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A parametric study on the evaluation of ductility demand distribution in multi-degree-of-freedom systems considering soil–structure interaction effects

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A B S T R A C T

The current code-compliant design lateral load patterns are based on the elastic behavior of fixed-base structures without considering soil–structure interaction (SSI) effects. As a result, the implementation of such a load pattern in seismic design of soil–structure systems may not be appropriate. Moreover, recently several new optimum loading patterns have been proposed by researchers for fixed-base systems while their adequacy for soil–structure systems have not been evaluated yet. This paper performs intensive parametric analyses of 7200 nonlinear multi-degree-of freedom (MDOF) systems with SSI subjected to a group of 30 earthquakes recorded on alluvium and soft soils to investigate the effect of SSI on height-wise distribution of ductility demands. Effect of many parameters including fundamental period, level of inelastic behavior, number of stories, damping model, damping ratio, structural strain hardening, earthquake excitation, level of soil flexibility, aspect ratio on height-wise distribution of damage (ductility demand) are intensively investigated. In addition, the adequacy of three different code-complaint lateral loading patterns including UBC-97, IBC-2009 and EuroCode-8 as well as three recently proposed optimum loading patterns for fixed-base structures are parametrically investigated for soil–structure systems by two methods associated to the economy of the seismic-resistant system. Results of this study indicate that among the aforementioned code-specified design lateral load patterns, UBC-97, generally, has the best performance in soil–structure systems. However, all of them loose their efficiency when the SSI effect is severe and inelastic response is pronounced. It is also demonstrated that although the structures designed according to some recently proposed optimum load patterns may have generally better seismic performance when compared to those designed by code-specified load patterns, their seismic performances are far from the optimum if the SSI effects are considered, and their efficiency significantly reduces with increasing the soil flexibility.

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1. Introduction

Nearly most of the seismic design procedures in current major seismic codes for regular structures in the world are mainly based on elastic structural behavior analyses under seismic lateral forces and account for inelastic behavior in a somewhat indirect manner. The shape of these lateral load patterns along the height of structures from various standards such as EuroCode-8 [1], Mexico City Building Code [2], Uniform Building Code (UBC-1997) [3], NEHRP 2003 [4], ASCE/SEI 7-05 [5], Australian Seismic code [6] and International Building Code, IBC-2009 [7] depends on the fundamental period of the structures and their mass. They are derived primarily based on elastic dynamic analysis of fixed-base structures without considering soil–structure interaction (SSI) effect. In the United States, the current code-specified seismic design procedures are mainly based on the NEHRP Recommended Provisions published in 2003 [4]. It should be mentioned that the seismic design criteria in ASCE/SEI 7-05 [5], exclusively based on the NEHRP 2003, is also adopted in IBC-2009 [7] for minimum design load criteria. The seismic lateral load patterns in all aforementioned provisions are based on the assumption that the soil beneath the structure is rigid, and hence the influence of SSI effect on load pattern is not considered. The reliability of using the code-specified lateral load patterns for fixed-base building structures have been investigated during the past two decades [8–10]. Chopra [10] evaluated the ductility demands of several shear building models with elastoplastic behavior subjected to the 1940 El Centro Earthquake. The relative story yield strength of these models complied with the lateral load pattern of the earthquake forces specified in the 1994 Uniform Building Code (UBC 94) [11]. It was concluded that utilizing this load pattern does not lead to equal ductility demand in all stories, and that generally the maximum ductility demands occurs in the first story. Leelataviwat et al. [12] evaluated the seismic demands of mid-rise moment-resisting frames designed in

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accordance to UBC 94. They proposed improved load patterns using the concept of energy balance applied to moment-resisting frames with a pre-selected yield mechanism. Lee and Goel [13] also proposed new seismic lateral load patterns by using high-rise moment-resisting frames up to 20-story with the same concept which Leelataviwat et al. [12] proposed. However, they used SDOF response modification factor as well as structural ductility factors and dealt with a limited number of ground motions. Their proposed load pattern fundamentally follows the shape of the lateral load pattern in the code provisions (i.e., UBC 1994, 1997) and is a function of mass and the fundamental period of the structure. In a more comprehensive research, Mohammadi et al. [14] investigated the effect of lateral load patterns specified by United States seismic codes on drift and ductility demands of fixed-base shear building structures under 21 earthquake ground motions, and found that using the code-specified design load patterns do not lead to a uniform distribution and minimum ductility demands. In another study, Moghaddam and Hajirasouliha [15], based on the nonlinear dynamic analyses on fixed-base shear building models subjected to 20 earthquake ground motions recorded on alluvium soil, proposed a new lateral load pattern as a function of the fundamental period of the structure and target ductility. Ganjavi et al. [16] investigated the effect of equivalent static and spectral dynamic lateral load patterns specified by the governing seismic codes on height-wise distribution of drift, hysteretic energy and damage subjected to severe earthquakes in fixed-base reinforced concrete buildings. They concluded that in strong ground motions, none of the lateral loading patterns will lead to uniform distribution of drift, hysteretic energy and damage, and an intense concentration of the values of these parameters can be observed in one or two stories especially in equivalent static method.

