Soil Dynamics and Earthquake Engineering 88 (2016) 356–368

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Optimum lateral load distribution for seismic design of nonlinear shear-buildings considering soil-structure interaction

Behnoud Ganjavi [a,*], Iman Hajirasouliha [b], Ali Bolourchi [c]

[a] Department of Civil Engineering, University of Mazandaran, Babolsar, Iran
[b] Department of Civil and Structural Engineering, University of Sheffield, Sheffield, UK
[c] Department of Civil and Environmental Engineering, University of Southern California, CA, USA

ARTICLE INFO

Article history:
Received 27 November 2015
Received in revised form
31 March 2016
Accepted 8 July 2016

Keywords:
Soil-structure interaction
Optimum strength distribution
Uniform damage distribution
Inelastic behaviour
Seismic code
Soft soil

ABSTRACT

The lateral load distributions specified by seismic design provisions are primarily based on elastic behaviour of fixed-base structures without considering the effects of soil-structure-interaction (SSI). Consequently, such load patterns may not be suitable for seismic design of non-linear flexible-base structures. In this paper, a practical optimisation technique is introduced to obtain optimum seismic design loads for non-linear shear-buildings on soft soils based on the concept of uniform damage distribution. SSI effects are taken into account by using the cone model. Over 30,000 optimum load patterns are obtained for 21 earthquake excitations recorded on soft soils to investigate the effects of fundamental period of the structure, number of stories, ductility demand, earthquake excitation, damping ratio, damping model, structural post yield behaviour, soil flexibility and structural aspect ratio on the optimum load patterns. The results indicate that the proposed optimum load patterns can significantly improve the seismic performance of flexible-base buildings on soft soils.

1. Introduction

The preliminary design of regular building structures in current seismic design codes is commonly based on the equivalent static force approach, in which the dynamic inertial forces due to seismic vibrations are represented by equivalent static forces (force-based design procedure). The height-wise distribution of the seismic design static forces in different standards is usually only a function of fundamental period of the structure and the height-wise distribution of structural mass (e.g. EuroCode 8 [1], International Building Code 2012 [2], ASCE/SEI 7-10 [3], NEHRP 2003 [4], Uniform Building Code [5]). This implies that the equivalent static forces are derived primarily based on the elastic dynamic response of fixed-base structures without considering soil-structure interaction (SSI) effects. The efficiency of using the code-specified lateral load patterns for fixed-base building structures has been extensively investigated [6–15]. The results of these studies indicated that the current design approach, in general, does not lead to a uniform distribution of deformation demands in multi-story structures.

Leelataviwat et al. [9] evaluated the seismic demands of mid-rise moment-resisting frames designed in accordance with Uniform Building Code [5]. They proposed improved load patterns using the concept of energy balance applied to moment-resisting frames with a pre-selected yield mechanism. Using the same concept, Lee and Goel [16] proposed new seismic lateral load patterns for high-rise moment-resisting frames (up to 20 stories). However, they dealt with a limited number of ground motions. Their proposed load pattern fundamentally follows the shape of the lateral load pattern in the Uniform Building Code [5] and is a function of the mass and the fundamental period of the structure. In a more comprehensive research, Mohammadi et al. [10] investigated the effect of design lateral load patterns on drift and ductility demands of fixed-base shear building structures under 21 earthquake ground motions. Their results indicate that using the code-specified design load patterns do not generally lead to a uniform distribution of story ductility demands. Ganjavi et al. [13] investigated the effect of using equivalent static and spectral dynamic lateral load patterns specified by the conventional seismic codes on height-wise distribution of drift, hysteretic energy and damage index of fixed-base reinforced concrete buildings subjected to severe earthquakes. They concluded that none of the code-based design load patterns leads to a uniform distribution of drift, hysteretic energy and structural damage under strong earthquakes. It was also observed that in the structures designed using the equivalent static method these performance parameters can be much higher in one or two stories (i.e. soft story phenomenon). More recently, several studies have been conducted to

---

* Corresponding author.
E-mail address: b.ganjavi@umz.ac.ir (B. Ganjavi).

