Earthquakes and Structures, *Vol. 12, No. 2 (2017) 153-163*
DOI: https://doi.org/10.12989/eas.2017.12.2.153

Soil and structure uncertainty effects on the Soil Foundation Structure dynamic response

Mohamed Elhebib Guellil*, Zamila Harichane[a], Hakima Djilali Berkane[b] and Amina Sadouki[c]

Geomaterials Laboratory, Civil Engineering Department, Hassiba Benbouali University of Chlef, P.O Box 151, Chlef 02000, Algeria

(Received June 29, 2016, Revised November 9, 2016, Accepted November 29, 2016)

Abstract. The underlying goal of the present paper is to investigate soil and structural uncertainties on impedance functions and structural response of soil-shallow foundation-structure (SSFS) system using Monte Carlo simulations. The impedance functions of a rigid massless circular foundation resting on the surface of a random soil layer underlain by a homogeneous half-space are obtained using 1-D wave propagation in cones with reflection and refraction occurring at the layer-basement interface and free surface. Firstly, two distribution functions (lognormal and gamma) were used to generate random numbers of soil parameters (layer's thickness and shear wave velocity) for both horizontal and rocking modes of vibration with coefficients of variation ranging between 5 and 20%, for each distribution and each parameter. Secondly, the influence of uncertainties of soil parameters (layer's thickness, and shear wave velocity), as well as structural parameters (height of the superstructure, and radius of the foundation) on the response of the coupled system using lognormal distribution was investigated. This study illustrated that uncertainties on soil and structure properties, especially shear wave velocity and thickness of the layer, height of the structure and the foundation radius significantly affect the impedance functions, and in same time the response of the coupled system.

Keywords: impedance function; circular foundation; cone model; Monte Carlo simulations

1. Introduction

Soil-structure interaction (SSI) effect plays important roles on the seismic behaviour of structures. Many approaches may be considered to deal with SSI analysis problems (Yazdchin *et al*. 1999, Liou and Chung 2009, Menglin *et al*. 2011). Various studies have been conducted on the effect of SSI, highlighting its important role in the analysis of structure (Jayalekshmi *et al*. 2014, Aydemir and Aydemir 2016). In the linear seismic buildings design, the most commonly used method for dynamic SSI analysis is the substructure method, which is customary and efficient approach (Cottereau *et al*. 2008). The key step in the method is the calculation of the interaction force displacement relationship (dynamic stiffness) on the basemat-soil interface (Zhang and Wolf 1998, Celebi *et al*. 2006). The calculation of the impedance functions of a foundation is a major issue in geotechnical engineering. An important concept to evaluate the dynamic response of foundation is the impedance function which provides valuable means to couple the two mutually interacting subdomains, the unbounded soil domain and the structure (Pitilakis 2006). These impedance functions are defined as the complex dynamic stiffness-flexibility coefficients at the interface points of the soil-foundation system (Celebi *et al*. 2006, Pena and Guzman 2014). The foundation impedance approach has received great impetus in past decades. This approach is presented by Gazetas (1983). Gazetas (1991) examined many experimental studies and compared the results with analytical methods. Kausel (2010) listed all these studies in a state of the art paper.

The foundation impedance functions represent the dynamic stiffness of the soil medium surrounding the foundation (Safak 2006). However, large errors might appear during the identification of the parameters of the soil model, and these parametric errors may in turn lead to large drifts in the overall design (Cottereau *et al*. 2008). The uncertainties in the spatial domain can include constant characteristic of materials, such as elastic modulus, Poisson's ratio and so on, and the geometrical ones, such as thickness. It is obvious that the behavior of systems is affected by the uncertainties in system parameters, and the degree of influence can only be assessed in a probabilistic context. The stochastic analysis of systems with uncertain parameters, whether it is analytical or numerical, has attracted considerable interests in the past several decades (Hryniewicz 2000, Hyuk Chun 2005, Raychowdhury and Jindal 2014). Three primary sources of geotechnical uncertainties are known namely: (i) inherent variability; (ii) measurement error; and (iii) transformation error (Nobahar 2003, Maheshwari 2011). Recently, other researchers (Maheshwari and Kashyap 2011, Huber 2013, Pradeep Kumar and Maheshwari 2013) have carried out similar

*Corresponding author, Assistant Professor
E-mail: mghebib@yahoo.fr
[a]Professor
E-mail: z_harichane@yahoo.fr
[b]Ph.D. Student
E-mail: dbhakima@yahoo.fr
[c]Assistant Professor
E-mail: amina_sadouki@yahoo.fr

ISSN: 2092-7614 (Print), 2092-7622 (Online)

investigation. For structural analysis with significant soil-foundation-structure-interaction (SFSI) effects, geotechnical uncertainties may play crucial role in the overall system response variability and consequently it is extremely important to identify and characterize the relevant parameters (Raychowdhury and Jindal 2014). Stochastic approaches provide a mean to take into account the soil model and parametric errors in the design of the building. For this reason, the variability of soil properties should be taken into account in the analysis and design of the soil structure systems, in order to ensure reliable and economic design.

On other hand, simplified methods continue to play an important role in soil dynamics and geotechnical engineering (Dobry 2014). Over the years, various methods have been accomplished for soil-foundation-structure interaction analysis (Dasgupta 2008, Salcher and Adam 2015). These methods can be classified as: (a) analytical, which usually refer to simple foundation geometries laying on elastic half-space, (b) semi-analytical, that combine analytical formulations for the half-space with numerical procedures, and (c) simplified discrete models, which allow fast calculation of the foundation-soil-structure system properties. More details on the subject can be found in various sources (Maravas *et al*. 2014, Anastasopoulos and Kontoroupi 2014). The substructuring techniques are helpful in developing simplified models. The purpose of the simplified models is to reduce computational and data management efforts and can provide an improved visualization tool for the engineer. Wolf (1994) proposed a simple cone model, which cannot only give the soil impedance but also can model the soil response.

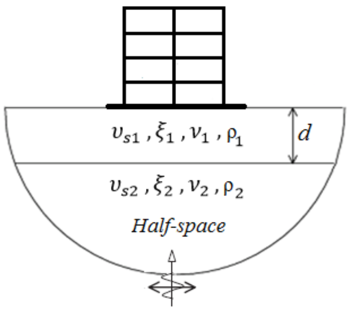
Dynamic SSI may include several complex effects and the beneficial or detrimental effect of seismic SSI is still a controversial issue (Renzy *et al*. 2013). The main effects of seismic SSI on buildings with shallow foundations consist of period lengthening and damping increase of the soil-structure system as established in major design codes (FEMA 440, ATC-3-06). In such provisions, it is concluded that SFSI consideration in the dynamics analysis has a beneficial effect translated by a reduction in the seismic response of structures. Likewise, it has been also recognized that SSI effects may be detrimental and increase the structural response as compared to a fixed base model (Gazetas and Mylonakis 1998). On other and, it has been shown that uncertainties incorporated into structural and geotechnical properties play an important role in predicting the performance of seismically excited structures (Mehanny and Ayoub 2008). For these reasons, the evaluation of SFSI effects on structural response needs to consider the combined impact of the uncertainty in soil and structural parameters.

