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Performance-based seismic design of flexible-base multi-storey buildings considering soil–structure interaction

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ABSTRACT

A comprehensive parametric study has been carried out to investigate the seismic performance of multi-storey shear buildings considering soil–structure interaction (SSI). More than 40,000 SDOF and MDOF models are designed based on different lateral seismic load patterns and target ductility demands to represent a wide range of building structures constructed on shallow foundations. The cone model is adopted to simulate the dynamic behaviour of an elastic homogeneous soil half-space. 1, 5, 10, 15 and 20-storey SSI systems are subjected to three sets of synthetic spectrum-compatible earthquakes corresponding to different soil classes, and the effects of soil stiffness, design lateral load pattern, fundamental period, number of storeys, structure slenderness ratio and site condition are investigated. The results indicate that, in general, SSI can reduce (up to 60%) the strength and ductility demands of multi-storey buildings, especially those with small slenderness ratio and low ductility demands. It is shown that code-specified design lateral load patterns are more suitable for long period flexible-base structures; whereas a trapezoidal design lateral-load pattern can provide the best solution for short period flexible-base structures. Based on the results of this study, a new design factor R_F is introduced which is able to capture the reduction of strength of single-degree-of-freedom structures due to the combination of SSI and structural yielding. To take into account multi-degree-of-freedom effects in SSI systems, a new site and interaction-dependent modification factor R_M is also proposed. The R_F and R_M factors are integrated into a novel performance-based design method for site and interaction-dependent seismic design of flexible-base structures. The adequacy of the proposed method is demonstrated through several practical design examples.

1. Introduction

While flexible foundations can affect the seismic responses of structures, current seismic codes either allow engineers to take advantage of Soil–Structure Interaction (SSI) by using a reduced response spectrum [1], or permit SSI effects to be neglected for common building structures [2]. This concept stems from the fact that the SSI effect increases the period of the system, which usually leads to a reduced design acceleration spectrum, and also provides additional energy dissipation capacity due to the soil material damping and radiation [3].

Several studies have been performed to investigate the effects of SSI on the seismic response of Single-Degree-of-Freedom (SDOF) structures using elasto-plastic oscillators supported by soil springs. Some studies [4,5] have reported beneficial SSI effects, while others [6,7] have shown opposite results. It has been generally accepted that the predominant period of the site motion plays an important role in SSI analyses [8,9]. Beneficial SSI effects have been found for structures with natural periods higher than the site period, whereas detrimental effects are observed in structures whose periods are shorter than the site period. This implies that neglecting SSI effects in the seismic design procedures does not necessarily lead to conservative design solutions.

While a number of investigations have been conducted to study the strength–ductility relationship of SDOF SSI systems [10–12], less attention has been paid to the inelastic strength demands of Multi-Degree-of-Freedom (MDOF) SSI systems. Santa-Ana and Miranda [13] studied the base shear strength relationship between MDOF and their corresponding SDOF systems using site-dependent ground motions. However, the compliance of the foundation was not included in their analysis. In a more recent study, Ganjavi and Hao [14] investigated the strength–ductility relationship of flexible-base multi-storey shear buildings subjected to a

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group of 30 real earthquake ground motions recorded on alluvium and soft soil deposits. Based on their results, a new equation was proposed to estimate the strength reduction factor for MDOF SSI systems. Based on a study on seismic response of SSI systems utilising a nonlinear Winkler-based model, Raychowdhury [15] concluded that foundation nonlinearity can reduce the ductility demands of buildings. Aydemir and Ekiz [16] studied the ductility reduction factor for flexible-base multi-storey frames subjected to 64 earthquake ground motions that were categorised into 4 groups according to the U.S. geological survey site classification system. They observed that the ductility reduction factor values for flexible-base frame systems are generally smaller than the code-specified values, especially for softer soil conditions.

As is well known, seismic design of building structures in modern codes and provisions is based on elastic response spectra derived for lightly damped fixed-base SDOF oscillators. Therefore, the code design response spectra cannot be directly used for seismic design of flexible-base structures with SSI effects. To address this issue, there is a need to provide a link between inelastic seismic demands of flexible-base multi-storey buildings and code design spectra for fixed-base SDOF systems. For the first time, this study aims to provide such a link through a comprehensive parametric analysis using an analytical model to study the seismic response of flexible-base inelastic multi-storey buildings under design spectrum-compatible earthquakes. To this end, a large number of nonlinear 1, 5, 10, 15 and 20-storey SSI models, representing a wide range of buildings founded on shallow foundations, are utilised to assess the seismic performance of flexible-base structures subjected to design spectrum-compatible earthquakes corresponding to different soil conditions. The effects of soil stiffness, design lateral load pattern, fundamental period, number of storeys, structure slenderness ratio and site condition on the structural strength and ductility demands are investigated. The results of the SSI systems subjected to code spectrum-compatible earthquakes in the parametric study are then used to develop a novel performance-based design approach for seismic design of flexible-base multi-storey buildings considering the effects of SSI and site conditions. By introducing new strength and MDOF reduction factors for SSI systems, the suggested design methodology only requires information from fixed-base SDOF elastic design spectra that are available from seismic design guidelines. The proposed design methodology is, therefore well suited for practical applications.

