ISET Journal of Earthquake Technology, Paper No. 578, Vol. 60, No. 2, June 2023, pp. 45–60

EFFECTS OF SUPERSTRUCTURE FLEXIBILITY ON FOUNDATION VIBRATIONS

M. Cibi Jacob
Graduate Student, Department of Civil Engineering
Indian Institute of Technology (IIT) Delhi, New Delhi - 110 016, India
E mail id: *cibijacobm@gmail.com*

Ramanathan Ayothiraman
Professor, Department of Civil Engineering
Indian Institute of Technology (IIT) Delhi, New Delhi - 110 016, India
E mail id: *araman@civil.iitd.ac.in*

Denise-Penelope N. Kontoni (Corresponding Author)
Associate Professor, Department of Civil Engineering
School of Engineering, University of the Peloponnese, GR-26334, Patras, Greece
E mail id: *kontoni@uop.gr*

Vasant A. Matsagar
Professor, Dogra Chair, and Head, Department of Civil Engineering
Indian Institute of Technology (IIT) Delhi, New Delhi - 110 016, India
E mail id: *matsagar@civil.iitd.ac.in*

ABSTRACT

Modeling of dynamic soil-foundation-structure interaction considering superstructure flexibility in various soil/foundation conditions using analytical/numerical approach is presented. The effect of superstructure flexibility on the response of the foundation when excited by different earthquakes is studied here. Initially, the foundation alone is considered, and its response is calculated. The foundation is then analyzed by lumping the total mass of the superstructure on the foundation - the same manner in which the foundation is generally analyzed for practical purposes. Different superstructures are then considered with varying flexibilities and the foundation is analyzed by considering the soil-foundation-structure interaction. The effect of soil stiffness on the response of the foundation is also investigated. Various types of soil are considered by varying their shear wave velocity and the response is calculated. The response of the model under combined sliding and rocking modes is analyzed. It is found from the analyses that the displacements in the foundation are highly influenced by the presence of a flexible superstructure. The translational displacement reduces when the superstructure is flexible, however the rotational displacement is substantially higher. The spectrum of natural frequency is also affected by the flexibility of superstructure. The foundation soil type has significant influence on the fundamental period of the soil-foundation-structure system.

KEYWORDS: Earthquake, Foundation, Flexibility, Soil, Soil-Structure Interaction

INTRODUCTION

Foundations supporting reciprocating engines, compressors, radar towers, punch presses, turbines, large electric motors, and generators, etc. are subjected to vibrations caused by unbalanced machine forces as well as the static weight of the machine. Also, the foundations themselves vibrate under the action of earthquakes. If these vibrations are excessive, they may damage the machine or cause it not to function properly. Further, the vibrations may adversely affect the building or persons working near the machinery unless the frequency and amplitude of the vibrations are controlled. The design of foundations for control of vibrations is often made based on increasing the mass of the foundation, which is uneconomical and consumes large space and material. Furthermore, it might not result in an accurate analysis because it doesn't consider the flexibility of the superstructure, and the response varies due to the interaction between the structure and the soil (Soil-Structure Interaction, SSI).

Given the frequent occurrence of earthquakes worldwide, it is crucial to study how structures behave under dynamic forces. Several factors influence a structure's dynamic response, including its type, foundation type, and soil properties. Observations from earthquake-damaged sites have shown that local soil characteristics and foundation design significantly impact a structure's dynamic behavior. The interaction between soil and foundation affects a structure's dynamic response in three ways: soil amplification, kinematic interaction, and inertial interaction, collectively referred to as SSI.

Structures always interact with their surrounding soil and behave differently depending on their properties and the supporting soil. However, in seismic analysis often the foundation soil is assumed rigid, which is suitable for average-sized structures on solid rock but leads to errors when the structure is on soil deposits.

The inability of the foundation soil to match the free-field motion causes the structure's base motion to deviate from it, and the structure's dynamic response leads to deformation in the supporting soil. This mutual influence between soil and structure is known as SSI. The flexibility of the foundation affects the dynamic characteristics of the structure, including vibration modes and frequencies.

In general, SSI lowers the natural frequency of the soil-structure system relative to the structure itself and increases the overall displacement due to foundation movements in reasonably flexible systems. In the late 20th century, the significance of dynamic SSI for structures on soft soils became well-recognized, leading to extensive research and computer-based simulations.

STATUS OF SOIL-STRUCTURE INTERACTION STUDIES

Gupta and Trifunac (1991) presented a simplified response spectrum superposition method which was generalized for the dynamic analysis of the multi-storeyed building-soil response to earthquake ground motions via Fourier transformed frequency domain. It involved the “scaling” of the Fourier amplitudes of the free-field translational and rocking motions to account for the SSI effects, and then analyzing the building as fixed at the base. Envelopes of peak displacements, shear forces, and overturning moments in the building were illustrated in terms of the order statistics of the response peaks.

Jianguo et al. (1993) presented a modified lumped parametric model for non-linear soil-structure interaction analysis. Most SSI analyses were conducted assuming linear material behavior or simulating non-linear effects through an equivalent linearization. It was recognized, however, that nonlinearities can play a significant role in the results. Two kinds of nonlinearities must be considered: (i) nonlinearities associated with inelastic soil behavior and (ii) nonlinearities resulting from the loss of contact between the foundation and the surrounding soil. In this article, a modified lumped parametric model for the analysis of non-linear SSI effects was proposed. In the model both nonlinearities were considered. The results of tests of the soil-structure system model were presented, which agree well with those obtained from analysis by using the proposed model.