The main objective of the present paper is to investigate the influence of the soil-foundation-structure uncertainty on the SSFS system response. For this purpose, a FORTRAN program based on the analytic solution is developed. Firstly, a probabilistic analysis based on Monte Carlo simulations have been generated, in order to assess the effect of soil properties' randomness, such as layer's thickness and shear wave velocity on the impedance functions. Then, uncertainties about the height of the structure as well as foundation radius are taken into account and their effects on structural response are investigated.

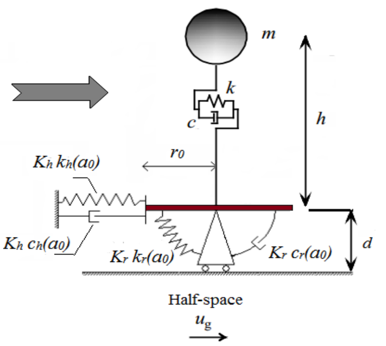
2. Dynamic soil-shallow foundation-structure model

The used SSFS model may be an idealization of multistory building (Stewart *et al.* 1999) resting on a random homogeneous layer underlain a deterministic homogeneous half-space (Fig. 1). The coupled system is excited by vertically incident SH wave; so only inertial interaction part has to be analyzed. The latter is examined for horizontally ground motion with amplitude u^g of frequency ω.

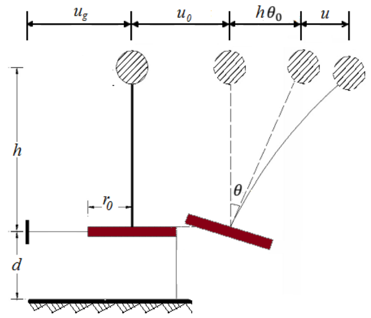
The governing parameters of the layer, i.e. thickness and shear wave velocity are modelled as random variables. The mass density is determinist because it doesn't exhibit randomness (Sadouki *et al*. 2012). The coupled system vibrates in horizontal and rocking directions because the effects of these motions are more important than the vertical



(a) Soi-structure interaction system



(b) Equivalent single degree of freedom (SDOF)



(c) Model's degrees of freedom

Fig. 1 Coupled dynamic SSFS system for horizontal earthquake and torsional ones (Durmus and Livaoglu 2015). The interaction force-displacement and interaction moment-rotation for the system (Fig. 1) which include ground damping (ξ) effects of the foundations-soil system are formulated as (Wolf 1994)

$$P_0(\omega) = K.k_{\xi g}(a_0).u_0(\omega) + \frac{r_0}{\upsilon_0} K.c_{\xi g}(a_0).\dot{u}_0.(\omega) = S(a_0).u_0(\omega) \quad (1)$$

$$M_0(\omega) = K_\theta.k_{\theta\xi g}(a_0).\theta_0(\omega) + \frac{r_0}{\upsilon_0} K_\theta.c_{\theta\xi g}(a_0).\dot{\theta}_0(\omega) = S_\theta(a_0).\theta_0(\omega) \quad (2)$$

For fixed base, the structure is modelled with a mass m, a lateral stiffness with spring coefficient k, a damper with coefficient c, and effective height h connected to a shallow foundation with radius r_0. The effective values m, k and c are associated with the fundamental mode of vibration of the structure. The fixed base frequency of the structure is denoted as ω_S and the hysteretic damping ξ ($\omega_S^2=k/m$, $c=2k\xi/\omega$). Dimensionless parameters are introduced, because the response of the dynamic system will depend on the properties of the structure compared to those of the soil. These dimensionless parameters are introduced (Wolf 1994): the ratio of the stiffness of the structure to that of the soil ($\bar{s}$), the slenderness ratio ($\bar{h}$), the mass ratio ($\bar{m}$), and the depth to radius ratio ($\bar{d}$) such as

$$\bar{s} = \frac{\omega_s h}{\upsilon_s} \quad ; \quad \bar{h} = \frac{h}{r_0} \quad ; \quad \bar{m} = \frac{m}{\rho r_0^{\,3}} \quad ; \quad \bar{d} = \frac{d}{r_0}; \quad (3)$$

The total displacement of the system (u^t) and that of the basmati (u_0^t) (Fig. 1(c)) are, respectively

$$u^t = u^g + u_0 + h\theta_0 + u$$

$$u_0^{\,t} = u^g + u_0$$

where u_0 is the horizontal displacement of the foundation, $h\theta_0$ the rocking displacement due to the rotation of the foundation, and u the structural distortion. The equation of motion of the coupled system is (Wolf 1994)

$$\begin{bmatrix} \frac{\omega_s^2}{\omega^2}(1+2i\xi)-1 & -1 & -1 \\ -1 & \frac{S_{\xi_g}(a_0)}{m\omega^2}-1 & -1 \\ -1 & -1 & \frac{S_{\theta\xi_g}(a_0)}{mh^2\omega^2}-1 \end{bmatrix} \begin{Bmatrix} u(\omega) \\ u_0(\omega) \\ h\theta_0(\omega) \end{Bmatrix} = \begin{Bmatrix} 1 \\ 1 \\ 1 \end{Bmatrix} u^g(\omega) \quad (4)$$

In Eq. (4), $S_{\xi g}(a_0)$ and $S_{\theta\xi g}(a_0)$ are horizontal and rocking components of the impedance functions, respectively.

3. Deterministic impedance functions

3.1 The adopted cone model

The general form of the foundation impedance function can be described by the following equation

$$K(\omega) = K[k(\omega) + i\omega.c(\omega)] \quad (5)$$

where K is the static component of the soil stiffness. The horizontal or rotational components $k(\omega)$ and $c(\omega)$, are the frequency-dependent stiffness and damping factors, respectively. The real part of the impedance function $k(\omega)$, denoted dynamic stiffness, reflects the stiffness and inertia of the supporting soil, and its dependency on frequency is solely attributed to the influence of frequency on inertia (Gazetas 1983). While, imaginary part $\omega c(\omega)$ represents the energy dissipation in the system generated as a result of the wave propagation away from the foundation (radiation damping) (Celebi *et al*. 2006). Here, the impedance functions are obtained based on the cone model approach (Meek and Wolf 1992a, b, Wolf 1994). The cone model consists in replacing the soil deposit, for each degree of freedom of the foundation, by a truncated semi-infinite elastic cone with the apex located at a height z_0 from the ground surface as depicted in Fig. 2. The last one shows the translational cones that are used to compute the horizontal dynamic responses of a shallow foundation. In similar way, we can outline cone model to compute the rocking dynamic response.

Cone model is simple one-dimensional model for foundation vibration analysis. Most of the published results using cone model are confined to the determination of the dynamic response of the foundation in the form of impedance functions. Pradhan *et al*. (2004) compared such results with rigorous elastodynamic solutions based on finite element or boundary element methods. Moreover, Pradhan *et al*. (2008) presented an experimental validation of an analytical solution based on cone model for machine foundation vibration analysis on layered soil. In the cone model, the dynamic soil-foundation system can be represented approximately by a massless rigid disk resting on a soil medium where the force transmits in the cone. The soil medium below the disk is modelled as a truncated semi-infinite bar with its area varying as in a cone with the same material properties as the half space. Therefore, in this model, properties of the cone segment section increase in the direction of wave propagation.

