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Estimation of inelastic displacement ratios for soil-structure systems with embedded foundation considering kinematic and inertial interaction effects

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ABSTRACT

In this research, the simultaneous effects of soil-structure interaction (SSI) and nonlinear behavior of the superstructure on inelastic displacement ratios of soil-structure systems with embedded foundation are parametrically investigated. Results involving both kinematic interaction (KI), including rocking foundation input motion (RFIM), and inertial interaction effects are considered and discussed. The effect of KI on the inelastic displacement ratios is investigated with special focus on the role of rocking foundation input motion. The soil-structure system is modeled by sub-structure method. The foundation is modeled as a rigid cylinder embedded in the soil with different embedment ratios. A large number of soil-structure systems with embedded foundation having various dynamics characteristics and SSI key interacting parameters have been analyzed under an ensemble of 19 earthquake ground motions recorded on alluvium deposits. Results reveal that using the inelastic displacement ratios of fixed-base systems leads to an underestimation of the peak inelastic demands for soil-structure systems. The phenomenon is less intensified as foundation embedment increases. Moreover, the effects of rocking foundation input motion due to KI on inelastic displacement demands are significant for deeply embedded foundation when the SSI effect is predominant. For practical purpose, a simplified expression for estimating inelastic displacement ratios of soil-structure systems with embedded foundation considering KI effects is proposed.

1. Introduction

It is known that the response of a structure to strong ground motions is affected by the soil beneath it. The effect is generally controlled by the structure, the foundation, and the soil surrounding the foundation through dynamics soil-structures interaction (SSI) phenomenon. This phenomenon has two main consequences: (a) kinematic interaction (KI), and (b) inertial interaction (II). In technical literature, the difference between the free-filed motions (FFM) and the motions which is experienced by the foundation is known as kinematic interaction. The deviation of the foundation input motion (FIM) from FFM happens because of the difference between the stiffness of the foundation and the surrounding soil. While the FFM is purely horizontal, the FIM consists not only of the translational component but also of a rotation [1]. Inertial interaction is introduced as the effect of soil flexibility on the structural response subjected to FIM. In contrast to KI effect, since these effects are sourced to structural inertia, they are referred to as inertial interaction effects. Based on the studies conducted in the early 1970s, the inertial interaction effects on elastic systems could be divided into two parts [2,3]. First, period of soil-structure system is greater than the fixed one and second, considering SSI increases the effective damping ratio of the soil-structure system due to radiation and inherent damping of soil beneath the structure. Numerous researches have been conducted to investigate the effects of inertial interaction on elastic response of structures, which, as described by several seismic codes, led to presenting an equivalent fixed-base system with effective fundamental period and damping ratio to include inertial interaction effects [4,5]. Bielak [6] evaluated the dynamic behavior of elastic soil-structure systems with embedded foundation. He showed that the natural frequency and damping in SSI systems increase with embedding. An investigation carried out by Luco et al. [7] on the elastic response evaluation of rigid embedded foundation subjected to several strong ground motions revealed that rocking component of FIM could play an important role in seismic response of structures with embedded foundation. Kausel et al. [8] proposed approximate procedures for the soil-structure interaction problems with embedded foundation, and the results were then verified with exact solution (i.e., full finite element analysis). Aviles and Perez-Rocha [9] performed an investigation on

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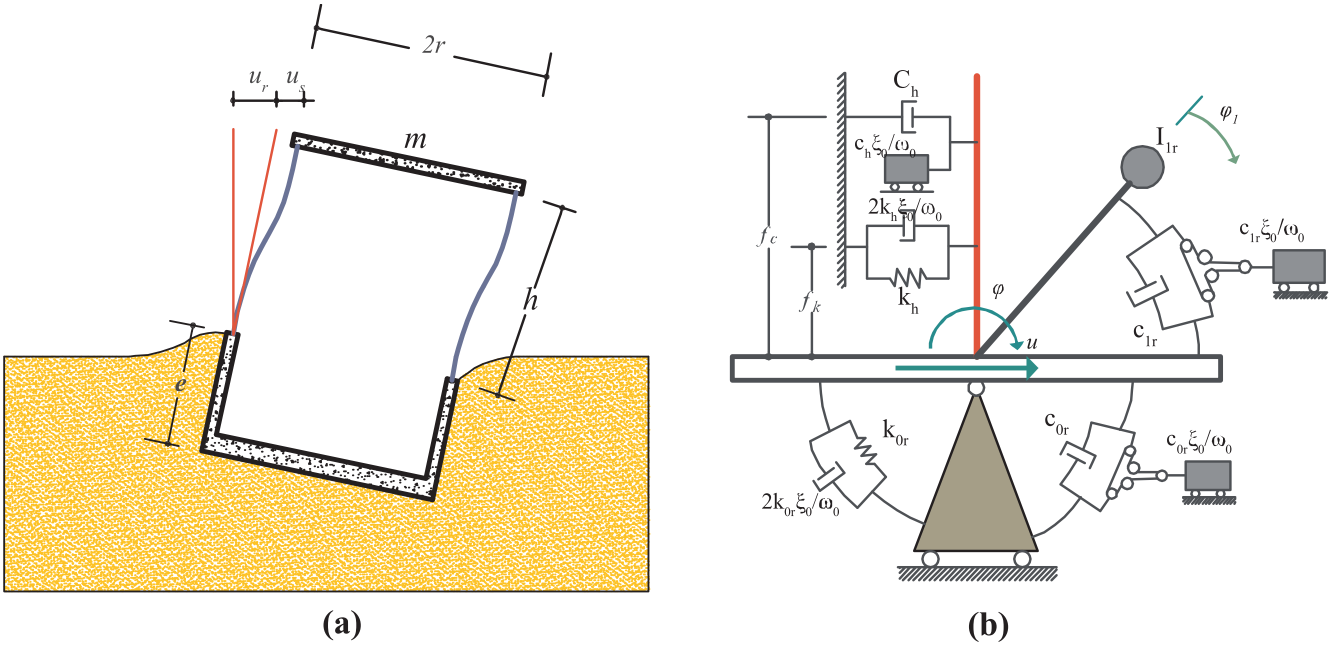

