Computers and Geotechnics 60 (2014) 9–19

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Three dimensional Finite Element modeling of seismic soil–structure interaction in soft soil

Hooman Torabi [*], Mohammad T. Rayhani

Department of Civil and Environmental Engineering, Carleton University, Ottawa, Ontario, Canada

A R T I C L E   I N F O

Article history:
Received 19 August 2013
Received in revised form 21 March 2014
Accepted 24 March 2014
Available online 13 April 2014

Keywords:
Soft soil
Elasto-plastic constitutive model
Soil–foundation–structure interaction
Stiffness ratio
Period elongation
Foundation rocking

A B S T R A C T

Earthquakes in regions underlain by soft clay have amply demonstrated the detrimental effects of soil–structure interaction (SSI) in such settings. This paper describes a new three dimensional Finite Element model utilizing linear elastic single degree of freedom (SDOF) structure and a nonlinear elasto-plastic constitutive model for soil behavior in order to capture the nonlinear foundation–soil coupled response under seismic loadings. Results from an experimental SSI centrifuge test were used to verify the reliability of the numerical model followed by parametric studies to evaluate performance of linear elastic structures underlain by soft saturated clay. The results of parametric study demonstrate that rigid slender (tall) structures are highly susceptible to the SSI effects including alteration of natural frequency, foundation rocking and excessive base shear demand. Structure–foundation stiffness and aspect ratios were found to be crucial parameters controlling coupled foundation–structure performance in flexible-base structures. Furthermore, frequency content of input motion, site response and structure must be taken into account to avoid occurrence of resonance problem.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

The observed damage and subsequent processing of strong ground motion recordings obtained from soft soil deposits during the 1985 Mexico City and 1989 Loma Prieta earthquakes have revealed the significant importance of seismic site response and SSI on the response of affected structures [1]. These data and others from instrumented sites have been used to verify the analytical methods developed for soil–structure interaction (SSI) prediction, and to calibrate numerical methods and soil constitutive models as well. Observation of SSI during field tests and laboratory model tests is difficult, especially for settings with complex geometries. Because of this, robust numerical modeling methods can be useful in SSI identification for engineering design purposes.

SSI can be defined as the mutual effects that the vibrating structure, the foundation and the ground have on each other, causing alterations in the vibrational characteristics of each. Basically, two mechanisms dominate SSI: *Kinematic* and *Inertial interaction*. Earthquake ground motion causes soil displacement in what is known as free field motion. The kinematic interaction effect results from the inability of a stiff foundation in or on the soil to move in the same way as the free field motion of the sediment. The main factors contributing to the kinematic interaction include the foundation embedment, the motion-producing wave inclination and incoherency.

The kinematic interaction effect is usually quantified by a frequency dependent transfer function. This is defined as the ratio of the foundation motion (FIM) to the free field ground motion assuming a massless foundation and structure [2]. Veletsos et al. [2] improved the expression introduced by Luco and Wong [3] and derived a transfer function for a rigid massless rectangular foundation resting on viscoelastic half-space for both the translational and rotational (rocking) components of the foundation motion. The transfer function was obtained in terms of normalized incoherency parameters using a space invariant power spectral density function (PSD) for translational and cross power spectra for rotational motion assuming unidirectional free field ground motion.

Inertial interactions also affect the vibrational characteristics of structures. The inertial force of the vibrating structure produces base shear and moment effects at the foundation level resulting in relative displacement between the foundation and the soil. More importantly, inertial interactions also result in changes in the modal characteristics of the structure including variations in modal frequencies and damping factors. A simplified model has generally been used to investigate the inertial interaction phenomenon in

---

* Corresponding author. Tel.: +1 (613) 292 7661.
E-mail addresses: hooman_torabi@carleton.ca (H. Torabi), mohammad.rayhani@carleton.ca (M.T. Rayhani).

http://dx.doi.org/10.1016/j.compgeo.2014.03.014
0266-352X/© 2014 Elsevier Ltd. All rights reserved.

theoretical and analytical studies [4–8]. This single degree of freedom system consists of frequency dependent translational and rotational springs, representing dynamic stiffness and damping of a flexible foundation–soil system.

Utilizing field test data in conjunction with SSI-identification analytical procedures has provided valuable insights into soil–foundation interaction in terms of impedance functions [9,10], kinematic interaction of soil–foundation based on calibrated models [11] and structure–foundation–soil interaction using the system identification method [12,13]. Moreover, several numerical investigations of SSI phenomena have been carried out taking into account nonlinear soil behavior and employing frequency domain Finite Element [14] and time domain finite difference methods [15].

The purpose of the current study is to develop a 3-D dynamic Finite Element (FE) simulation to capture seismic site response and coupled soil–foundation–structure interaction by taking into account the progressive softening (inelasticity) of soft saturated clay. This was accomplished by implementing an elasto-plastic constitutive model of soil to capture the elasto-plastic foundation–soil coupled response under irregular seismic loadings. Initially, model calibration using centrifuge tests conducted by Rayhani and Elnaggar [16] was carried out, followed by a parametric investigation of SSI. The analytical methods developed for SSI evaluation were used in the parametric study phase to investigate the capability of the soil-structure continuum model in predicting SSI effects. In this study, analyses were performed for linear elastic structures, represented by a single degree of freedom system (SDOF), supported by elastic foundation. The soil profile underlying foundation was assumed to be uniform with constant shear wave velocity to eliminate the effect of soil non-uniformity on SSI.