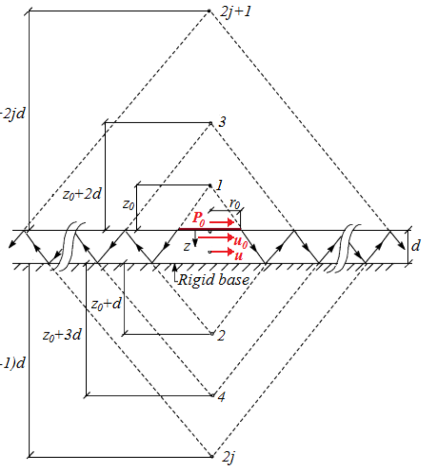


Fig. 2 Horizontally loaded disk on a homogeneous layer underlain a homogeneous half-space: truncated semi-infinite cone for horizontal motions with wave pattern generated by reflection and refraction

3.2 Impedance functions

The coupled system show in Fig. 1 is subjected to horizontal earthquake. So, the foundation's degrees of freedom consist of the horizontal displacement with amplitude $u_0(\omega)$ and rocking with amplitude $\theta_0(\omega)$. Then, to study the dynamic response of a foundation resting on the surface of a soil layer underlain by a half-space, a rigid massless foundation of radius r_0 is addressed for horizontal motions (Fig. 1(a)). The layer with depth d has a shear wave velocity υ_{S1}, Poisson's ratio ν_1, mass density ρ_1, and hysteretic damping ratio ξ_1. The corresponding parameters of the half-space are υ_{S2}, ν_2, ρ_2, ξ_2. The interaction force and moment, P_0 and M_0, respectively, and the corresponding displacement and rotation, u_0 and θ_0, are assumed to be harmonic. The dynamic response of the foundation, for both horizontal and rocking motions, can be expressed by the impedance function (Eq. (5)) which can be rewritten in term of the dimensionless frequency ($a_0=\omega r_0/\upsilon_s$)

$$K(a_0) = K\left[k(a_0) + ia_0.c(a_0)\right] \tag{6}$$

the static stiffness K, for horizontal motion (K_h) and rocking motion (K_r) are as follow

$$K_h = \frac{8G_1 r_0}{2-\nu_1}, \qquad K_r = \frac{8G_1 {r_0}^3}{3(1-\nu_1)} \tag{7}$$

where G_1 ($=\upsilon_{S1}{}^2.\rho_1$) is the shear modulus of the soil layer. The horizontal undamped dynamic stiffness $k(a_0)$ and damping coefficients $c(a_0)$, and rocking ones $k_\theta(a_0)$ and $c_\theta(a_0)$ of the rigid foundation can be calculated by direct application of the correspondence principle (Wolf 1994) to Eqs. (I-a) and (II-a), respectively, in the appendix.

4. Stochastic approach

4.1 Selection of uncertain soil parameters

Quantification of uncertainties is usually done within the framework of probability theory where random soil parameters are modelled as random variables or random fields depending on space and time, in the concept of stochastic soil dynamics (Sadouki *et al*. 2012). The spatial variation of soil properties are modelled using the mathematics of random processes not because soil properties are random, but because our information about those properties is limited (Baecher and Christian 2003). Various probability distributions for soil properties have fitted by many researches where it was stated that each soil property can follow different probability distributions for various materials and sites (Nobahar 2003). The better known and most common analytical distribution functions that play a central role in statistical theory and data analysis are the normal, lognormal, exponential, and Gamma (Baecher and Christian 2003). On other hand, soil properties which greatly depend on the type of soil deposition conditions and loading history may be derived from a common set of in situ or laboratory test data. For this reason, the estimation of ranges of variability of random fields of soil properties at different scales has received wide attention. For example but not limited to, Phoon and Kulhawy (1999) found the range between about 5% to 45% for field and 5% to 40% for laboratory tests. This may imply positive or negative correlation among these parameter estimates, which is purely due to numerical processing of the test data. Correlation should be taken into account in stochastic field model.

In order to reveal the important effects of parameters uncertainty, two main parameters (thickness of layer d and shear-wave velocity υ_{S1} are considered as dependent or independent random variables according to a given distribution function with mean value and variance.

4.2 Selection of uncertain structural parameters

Among the structural parameters that may influence the response of the coupled system shown in Fig. 1, we select the effective height of the structure, and the foundation radius, as random variables. The range of variation of the height may be defined based on a typical period-height relationship as stated by Moghaddasi *et al.* (2009) where uniform distribution with ranges of variation for height and radius about 35% is used. The foundation radius is obtained from the slender ration which varies from 1 to 4 for ordinary (residential/commercial) structures.

5. Methodology for Monte Carlo simulations

In order to consider system uncertainties, various approaches such as Monte Carlo simulations, moment equation approach, and stochastic finite-element method have been developed. However, Monte Carlo simulation is the most common approach, in which a deterministic problem is solved many times using a large number of simulated random variables and statistical properties of responses (Manolis 2002, Lee *et al*. 2013, Laudarin *et al*. 2013). In other words, Monte Carlo simulation is useful for obtaining numerical solutions for complicated problems especially when the number of variables is large or variables are correlated. Soesilo (1997) stated that randomness of many soil parameters tends to follow classical statistical distributions (normal and lognormal). Jones et al. (2002) reviewed the statistical parameters and the most commonly used probability distributions (uniform, normal, lognormal, Gamma, and exponential) to estimate uncertainty in geotechnical properties for performance-based earthquake engineering. Popescu *et al*. (2005) investigated the three-dimensional effects in seismic liquefaction analysis of stochastically heterogeneous soils using the beta, gamma and lognormal distributions by means of Monte-Carlo simulations. They showed that the coefficient of variation (Cv) and the marginal probability distribution of the soil's shear strength are the two most important parameters in reducing the bearing capacity. Jimenez and Sitar (2009) investigated the influence of different types of statistical distributions (lognormal, gamma, and beta) to characterize the variability of Young's modulus of soils in random finite element analyses of shallow foundation settlement. Moghaddasi *et al*. (2011) used uniform distribution for the randomly soil and structure selected parameters to investigate the effects of SFSI on seismic response of structures through a Monte Carlo simulation.

In the present study, two distributions functions with mean and variance are used to generate random draws of each soil and structural parameters: lognormal and gamma distributions. Then, a mathematical expectation of the defined function (impedance function, structural response …) is computed. For example, the expected value of the impedance function, for each dimensionless frequency a_0, is calculated as (Tanizaki 2004, Scherer 2005)

$$E(K(a_{\grave{a}},X,Y)=\int_{d}\int_{\upsilon_{s1}} K(a_0,d,\upsilon_{s1}).f_{d\upsilon_1}(d,\upsilon_{s1}).d(d).d(\upsilon_{s1}) \quad (8)$$

for stochastically correlated random variables. X, Y are the random variables of the layer's thickness and shear wave velocity, respectively. $f_{dv_{s1}}(d,v_{s1})$ represents the joint density function of X and Y. If the random variables are stochastically uncorrelated, the joint density function becomes

$$f_{d\upsilon_{s1}}(d,\upsilon_{s1})=f_d(d).f_{\upsilon_{s1}}(\upsilon_{s1}) \quad (9)$$

where $f_d(d), f_{\upsilon_{s1}}(\upsilon_{s1})$ are the marginal density functions of X and Y. The expected value of the impedance function is estimated from a sum with Monte Carlo approach to numerical quadrature where the abscissas are chosen randomly according to the probability density function (PDF) $f(x)$. x may be one of the soil parameters. Explicitly, the straightforward Monte Carlo quadrature scheme proceeds as follows (Dunn and Shultis 2012):

- generate N values x_i of the random variable x from the PDF $f(x)$;
- define the quadrature abscissas as the sampled values x_i; and;
- form the arithmetic average of the corresponding values of $K(a_0,x_i)$, i.e.

$$\overline{K(a_0,d,\upsilon_{s1})}\equiv\frac{1}{N}.\sum_{i=1}^{N}K(a_0,d,\upsilon_{s1}) \quad (10)$$

x_i are the N generated values of the random variable parameter x, or quadrature abscissa.