Fig. 1. (a) The soil-structure system; (b) the discrete model for embedded foundation.

structural properties, i.e., effective period and damping, and seismic response of soil-structure systems with embedded foundation. They concluded that the kinematic interaction reduces the maximum response of short-period squat structures. Also, the effects of kinematic interaction on seismic response of structures with embedded foundation were studied by Jahankhah et al. [10]. It was concluded that ignoring the effects of rocking input motion can underestimate the response of slender structures with deep embedded foundation.

In all the aforementioned studies, the results were obtained from numerical analyses based on elastic response of structures. Avilés and Pérez-Rocha [11] investigated the effects of SSI on nonlinear structures. The results, which were obtained only based on SCT record of the 1985 Mexico City earthquake, showed that the kinematic interaction effects are not significant. Most of the conventional seismic codes such as FEMA 440 [5], ASCE 41-13 [12] and NEHRP-2015 [13] just consider the reduction effect of kinematic interaction and neglect the rocking component of FIM due to kinematic interaction. More recently, however, the study carried out by Mahsuli and Ghannad [14] on the effects of SSI on ductility demand of SSI systems with embedded foundation demonstrated that the rocking component of FIM due to kinematic interaction could have remarkable influence. Although, they considered the effect of nonlinearity of the superstructures, all the analyses were performed based on Poisson's ratio equal to 0.25. It is known that for soft soil profile in which SSI effects can be more prominent, the values of Poisson's ratio are observed larger, up to 0.5, which can affect the response of SSI systems. A new lumped mass parameter model incorporating SSI was developed by Ogut et al. [15], based on the results of the thin layer method for embedded foundations located on homogeneous elastic half-space with soil Poisson's ratio of 0.42. They showed that by increasing ductility factor values, the effect of rocking component of FIM becomes more important especially for the case of high-rise buildings with deep embedment ratios. However, they only used two earthquake ground motions in their nonlinear dynamic analyses.

Performance-based seismic design (PBSD) has developed significantly in the past twenty years. As a part of PBSD, estimation of inelastic displacement plays a key role. Some recommendations for evaluation and rehabilitation of existing structures, i.e. FEMA 356 [16], introduced an analysis procedure to compute the target inelastic displacement using equivalent inelastic single-degree-of-freedom (SDOF) system. In this method, the target inelastic displacement can be approximated by modifying the maximum elastic displacement demand. As a known modification approach, FEMA 356 [16] introduced inelastic displacement ratio for estimating the target displacement. Inelastic displacement ratio is defined as the ratio of the maximum displacement of an inelastic SDOF system to the maximum elastic displacement of the SDOF system with the same period and damping ratio. The effects of SSI with shallow foundation on inelastic response of structures were studied by several researches [17–25]. Furthermore, inelastic displacement ratios of soil-structure systems with shallow foundation were investigated and some expressions were proposed to estimate the inelastic displacement ratios of soil-structure systems [26,27]. However, the effects of kinematic interaction and also rocking component of FIM on inelastic displacement ratios of SSI systems with embedded foundation have not been studied yet and further investigation is required. In this study therefore, the effects of kinematic interaction on inelastic displacement and inelastic displacement ratios are parametrically investigated with special emphasis on the role of rocking component of FIM. Finally, for practical purpose, trough statistical regression analyses a simplified expression is proposed for estimating the inelastic displacement ratios of SSI systems taking into account for both kinematic and inertial interaction effects. The efficiency and accuracy of the proposed expression are demonstrated trough several statistical indices and by comparing the results obtained from the proposed expression with those of analytical data.

2. Soil structure model

The two dimensional model shown in Fig. 1(a) is employed to represent the soil-structure system with embedded foundation. Superstructure is represented by an SDOF oscillator with mass (m), height (h), and mass moment of inertia I_{str} resting on a soil. The structure is supported by a rigid circular foundation with embedment depth e, mass m_f and mass moment of inertia I_f. The foundation is assumed perfectly bonded to the surrounding soil. There are various methods which can be used to model the soil beneath the structure in SSI problems. In this study, the supporting soil is adopted as a discrete model based on the concept of cone model for embedded foundation [28]. As shown in Fig. 1(b), the supporting soil is substituted with three-degree-of-freedom mass- spring-dashpot system. Two DOFs of u and φ are introduced to represent the sway and rocking motions of foundation,