The paper is organised into seven main sections. An outline of the adopted analysis methods is presented first, followed by an assessment the effect of influential parameters. The limitations of existing strength reduction and MDOF modification factors are then illustrated. The following sections present the newly proposed strength reduction and MDOF modification factors, which are then used in a novel approach for performance-based seismic design of MDOF SSI systems. Finally, the efficiency of the proposed method is demonstrated through several design examples.

2. Modelling and assumptions

2.1. Soil–structure interaction model

Shear-building models, despite some limitations, have been widely adopted in seismic analyses of multi-storey buildings (e.g. [17,18]) due to their capability of capturing both nonlinear behaviour and higher mode effects without compromising the computational effort, which makes them suitable for large parametric studies. In shear-building models, each floor is idealised as a lumped mass m connected by elastic-perfectly-plastic springs that only experience shear deformations when subjected to lateral forces, as shown in Fig. 1(a). The height-wise distribution of stiffness and strength in shear building models are assumed to follow the same pattern as storey shear forces derived from the design lateral load pattern [17,18]. This implies that the yield displacement (=storey strength/storey stiffness) is considered to be constant at all storey levels. It should be noted that the design parameters to define shear-building models can be obtained based on the results of a single push-over analysis on the fixed-base structure [18]. To accomplish this, a pushover analysis is conducted on the fixed-base frame structure and the relationship between the storey shear force and the total inter-storey drift is extracted. The nonlinear force–displacement relationships are then replaced with an idealised bi-linear relationship to calculate the nominal stiffness, strength, and yield displacement of each storey. The storey ductility can then be calculated as the ratio of maximum inter-storey drift to the storey yield displacement. The ductility demand of the multi-storey building is defined as the maximum of the inter-storey ductility ratios. In this study, the total mass of each building was uniformly distributed along its height, and the height h between floors was assumed to be 3.3 m. Rayleigh damping was applied to the shear-building models with a damping ratio of 5% assigned to the first mode and to the mode at which the cumulative mass participation exceeded 95%.

A discrete-element model was used to simulate the dynamic behaviour of a rigid circular foundation overlying a homogenous soil half-space. This model is based on the idealization of homogeneous soil under a base mat by a semi-infinite truncated cone [19], and its accuracy has been found to be adequate for practical applications compared to more rigorous solutions [20]. The stiffness of the supporting soil was modelled through a sway and rocking cone model (see Fig. 1(b)), whose properties are given by Wolf [21] as follows:

$$k_h = \frac{8\rho V_s^2 r}{2 - \nu}, c_h = \rho V_s \pi r^2 \tag{1}$$

$$k_\theta = \frac{8\rho V_s^2 r^3}{3(1 - \nu)}, c_\theta = \frac{\rho V_p \pi r^4}{4} \tag{2}$$

$$M_\theta = 0.3\left(\nu - \frac{1}{3}\right)\pi\rho r^5, M_\varphi = \frac{9}{128}(1 - \nu)\pi^2 \rho r^5 \left(\frac{V_p}{V_s}\right)^2 \tag{3}$$

where k_h, k_θ and c_h, c_θ are the equivalent stiffness (denoted by k) and radiation damping coefficient (denoted by c) for the horizontal (denoted with subscript h) and rocking (denoted with subscript θ) motions, respectively. The homogeneous soil half-pace beneath the circular surface foundation with a radius r is defined by its mass density ρ, Poisson's ratio ν, shear wave velocity V_s and dilatational wave velocity V_p. For simplicity, each floor of the superstructure was assumed to have an equivalent radius r, so that the centroidal moment of inertia of each floor and the foundation are, respectively, $J = 0.25mr^2$ and $J_f = 0.25m_f r^2$, where m_f is the mass of the foundation, which was set to ten percent of the total mass of the superstructure.

An additional rotational degree of freedom φ, with its own mass moment of inertia M_φ, is introduced so that the convolution integral embedded in the foundation moment–rotation relation can be satisfied in the time domain [21]. It should be noted that for nearly incompressible soil (i.e. $1/3 < \nu \leqslant 1/2$), the use of V_p would overestimate the rocking radiation damping. This is remedied by adding a mass moment of inertia M_θ to the rocking degree of freedom and replacing V_p by $2V_s$ [21]. The material damping of the soil half-space is also modelled by augmenting each of the springs and dashpots with an additional dashpot and mass, respectively [22]. In this study, the soil material damping ratio $\xi_g = 5\%$ was specified at the lowest Eigen-frequency ω_0 of an SSI system, which can be calculated iteratively according to Veletsos and Nair [23] and Luco