In the present study, firstly, 1 million random draws are generated for each one of the two main soil parameters (layer's thickness and shear wave velocity) according to each kind of the two distribution functions, for horizontal and rocking component of the impedance functions. Secondly, 1 000 000 random draws are generated for each of the two main soil parameters and the two main structural parameters (height of the superstructure, and the foundation radius), according to the lognormal distribution. In total, 12 million scenarios are generated to study the effects of randomness of soil and structure parameters on the foundation and superstructure responses.

6. Numerical results

6.1 Stochastic investigation on impedance functions

6.1.1 Influence of random variation of each soil parameter

In the present stochastic modelling of dynamic SSI, we firstly study the influence of randomly varying soil properties on the impedance functions of a circular foundation (Fig. 1(a)). The mean values of soil parameters given in Fig. 1(a) are selected such as the ratios d/r_0=1, G_1/G_2=0.544, ρ_1/ρ_2=0.85. The Poisson's ratio is $\nu_1=\nu_2$=0.25, and the damping ratio $\xi_1=\xi_2$=0.05. These data which result in an impedance ration $(\rho_1\ \upsilon_{S1})/(\rho_2\ \upsilon_{S2})$=0.68 correspond to more common case of more flexible and less denser layer than the half-space (rock) (Wolf 1994). Without losing generality, coefficients of variation (Cv) for each soil parameters is assumed in range of 5% to 20%. 0 % coefficient of variation corresponds to the deterministic case.

Figs. 3 to 4 show the influence of random variations of layer's thickness and shear wave velocity on mean values of the impedance functions for the horizontal motion for the given distribution functions, and Figs. 5 to 6 show the influence of the randomness of the same parameters on the same functions for the rocking motion.

From figs. 3-6, we observe that the increasing coefficient of variation of soil properties leads to smaller spring and damping coefficients for all the two-distribution functions (Figs. 3 to 4 and 5 to 6) and there is no significant difference between mean values of these coefficients obtained by the two different distribution functions. Similar finding was obtained by Ahmed and Rupani (1999) when studying, deterministically, the variation of shear wave velocity on horizontal impedance of square foundation, and they attributed the decrease in spring coefficient to the increase of velocity value. It should be noted that these observations are valid for the present applications and for

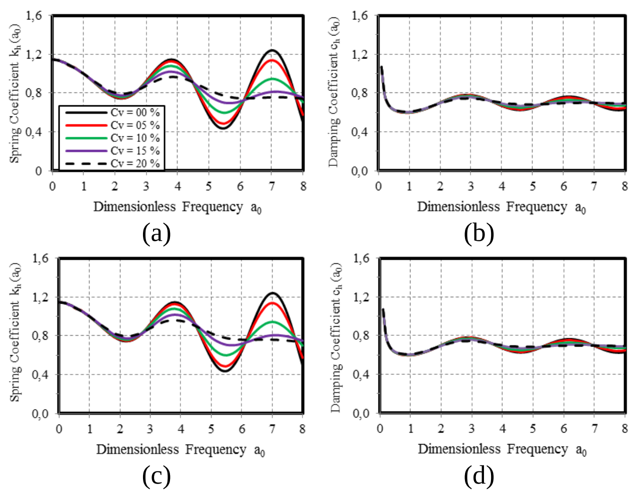


Fig. 3 Expected impedance functions for the circular foundation in horizontal motion for various Cv of layer's thickness distributed: (a) - (b) lognormally, (c) - (d) gamma

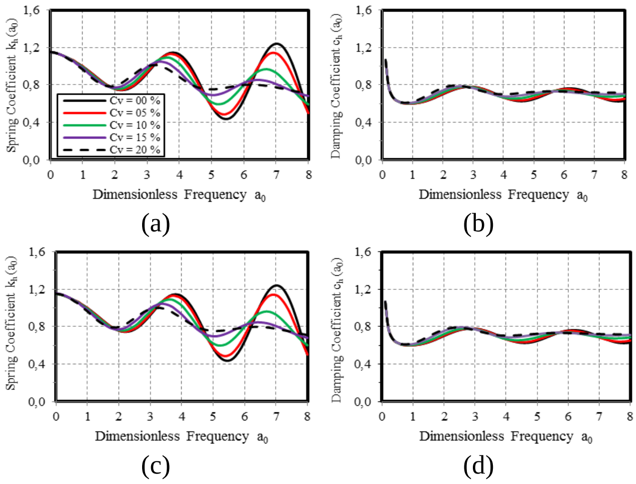


Fig. 4 Expected impedance functions for the circular foundation in horizontal motion for various Cv of shear wave velocity distributed: (a) - (b) lognormally, (c) - (d) gamma

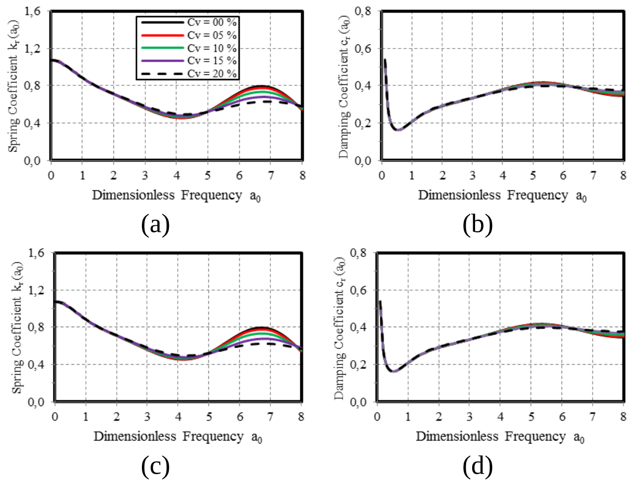


Fig. 5 Expected impedance functions for the circular foundation in rocking motion for various Cv of layer's thickness distributed: (a) - (b) lognormally, (c) - (d) gamma

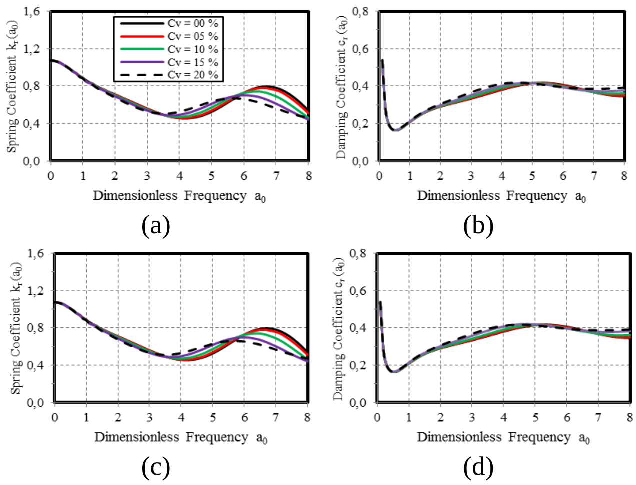


Fig. 6 Expected impedance functions for the circular foundation in rocking motion for various Cv of shear wave velocity distributed: (a) - (b) lognormally, (c) - (d) gamma

relatively small coefficient of variation. Further observations need more applications varying foundation shape and depth, as well as larger coefficient of variation.

