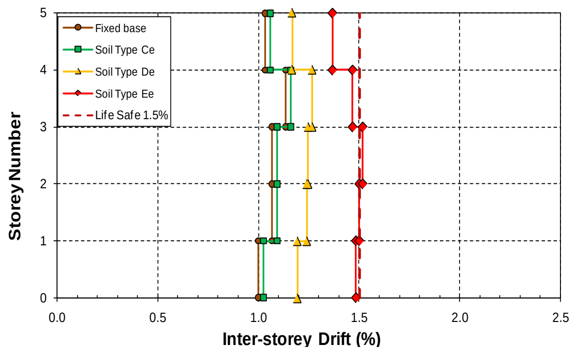

Figure 7. Inter-story drifts for 5 storey fixed base and flexible base models (Hachinohe earthquake, 1968)

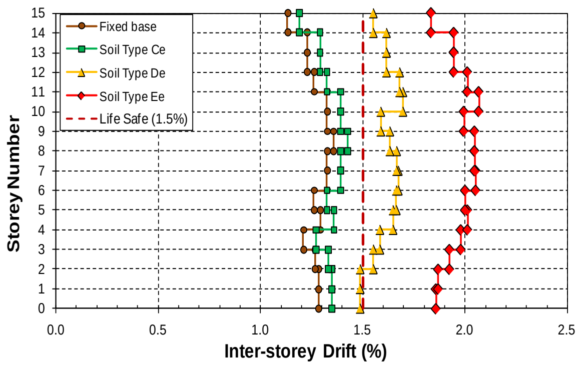

Figure 8. Inter-story drifts for 15 storey fixed base and flexible base models (Northridge earthquake, 1994)

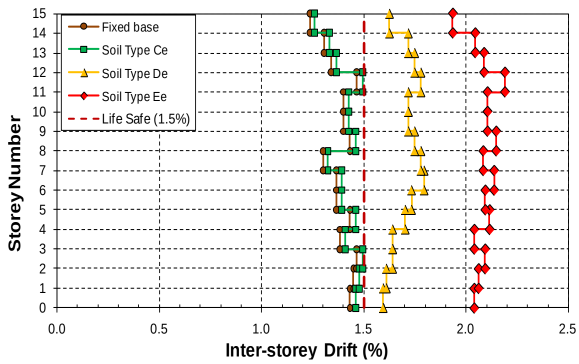

Figure 9. Inter-story drifts for 15 storey fixed base and flexible base models (Kobe earthquake, 1995)

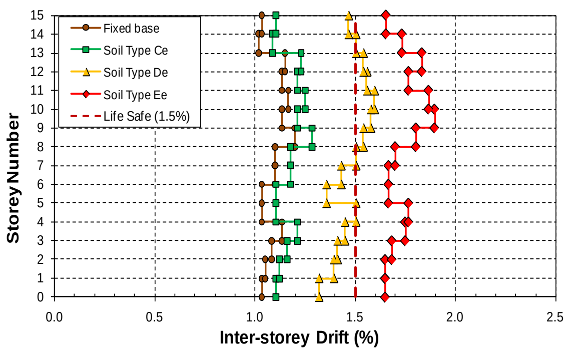

Figure 10. Inter-story drifts for 15 storey fixed base and flexible base models (Northridge earthquake, 1994)

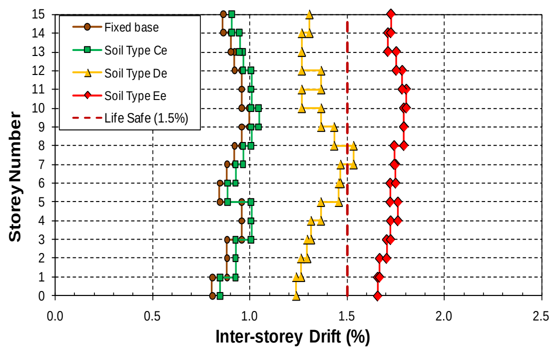

Figure 11. Inter-story drifts for 15 storey fixed base and flexible base models (Kobe earthquake, 1995)

The results are more adverse for the models on soil class Ee as the performance level of the structures substantially increase from life safe to near collapse or collapse levels as in Figures 4 to 11, the inter-storey drifts exceed 1.5% lateral drift criterion. Such a significance change in the inter-storey drifts and subsequently performance level of the model resting on soils De and Ee (especially for soil class Ee) can be safety threatening. Thus, design engineers need to precisely take the effects of dynamic SSI into account in their design especially for construction projects on soft soils.

7 CONCLUSIONS

According to the results of the numerical investigation conducted in this study for the 5 and15 storey concrete moment resisting building frames resting on soil classes Ce, De and Ee, it is observed that base shear of the structures modelled with soil as flexible-base are always less than the base shear of structures modelled as fixed base. In addition, by decreasing the shear wave velocity of the subsoil, the base shear ratios decrease relatively. It is also observed that the performance levels of the structures resting on soil class Ce do not change substantially and remain in life safe level. Therefore, the effects of soil-structure interaction for inelastic seismic design of moment resisting buildings founded on soil type Ce is negligible. However, performance levels of the structures resting on soil class De, under influence of earthquakes with high PGA, increase from life safe to near collapse while lateral drift increments for low PGA earthquakes are negligible. For the models resting on soil class Ee, as the inter-storey drifts substantially exceed the life safe criterion, the performance level of the models increase dramatically from life safe to near collapse or total collapse. As a result, considering SSI effects in inelastic seismic design of concrete moment resisting building frames resting on soil classes De (under influence of high PGA earthquakes) and Ee is vital. Thus, the conventional inelastic design procedure excluding SSI is not adequate to guarantee the structural safety for the moment resisting building frames resting on soil classes De and Ee. It is highly recommended to practicing engineers and engineering companies working in high earthquake risk zones, to consider SSI influences in the dynamic analysis and design of moment resisting building frames on soft soils to ensure designs are reliable and the structures perform safely.

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