2. Soil–foundation–structure interaction

Generally, two concepts of “fixed-base” and “flexible-base” building are taken into account in any SSI evaluation process. The latter refers to a building founded on a soil deposit which enables the foundation of the building to vibrate when subjected to dynamic loadings. These conditions alter the vibrational characteristics of a fixed-base foundation compared to buildings founded on a rigid base. Several experimental studies using field test data and recorded strong ground motions and analytical analyses have been conducted on the effects of SSI on the modal response of structures. Two procedures have been recommended for the extraction of modal parameters for flexible-base and fixed-base buildings [12,17]. These approaches, known as “System Identification” methods, are used when recordings of the structure’s roof and foundation motions are available whereas free field ground motion as soil–foundation–structure input is missing. However, in the present study, all the input and output recordings for SSI evaluation are obtained.

Soil–foundation–structure interaction (SFSI) introduces complexities requiring thorough investigation of the contributing parameters. Veletsos and Meek [5] defined several critical parameters controlling the vibrational properties of fixed and flexible-base buildings by assuming a SDOF system resting on a viscoelastic half space soil (Fig. 4a). These dimensionless parameters are expressed in terms of the underlying soil shear wave velocity V_s, soil mass density ρ, structural mass m_s, effective height of the structure h_{eff}, fixed-base period of the structure T_s, and rotational r_θ and translational r_u radius of an equivalent circular foundation, and are as follows:

$$\sigma = \frac{V_s T_s}{h_{eff}} \tag{1}$$

$$\gamma = \frac{m_s}{\rho \pi r_u^2 h_{eff}} \tag{2}$$

$$A = \frac{h_{eff}}{r_u} \tag{3}$$

The above defined parameters are the soil to structure stiffness ratio σ, structure to soil mass ratio γ and the aspect ratio A. When comparing the performance of flexible and fixed-base structures, changes in the modal vibrational parameters are important due to their direct consequences on base shear and foundation motion. Previous studies indicate that in the case of a flexible-base structure, oscillation occurs with a longer natural period ($\widetilde{T}_s$) rather than the fixed-base natural period (T_s), and the damping ratio ($\tilde{\zeta}$) increases compared to the fixed-base ratio (ζ). Base shear and FIM are influenced as a result [4,5,17]. Also, simplified analytical procedures confirm the significant roles of the structure to foundation stiffness ratio and the aspect ratio in period lengthening, and the associated impacts on structural demands [5,6].

Assuming the structure–foundation system to be a 2 DOF system (Fig. 4a) subjected to free field ground motion, the structure and foundation motion can influence the vibrational motions of each. An analytical solution is presented for the coupled equation of motion for this system for which two natural frequencies are obtained. Previous studies have shown that the structure to foundation stiffness ratio is a main contributing factor in structure–foundation interaction in flexible-base structures [5,12,18].

Safak [12] performed parametric analyses based on analytical solutions of coupled equations of motion for 2DOF system (Fig. 4a) assuming that the foundation rocking motion is negligible. It was shown that the fixed-base circular frequency ratio ($\mu = \omega_s/\omega_f$) for the structure and foundation and their mass ratio ($\eta = m_s/m_f$) affect the deviation in the natural frequency of the coupled system compared to the fixed-base system (period lengthening). The structure-foundation stiffness ratio can be expressed in terms of these parameters using equations of natural circular frequencies; $k_s = m_s.\omega_s^2$ and $k_f = m_f.\omega_f^2$ as follows:

$$r_K = \frac{k_s}{k_f} = \frac{m_s \cdot \omega_s^2}{m_f \cdot \omega_f^2} = \eta\mu^2 \tag{4}$$

where k_s and k_f are the stiffness of the structure and foundation, respectively. In addition to Eq. (4), the impedance function of the foundation ($\overline{K}$) is a complex valued function controlling the force–displacement relationship between the foundation and the surrounding soil. This function consists of dynamic stiffness as the real part and the frequency dependent imaginary part as damping [8]:

$$\overline{K} = k_f + i\omega c \tag{5}$$

In Eq. (5), c is the damping coefficient including both radiation damping between the soil and the foundation and the hysteretic damping of the soil as well. The real part, k_f is the frequency dependent translational stiffness or the real part of the impedance function of a circular foundation resting on viscoelastic soil half space. It is expressed by Veletsos and Meek [5] as follows:

$$k_f = \alpha_u k_u \tag{6}$$

$$k_u = \frac{8}{2-v} G r_u \tag{7}$$

where α_u and k_u are the frequency dependency coefficient accounting for embedment effect and the foundation static stiffness respectively. v and G are the Poisson ratio and the shear modulus of the underlying soil. Substituting the equation $\omega_s = 2\pi/T_s$ and Eqs. 6 and 7 in Eq. (4) the relative stiffness is reformulated as follows:

$$r_k = \frac{m_s(2\pi/T_s)^2}{\alpha_u(8Gr_u/(2-v))} \tag{8}$$

Employing classic shear modulus equation ($G = \rho v_s^2$) and rearranging parameters in Eq. (8), the stiffness ratio equation can be expressed as:

Download English Version:

https://daneshyari.com/en/article/254630

Download Persian Version:

https://daneshyari.com/article/254630

Daneshyari.com