6.1.2 Influence of random variation of all soil parameters

The previous investigations concerned the effect of each soil parameter on the impedance functions assuming only one soil parameter, namely either layer's thickness and shear wave velocity, as random, while the others parameters are assumed to be deterministic in the computation.

In this section, the influence of randomly varying soil properties on the impedance functions is studied assuming a stochastic homogeneous media, where all governing parameters, i.e., layer's thickness and shear wave velocity are modelled as random variables. Firstly, the random variables are assumed uncorrelated, and all follow, successively, lognormal distribution and gamma distribution. Then, the parameters are assumed correlated and all follow only lognormal distribution.

So, Figs. 7 and 8 depict the influence of theses fluctuations on the impedance functions for coefficients of variation for all independent parameters ranging between 0 and 20%, for the two used distribution functions, for horizontal and rocking motions, respectively. The results of the present multivariate case are somewhat different from those of the previous univariate case. A remarkable decrease in the mean stiffness coefficient amplitudes is observed when fluctuation sizes increase, for both horizontal and rocking modes of vibration and for the two used distribution functions.

Secondly, to show if the random parameters are correlated, the effects of random fluctuations on the same quantities as done in the previous application, by assuming layer's thickness and shear wave velocity are random fields, are investigated. Therefore, Fig. 9 shows the influence of theses fluctuations on the impedance functions for

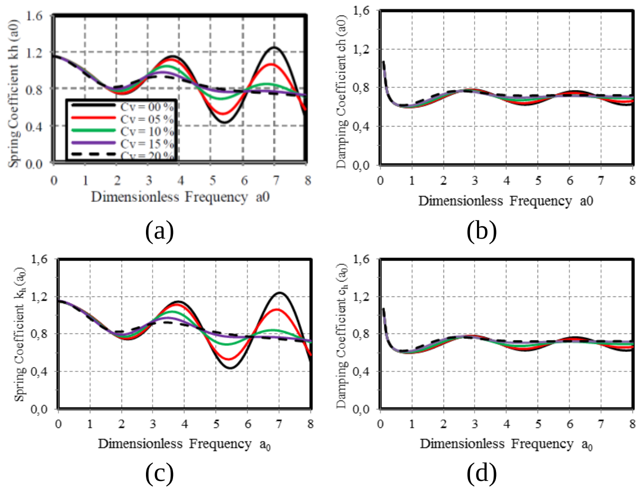


Fig. 7 Expected impedance functions for the circular foundation in horizontal motion for various Cv of layer's thickness and shear wave velocity, distributed: (a) - (b) lognormally, (c) - (d) gamma

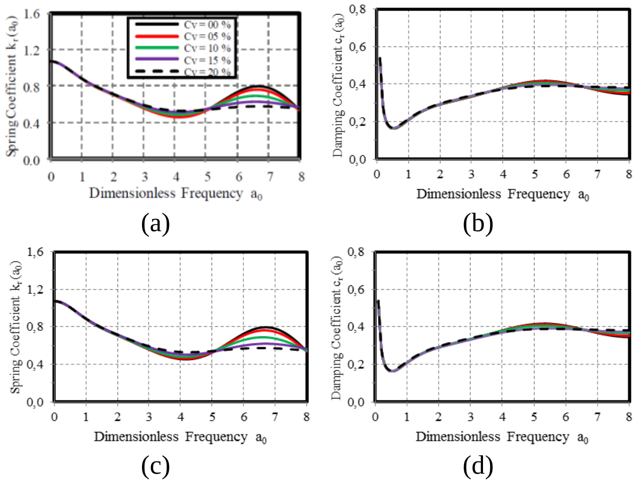


Fig. 8 Expected impedance functions for the circular foundation in rocking motion for various Cv of layer's thickness and shear wave velocity, distributed: (a) - (b) lognormally, (c) - (d) gamma

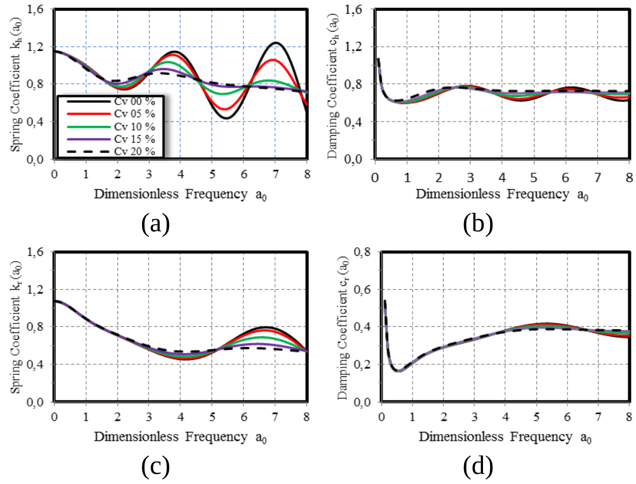


Fig. 9 Expected impedance functions for the circular foundation in multivariate normal distribution for various Cv of layer's thickness and shear wave velocity: (a) - (b) horizontal motion, (c) - (d) rocking motion

coefficients of variation for all the parameters ranging between 0 and 20%, in same time, for the lognormal distribution function, for horizontal and rocking motions, respectively. No significant differences appear between curves of Figs. 7(a), (b) and 9(a), (b), and Figs. 8(a), (b) and 9(b), (c), respectively. These results mean that soil parameters (layer's thickness and shear wave velocity) are non-correlated.

6.2 Stochastic structural response

The normalized magnitudes of the structural distortion $|u(\omega)|$, the displacement of the mass relative to the free field $|u_0(\omega)+h\theta_0(\omega)+u^g(\omega)|$, and the total displacement of the base $|u_0(\omega)+u^g(\omega)|$ are plotted versus excitation frequency

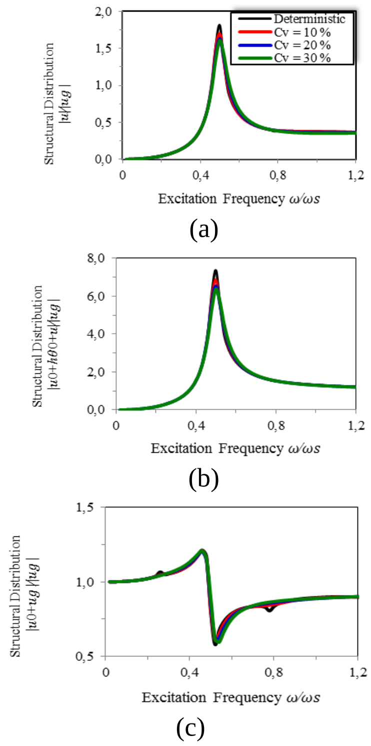


Fig. 10 Stochastic response of soil-foundation-structure system for various Cv of layer's thickness distributed lognormally, for harmonic ground motion: (a) structural distortion, (b) displacement of mass relative to free field, (c) total displacement of base