http://dx.doi.org/10.1016/j.soildyn.2016.07.003
0267-7261/

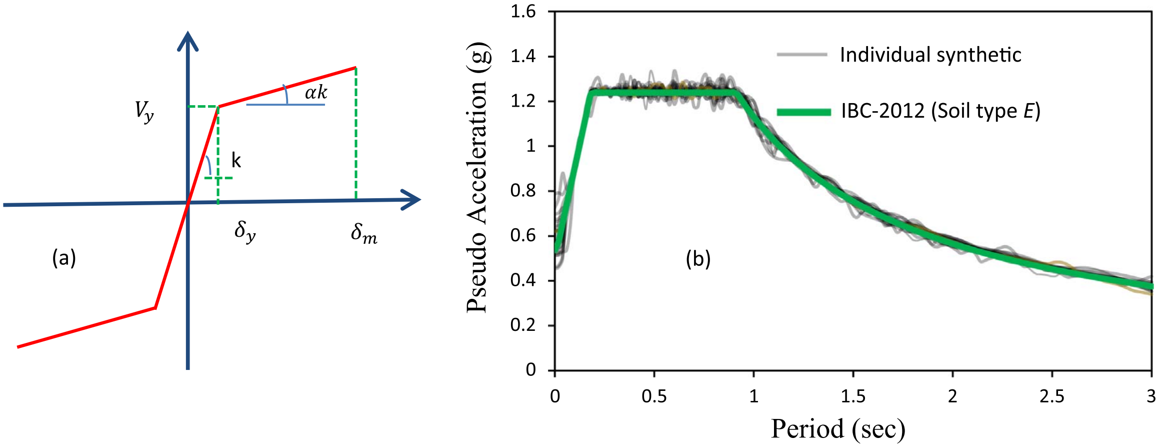

Fig. 1. (a) Bilinear elasto-plastic model for force-displacement relationship; (b): IBC-2012 (ASCE/SEI 7-10) design spectrum for soil type *E* and response spectra of 21 adjusted earthquakes (5% damping).

evaluate and improve the code-specified design lateral load patterns based on the inelastic behaviour of the structures e.g. [11,15,17,18]. However, none of the above studies considered the effects of SSI.

Several studies investigated the effects of SSI on elastic and inelastic response of buildings [19–27]. In general, the results of these studies demonstrated that SSI can significantly affect the seismic response of structures located on soft soils by altering the overall stiffness and energy dissipation mechanism of the systems. Compared to fixed-base systems, soil-structure systems possess longer periods and generally higher damping ratios due to the energy dissipation provided by hysteretic behaviour and wave radiation in the soil medium. Ganjavi and Hao [28] investigated the adequacy of IBC-2009 lateral loading patterns for seismic design of elastic and inelastic soil-structure systems through analyses of 7200 shear-buildings with SSI effects subjected to a group of 30 earthquakes recorded on alluvium and soft soils. They concluded that using the code-specified design load patterns leads to nearly uniform ductility demand distributions for structures having short periods and within the elastic range of response. For structures with longer periods, however, the efficiency of the IBC design load pattern was considerably reduced, which was more evident by increasing the soil flexibility and the story ductility demands. In another study, Ganjavi and Hao [29] developed a new optimisation algorithm for optimum seismic design of elastic shear-building structures with SSI effects. Their adopted optimisation method was based on the concept of uniform damage distribution proposed by Mohammadi et al. [10] and Moghaddam and Hajirasouliha [11,12] for fixed-base shear building structures. Based on the results of their study, Ganjavi and Hao [29] proposed a new design lateral load pattern for seismic design of elastic soil-structure systems, which can lead to a more uniform distribution of deformations and up to 40% less structural weight as compared with code-compliant structures. However, their proposed load pattern was developed only for elastic SSI systems and, therefore, may not be applicable for non-linear structures on soft soils. Through performing a parametric study on nonlinear shear-buildings with SSI effects, Bolourchi [30] showed that SSI can significantly affect optimum lateral load patterns when compared to the corresponding fixed-base systems. However, the results of that study were based on very limited fixed-base fundamental periods and earthquake ground motions, and also the soil-structure systems were modelled using cone model with frequency independent impedances in which no material damping was considered.

This study aims to provide a fundamental step towards the development of a more rational seismic design methodology that explicitly accounts for the complex phenomenon of soil-structure interaction and inelastic behaviour of structures. The optimisation algorithm adopted by Ganjavi and Hao [29] to obtain optimum design load patterns for elastic soil-structure systems is further developed to incorporate the inelastic behaviour of structures. By performing extensive numerical simulations on a wide range of inelastic soil-structure systems, the effects of fundamental period of the structure, number of stories, slenderness ratio, maximum ductility demand, earthquake excitation, damping ratio, damping model, structural post yield behaviour and soil flexibility on optimum design load patterns are investigated. The efficiency of the proposed optimum load patterns is demonstrated through several design examples.

2. Modelling of superstructures and selected ground motions

In this study, superstructures are modelled based on the procedure proposed by FEMA 440 [31], which allows engineers model certain complex structures as MDOF shear buildings. Shear building models can represent multi-story structures with shear beams or those with relatively stiff diaphragms with respect to columns. In spite of some drawbacks, these models have been widely used to study the seismic response of multi-story buildings because of simplicity and low computational effort that enables a wide range of parametric studies e.g. [14,25,27,29,30]. In MDOF shear-buildings, floors are modelled as lumped masses which are connected by elasto-plastic springs. As shown in (Fig. 1(a)), in this study a bilinear elasto-plastic model with 2% post-yield strain hardening is used to represent the story lateral stiffness of each floor. The effect of using different strain hardening ratios is also investigated in this study. This model is selected to represent the behaviour of non-deteriorating steel-framed structures with high beam-to-column stiffness ratio. However, moment resisting frames with high beam-to-column stiffness ratio may not comply with current seismic design provisions to enforce the formation of plastic hinges in the beams. It should be noted if member joints and connections are not well detailed, steel-framed structures may exhibit some cyclic strength and stiffness degradation that can influence their seismic performance under strong earthquakes. In the present study, these effects are not taken into account.

Story heights are considered to be 3 m and the mass of the structure is uniformly distributed over the height (i.e. all stories have the same lumped mass). In all MDOF models, lateral story stiffness is assumed to be proportional to the story shear strength distributed over the height of the structure [14,15]. The height-