More recently, several studies have been conducted by researchers to evaluate and improve the code-specified design lateral load patterns based on the inelastic behavior of the structures [17–19]. However, all researches have been concentrated on the different types of structures with rigid foundation, i.e., without considering SSI effects. SSI is one of the important factors that can significantly affect the seismic responses of structures located on soft soils by altering the overall stiffness and energy dissipation mechanism of the systems. In fact, a soil–structure system behaves as a new system having longer period and generally higher damping due to energy dissipation by hysteretic behavior and wave radiation in the soil. The general effects of SSI on elastic response of SDOF and MDOF systems with an emphasis on the former were the subject of many studies in the 1970s [20–26]. These works led to providing tentative provisions in ATC3-06 [27], which is actually the foundation of new provisions on earthquake-resistant design of soil–structure systems [4,28]. Code-compliant seismic designs for SSI systems are, conventionally, based on the approximation in which the predominant period and associated damping of the corresponding fixed-base system are modified [22,24]. In fact, the current seismic provisions consider SSI, generally, as a beneficial effect on seismic response of structures since SSI usually causes a reduction of total shear force of building structures [4,5]. However, the inelastic behavior of the superstructure, inevitable during severe earthquakes, has not been well investigated. On the other hand, the current seismic design philosophy is based on inelastic behavior of structures when subjected to moderate and severe earthquakes. Hence, there is a necessity to investigate the effect of SSI on inelastic response of building structures. In recent years, many studies have been made by researchers to investigate the SSI effects on inelastic behavior of structures [29–35]. However, most of them focused on SDOF systems while the SSI effect on inelastic response of MDOF systems due its more complexity has not been investigated in detail. In a more recent study, Ganjavi and Hao [36] through intensive parametric calculations investigated the effect of SSI on the strength and ductility demands of MDOF as well as its equivalent SDOF buildings considering both elastic and inelastic behaviors and concluded that the common SDOF systems may not lead to accurately estimation of the strength and ductility demands of MDOF soil–structure systems, especially for the cases of mid- and high-rise buildings, due to the significant contributions from higher vibration modes.

A few studies of SSI effects on MDOF systems have been conducted by Barcena and Esteva [37], Chouw and Hao [38,39], Raychowdhury [40] and Tang and Zhang [41]. However, the SSI effects on seismic demands of MDOF systems are not well studied and further investigations are deemed necessary. In fact, it is necessary to clarify the influence of structural properties distribution on the local and global ductility demands when SSI is to be considered. This is because the pattern of local plastic deformation is definitely influenced by soil characteristics as well as the distribution of stiffness and strength along the building height. Here, in this paper a comprehensive parametric study has been performed to investigate the effect of inertial SSI on height-wise distribution of ductility demands in shear-building structures with different structural properties, with emphasis on code-specified-seismic design load pattern, using a simplified soil–structure model for shallow foundation in which the kinematic interaction is zero. This is carried out for a wide range of structural models and non-dimensional parameters to investigate the role of SSI on seismic demands distribution along the height of the MDOF building structures. In addition, adequacy of three recently proposed lateral load patterns for fixed-base structures on height wise distribution of ductility demand in soil–structure systems is parametrically investigated and discussed.

2. Superstructure model

Due to its simplicity and capability of considering higher modes effects, the well-known shear-beam model is indeed one of the most frequently used models that facilitate performing a comprehensive parametric study [14,15,18]. In the MDOF shear-building models utilized in the present study, each floor is assumed as a lumped mass to be connected by elasto-plastic springs. Story heights are 3 m and total structural mass is considered as uniformly distributed along the height of the structure. A bilinear elasto-plastic model with 2% strain hardening in the force–displacement relationship is used to represent the hysteretic response of story lateral stiffness. However, the effect of different post-yield behavior is also investigated. This model is selected to represent the behavior of non-deteriorating steel-framed structures of different heights. In all MDOF models, lateral story stiffness is assumed as proportional to story shear strength distributed over the height of the structure, which is obtained in accordance to the different lateral load patterns [14]. Five percent Rayleigh damping was assigned to the first mode and the mode in which the cumulative mass participation was at least 95%.

3. Soil–structure model

Sub-structure method is used to model the soil–structure system. Using the sub-structure method, the soil can be modeled separately and then combined to establish the soil–structure system. The soil–foundation element is modeled by an equivalent linear discrete model based on the cone model with frequency-dependent coefficients and equivalent linear model [31,42]. Since all analyses were carried out in time domain, it was dependent to the natural frequency of the system through an iteration method. Cone model based on the one-dimensional wave propagation

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