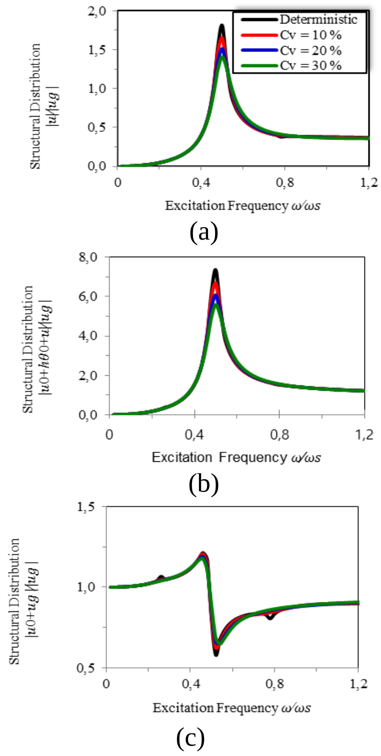
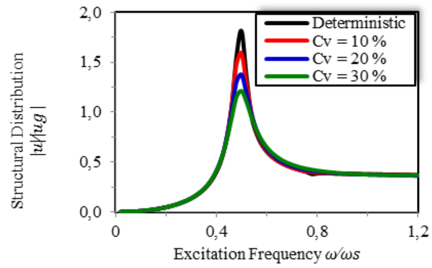
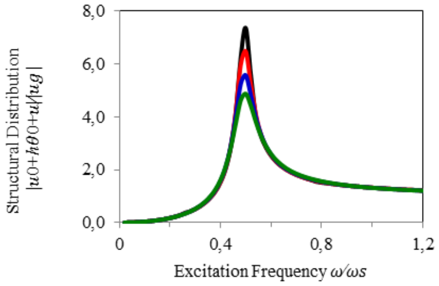


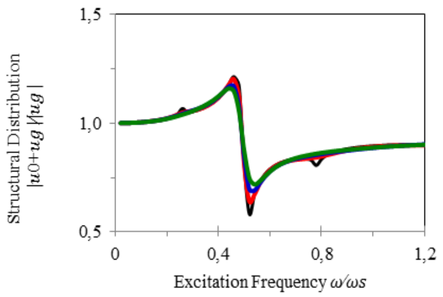
Fig. 11 Stochastic response of soil-foundation-structure system for various Cv of shear wave velocity distributed lognormally, for harmonic ground motion: (a) structural distortion, (b) displacement of mass relative to free field, (c) total displacement of base



(a)

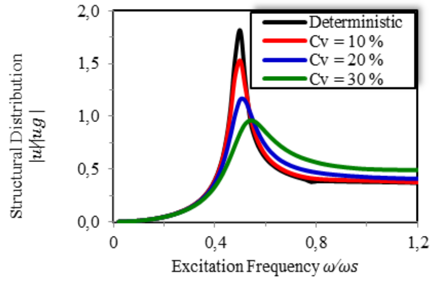


(b)

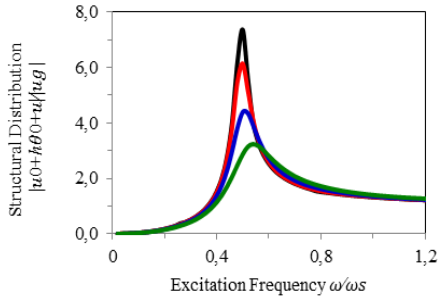


(c)

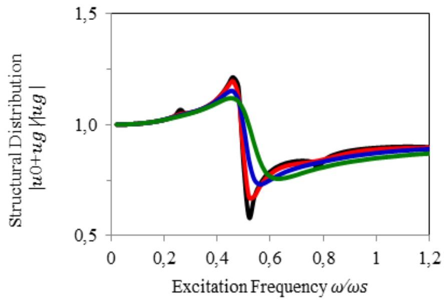
Fig. 12 Stochastic response of soil-foundation-structure system for various Cv of height of the superstructure distributed lognormally, for harmonic ground motion: (a) structural distortion, (b) displacement of mass relative to free field, (c) total displacement of base



(a)



(b)



(c)

Fig. 13 Stochastic response of soil-foundation-structure system for various Cv of foundation's radius distributed lognormally, for harmonic ground motion: (a) structural distortion, (b) displacement of mass relative to free field, (c) total displacement of base

in Figs. 10 to 13.

A comparison on the effects of uncertainties about soil parameters (layer's thickness and shear wave velocity), structural parameters (height of the superstructure), and foundation parameter (radius) with coefficient of variation (Cv) equals to 0,0 %(deterministic), 10%, 20%, and 30% for each parameter on the dynamic responses of the coupled system is carried. The same data used in the previous section are used, except that Poisson's ratio is changed to 1/3 and layer's thickness such that $\bar{d} = 4$. The other dimensionless parameters are $\bar{h} = 2$, $\bar{m} = 1$, ξ=0.025 and the stiffness ratio $\bar{s} = 3$.

It is observed that the structural distortion and the displacement of the mass are more influenced by stochastic variations of soil parameters than the total displacement (Figs. 10 and 11). The peak responses of the structural distortion and the displacement of the mass decrease as coefficients of variation of layer's thickness and shear wave velocity increase but the effect of uncertainties about shear wave velocity is larger (Fig. 11) than that of the layer's thickness (Fig. 10) indicating that the simulated ground becomes softer. In other words, the damping in the system is larger when soil parameters are considered stochastic.

Moreover, the response of the coupled system is more affected by the variations about foundation-structure system parameters. In fact, when an increase in variations about the height of the structure (Fig. 12) reduces the peaks of the structural distortion and the displacement of the mass as well as the total displacement. However, the most parameter that is sensitive to random fluctuations is the foundation radius. An increase in fluctuations about this parameter does not only significantly attenuate the peaks of the structural distortion, the displacement of the mass, and the total displacement but also shifts the frequency to right with a widening of the frequency content (Fig. 13). This agrees with the finding by Yan Xiaorong (2012), when investigating, detministically, the effects of the effective height of structure and the foundation size on the structure transfer function.

These results indicate that as the stochasticity of the system becomes important, i.e., coefficients of variation increase; the frequency content is dominated by higher frequencies.

5. Conclusions

In the present study, it was proposed to investigate the contribution of soil properties' randomness in the applicability of the cone model for a soil layer underlying a half-space. A probabilistic method based on Monte Carlo simulations is carried in this investigation. The taking into account of uncertainties about soil properties, especially layer's thickness and shear wave velocity, in the soil-structure interaction (SSI) system analysis may result in large variations about the impedance functions. It has been observed that a coefficient of variation of 20% about the layer's thickness and the shear wave velocity results in significant variation on the impedance functions with order of 40% and 36%, respectively. So, soil parameters' uncertainties may significantly influence the accuracy in expecting SSI response by substructure method where a key step is the impedance functions evaluation.

Moreover, the present study demonstrated that stochastic variations about soil, structure and foundation parameters greatly alter the response of the coupled system. Stochastic fluctuations on the thickness and the shear wave velocity of the soil layer attenuate the peak responses with an average order of 12% and 22% due to uncertainties in thickness and shear wave velocity, respectively. Also, the random variation of the height of the structure alters the response of the system in same manner but more significantly so that a 30% Cv reduces the response to order of 32%. However, the foundation radius when considered as random parameter significantly influences the response of the system in such a way that 30% Cv reduces the structural response about 60% and shifts the frequency to right with a widening of the frequency content.

In conclusion, performance of structures during dynamic shaking such as earthquakes depends strongly on the properties of the soil beneath the structure of interest as well on structure height and foundation radius. If facts, uncertainties in parameters of the soil-foundation-structure system taken into account by describing those properties by probabilistic models using probability distribution functions together with Monte Carlo simulations, meaningfully alter the dynamic system response. Based on some codes' provisions (FEMA 440, ATC-3-06), it may be concluded that the finding of the present study in terms of reduction in the soil foundation structure dynamic response magnitude and damping increase has a beneficial effect in structures performance.

References

Ahmed, S. and Rupani, A.K. (1999), "Horizontal impedance of square foundation in layered soil", *Soil Dyn. Earthq. Eng.*, **18**(1), 59-69.

Anastasopoulos, I. and Kontoroupi, T. (2014), "Simplified approximate method for analysis of rocking systems accounting for soil inelasticity and foundation uplifting", *Soil Dyn. Earthq. Eng.*, **56**, 28-43.

Applied TechnologyCouncil (1984), *Tentative Provisions for the Development of Seismic Regulations for Buildings*, ATC-3-06: California.

Aydemir, M.E. and Aydemir, C. (2016), "Overstrengh factors for SDOF and MDOF systems with soil structure interaction", *Earthq. Struct.*, **10**(6), 1273-1289.

Baecher, G.R. and Christian, J.T. (2003), *Reliability and statistics in geotechnical engineering*, John Wiley & Sons Ltd, England.

Bargman, H. (1997), "The role of stochastic modelling in engineering science", *Acta Mechanica*, **125**(1-4), 63-71.

Celebi, E., Firat, S. and Cankaya, I. (2006), "The evaluation of impedance functions in the analysis of foundations vibrations using boundary element method", *Appl. Math. Comput.*, **173**(1), 636-667.

Cottereau, R., Clouteau, D. and Soize, C. (2008), "Probabilistic impedance of foundation: Impact of the seismic design on uncertain soils", *Earthq. Eng. Struct. Dyn.*, **37**(6), 899-918.

Dasgupta, G. (2008), "Stochastic shape function and stochastic strain-displacement matrix for a stochastic finite element stiffness matrix", *Acta Mechanica*, **195**(1-4), 379-395.

Dobry, R. (2014), "Simplified methods in soil dynamics", *Soil Dyn. Earthq. Eng.*, **61-62**, 246-268.

Dunn, W.L. and Shultis, J.K. (2012), *Exploring Monte Carlo Methods*, Ed. Elsevier, 384 pp.

Durmus, A. and Livaoglu, R. (2015), "A simplified 3 D.O.F. model of A FEM model for seismic analysis of a silo containing elastic material accounting for soil- structure interaction", *Soil Dyn. Earthq. Eng.*, **77**, 1-14.

FEMA 440 (2005), *Recommended Improvements of Nonlinear Static Seismic Analysis Procedures*, Applied Technology Council: California.

Gazetas, G. (1983), "Analysis of machine foundation vibrations: state of the art", *Soil Dyn. Earthq. Eng.*, **2**(1), 1-41.

Gazetas, G. (1991), "Formulas and chart s for impedances of surface and embedded foundations", *J. Geotech. Eng.*, **117**(9), 1363-1381.

Gazetas, G. and Mylonakis, G. (1998), "Seismic soil-structure interaction: new evidence and emerging issues", *Geotech. Earthq. Eng. Soil Dyn.*, **3**, 1119-1174.

Hryniewicz, Z. (2000), "Dynamic response of a bar embedded in semi-infinite medium: stochastic approach", *Acta Mechanica*, **143**(3-4), 141-153.

Huber, M. (2013), "Soil variability and its consequences in geotechnical engineering", PhD. Thesis, Stuttgart University, Germany.

Hyuk Chun, N. (2005), "Stochastic behavior of Mindlin plate with uncertain geometric and material parameters", *Prob. Eng. Mech.*, **20**(4), 296-306.

Jayalekshmi, B.R., Thomas, A. and Shivashankar, R. (2014), "Dynamic soil-structure interaction studies on 275m tall industrial chimney with opening", *Earthq. Struct.*, **7**(2), 233-250.

Jimenez, R. and Sitar, N. (2009), "The importance of distribution types on finite element analyses of foundation settlement", *Comput. Geotech.*, **36**(3), 474-483.

Jones, A.L., Kramer, S.L. and Arduino, P. (2002), *Estimation of Uncertainty in Geotechnical Properties for Performance-Based Earthquake Engineering*, PEER Report 2002/16, Pacific Earthquake Engineering Research Center College of Engineering University of California, Berkeley, USA.

Kausel, E. (2010), "Early history of soil-structure interaction", *Soil Dyn. Earthq. Eng.*, **30**(9), 822-832.

Laudarin, F., Desceliers, C., Bonnet, G. and Argoul, P. (2013), "A non-parametric probabilistic model for soil-structure interaction", *Comput. Mech.*, **52**(1), 53-64.

Lee, J.H., Kim, J.K. and Tassoulas, J.L. (2013), "Stochastic dynamic analysis of a layered half-space", *Soil Dyn. Earthq. Eng.*, **48**, 220-233.

Liou, G.S. and Chung, I.L. (2009), "Impedance matrices for circular foundation embedded in layered medium", *Soil Dyn. Earthq. Eng.*, **29**(4), 677-692.

Maheshwari, P. and Kashyap, D. (2011), "Stochastic analysis of beam on reinforced earth beds", *Georisk*, Taylor and Francis, **5**(3-4), 207-217.

Manolis, G.D. (2002), "Stochastic soil dynamic", *Soil Dyn. Earthq. Eng.*, **22**(1), 3-15.

Maravas, A. Mylonakis, G. and Karabalis, D.L. (2014), "Simplified discrete systems for dynamic analysis of structures on footings and piles", *Soil Dyn. Earthq. Eng.*, **61-62**, 29-39.

Meek, J.W. and Wolf, J.P. (1992a), "Cone models for homogeneous soil. I", *J. Geotech. Eng.*, **118**(5), 667-685.

Meek, J.W. and Wolf, J.P. (1992b), "Cone models for soil layer on rigid rock. II", *J. Geotech. Eng.*, **118**(5), 686-703.

Mehanny, S.S.F. and Ayoub, A.S. (2008), "Variability in inelastic displacement demands: Uncertainty in system parameters versus randomness in ground records", *Eng. Struct.*, **30**(4), 1002-1013.

Menglin, L.W., Huaifeng, C. Xi and Yongmei, Z. (2011), "Structure-soil-structure interaction: Literature review", *Soil Dyn. Earthq. Eng.*, **31**(12), 1724-1731.

Moghaddasi, M., Cubrinovski, M., Pampanin, S., Carr, A. and Chase, J.G. (2009), "Monte Carlo simulation of SSI effects using simple rheological soil model" *2009 NZSEE Conference*.

Moghaddasi, M., Cubrinovski, M., Chase, J.G., Pampanin, S. and Carr, A. (2011), "Effects of soil-foundation-structure interaction on seismic structural response via robust Monte Carlo simulation", *Eng. Struct.*, **33**(4), 1338-1347.

Nobahar, A. (2003), "Effects of soil spatial variability on soil-structure interaction", Ph.D thesis, University St. John's Newfoundland, Canada.

Pena Ruiz, D. and Guzman Gutiérrez, S. (2014), "Finite element methodology for the evaluation of soil damping in LNG tanks supported on homogeneous elastic half space", *Bull. Earthq. Engineer*, Springer.

Phoon, K.K. and Kulhawy, F.H. (1999), "Evaluation of geotechnical property variability", *Can. Geotech. J.*, **36**(4), 625-639.

Pitilakis, D. (2006), "Soil-structure interaction modeling using equivalent linear soil behavior in the substructure method", PhD. Thesis, Ecole Centrale Paris, France.

Popescu, R., Deodatis, G. and Nobahar, A. (2005), "Effects of random heterogeneity of soil properties on bearing capacity", *Prob. Eng. Mech*., **20**(4), 324-341.

Pradeep Kumar, P. and Maheshwari, P. (2013), "Stochastic analysis of strip footing on elastic layered soil", *Korean Soc. Civ. Engineer.*, **17**(7), 1621-1629.

Pradhan, P.K., Baidya, D.K. and Ghosh, D.P. (2004), "Dynamic response of foundation resting on layered soil by cone model", *Soil Dyn. Earthq. Eng.*, **24**(6), 425-434.

Pradhan, P.K., Mandal, A., Baidya, D.K. and Ghosh, D.P. (2008), "Dynamic response of machine foundation on layered soil", *Geotech. Geol. Eng.*, **26**(4), 453-468.

Raychowdhury, P. and Jindal, S. (2014), "Shallow foundation response variability due to soil and model parameter uncertainty", *Front Struct. Civ. Eng.*, **8**(3), 237-251.

Renzi, S., Madiai, C. and Vannucchi, G. (2013), "A simplified empirical method for assessing seismic soil-structure interaction effects on ordinary shear-type buildings", *Soil Dyn. Earthq. Eng.*, **55**, 100-107.

Sadouki, A., Harichane, Z. and Chehat, A. (2012), "Response of a randomly inhomogeneous layered media to harmonic excitations", *Soil Dyn. Earthq. Eng.*, **36**, 84-95.

Safak, E. (2006), "Time-domain representation of frequency-dependent foundation impedance functions", *Soil Dyn. Earthq. Eng.*, **26**(1), 65-70.

Salcher, P. and Adam, C. (2015), "Modeling of dynamic train-bridge interaction in high-speed railways", *Acta Mechanica*, **226**(8), 2473-2495.

Scherer, R.J. and Faschingbauer, G. (2005), "Stochastic moments of seismic waves in stochastic homogeneous and heterogeneous media", *Proceedings ICOSSAR (2005)*.

Soesilo J.A. (1997), *Site Remediation: Planning and Management Popular Online*, CRC Press.

Stewart, J.P., Fenves, G.L. and Seed, R.B. (1999), "Seismic soil-structure interaction in buildings. I: Analytical aspects", *J. Geotech. Geoenviron. Eng.*, ASCE, **125**(1), 26-37.

Tanizaki, H. (2004), *Computational Methods in Statistics and Econometrics*, Mercel Dekker, INC, 512p.

Wolf, J.P. (1994), *Foundation vibration analysis using simple physical models*, Prentice-Hall, Upper Saddle River, NJ.

Yan Xiaorong (2012), "Soil-structure interaction under multi-directional earthquake loading", Ph.D. thesis, The university of Hong Kong, China.

Yazdchi, M. Khalili, N. and Valliapan, S. (1999), "Dynamic soil-structure interaction analysis via coupled finite-element-boundary-element-method", *Soil Dyn. Earthq. Eng.*, **18**(7), 499-517.

Zhang, C. and Wolf, J.P. (1998), *Dynamic soil-structure interaction*, Elsevier science, Netherlands.

AG

Appendix

$$K_h(\omega) = K \frac{1 + i\omega \frac{T}{\kappa}}{1 + 2\sum_{j=1}^{\infty}\left(-\alpha(\omega)\right)^j \frac{e^{-i\omega jT}}{1 + j\kappa}} \,, \qquad \text{(I-a)}$$

where

$$-\alpha_j(\omega) = \frac{\frac{\rho_1 \upsilon_{S1}^{\ 2}}{z_{01} + (2j-1)d_1} - \frac{\rho_2 \upsilon_{S2}^{\ 2}}{\left(z_{01} + (2j-1)d_1\right)z_{02}/\left(z_{01} + d_1\right)} + i\omega\left(\rho_1.\upsilon_{S1} - \rho_2.\upsilon_{S2}\right)}{\frac{\rho_1 \upsilon_{S1}^{\ 2}}{z_{01} + (2j-1)d_1} + \frac{\rho_2 \upsilon_{S2}^{\ 2}}{\left(z_{01} + (2j-1)d_1\right)z_{02}/\left(z_{01} + d_1\right)} + i\omega\left(\rho_1.\upsilon_{S1} + \rho_2.\upsilon_{S2}\right)} \,, \text{(I-b)}$$

and

$$K_\theta(\omega) = K_r \frac{1 - \frac{1}{3}\frac{(\omega T)^2}{\kappa^2 + (\omega T)^2} + i\frac{\omega T}{3\kappa}\frac{(\omega T)^2}{\kappa^2 + (\omega T)^2}}{1 + \frac{2}{1 + i\frac{\omega T}{\kappa}\left(\sum_{j=1}^{\infty}\left(-\alpha(\omega)\right)^j \frac{e^{-i\omega jT}}{(1 + j\kappa)^3} + i\frac{\omega T}{3\kappa}\sum_{j=1}^{\infty}\left(-\alpha(\omega)\right)^j \frac{e^{-i\omega jT}}{(1 + j\kappa)^3}\right)}} \,, \text{(II-a)}$$

$$-\alpha(\omega) = \frac{\beta - \beta'}{\beta + \beta'} \,, \qquad \text{(II-b)}$$

with

$$\beta = \rho_1.\upsilon_{S1}^{\ 2} \frac{\frac{3}{z_{01} + d_1} + 3i\frac{\omega}{\upsilon_{S1}} + \left(\frac{i\omega}{\upsilon_{S1}}\right)^2\left(z_{01} + d_1\right)}{1 + i\frac{\omega}{\upsilon_{S1}}\left(z_{01} + d_1\right)} \,, \quad \text{(II-c)}$$

$$\beta' = \rho_2.\upsilon_{S2}^{\ 2} \frac{\frac{3}{z_{02}} + 3i\frac{\omega}{\upsilon_{S2}} + \left(\frac{i\omega}{\upsilon_{S2}}\right)^2 z_{02}}{1 + i\frac{\omega}{\upsilon_{S2}} z_{021}} \,, \qquad \text{(II-d)}$$

where: $\kappa = \frac{2d}{z_0}$, $T = \frac{2d}{\upsilon_{S1}}$,(II-e)