Wolf (1997) presented spring-dashpot-mass models for foundation vibrations considering SSI. The foundation on deformable soil, which, in general, radiates energy, is represented in structural dynamics as a simple spring-dashpot-mass model with frequency-independent coefficients. For the two limiting cases of a site, the homogeneous half-space and the homogeneous layer fixed at its base, the coefficients are specified in tables for various parameters such as ratios of dimensions and Poisson’s ratio. Rigid foundations on the surface and with embedment are considered for all translational and rotational motions. In a practical analysis of soil-structure interaction, this dynamic model of the foundation is coupled directly to that of the structure, whereby a standard dynamics program can be used for the analysis.

Kutanis and Elmas (2001) presented a non-linear SSI analysis based on the substructure method in the time domain. They presented an idealized two-dimensional plane strain finite element seismic SSI analysis based on a substructure method by using original software developed by the authors.

Wu and Chen (2001) developed an effective fixed-base model with classical normal modes for soil-structure interacting systems. To simplify the analysis of soil-structure interacting systems various fixed-base models were proposed to efficiently represent the SSI effects and it has been found that these models yielded very good accuracy in the results.

Takewaki et al. (2003) presented a simple and fast evaluation method of soil-structure interaction effects of embedded structures presented via a cone model. The impedances and the effective input motions at the bottom of an embedded foundation were evaluated by means of the cone model. Those quantities were transformed exactly to the corresponding values at the top of the foundation.

Shakib and Fuladgar (2004) discussed the impact of SSI on the seismic response of asymmetric buildings, particularly in the time domain. They developed an approach for the linear analysis of three-dimensional dynamic SSI for these buildings, modeling the soil as linear elastic solid elements beneath the structure. The contact surface between the foundation and the soil was represented using linear plane interface elements.

Jean et al. (2006) introduced a method to analyze soil foundations for dynamic response evaluation in the time domain. They proposed a system with lumped parameters that doesn't depend on the frequency to represent the soil medium. When compared to the dynamic response of the theoretical half-space model, the lumped parameter system produced satisfactory results.

Wu and Smith (2006) presented an efficient approach for analyzing structures with SSI. They employed modal analysis in the frequency domain to determine the structural response in the presence of SSI. Interaction effects were characterized using a ground motion modification factor for each vibration mode, simplifying the analysis of SSI for fixed-base structures. This method harnessed the benefits of modal superposition while requiring fewer computational resources by considering only the initial vibration modes.

Chopra and Gutierrez (2007) presented an article on the earthquake response analysis of multi-storey buildings including foundation interaction. An efficient method, based on the Ritz concept, for dynamic analysis of the response of multistorey buildings including foundation interaction to earthquake ground motion was presented. The system considered was a shear building on a rigid circular disc footing attached to the surface of a linearly elastic half-space. In this method, the structural displacements were transformed to normal modes of vibration of the building on a rigid foundation. The analysis procedure was developed, and numerical results were presented to demonstrate that excellent results can be obtained by considering only the first few modes of vibration. As the number of unknowns was reduced by transforming to generalized coordinates, the method presented was much more efficient than direct methods.

The existing literature shows that the lumped parameter model provides satisfactory results. However, there is a gap in research regarding the influence of the superstructure flexibility on the foundation vibrations in an SSI context. Additionally, there is limited discussion on how different soil types affect this foundation response. Recent studies in the field of SSI highlight its significant impact on dynamic structural behavior when the soil is soft. Nonetheless, prior research primarily focused on the effect of different foundations and soil conditions, often neglecting the role of superstructure flexibility in influencing foundation response. Consequently, this study aims to investigate how the flexibility of the superstructure affects the dynamic response of foundations in an SSI scenario.

In view of the gap in knowledge, the specific objectives of this study are: (1) to develop a two-dimensional (2D) model of the structure-foundation-soil system and model the structure and soil using representative models; (2) to obtain the responses of the system in time domain for any digital earthquake time history by developing a computer code; (3) to compare the seismic response of the foundation with lumped superstructure mass and the foundation with a flexible superstructure; (4) to study the influence of the stiffness of soil on the response of the foundation by considering different soil types; and (5) to investigate the effects of superstructure flexibility on the response of rigid foundation structures.

MATHEMATICAL MODELING

1. Modeling Background

Lumped mass modeling is carried out for the superstructure, foundation, and the soil in the present study. Three idealized cases are analyzed: (i) foundation mass alone with single-degree-of-freedom (SDOF) system, (ii) foundation mass plus the sum of superstructure mass(es) (lumped mass) and analyzed as SDOF system (neglecting the flexibility of columns/storeys) and (iii) analyzing the multi-degree-of-freedom (MDOF) system considering the flexibility of each storey and the mass of each storey is considered as independent mass at the respective floor, without lumping as single mass for all the storeys. The effect of rotation in the structure is not taken into consideration. The behavior of the soil is assumed to be linear. The equations of motion are written in time domain and the full matrices are written for an example five-storey building.

2. Foundation and Soil Modeling

The foundation on deformable soil, which, in general, radiates energy is represented in structural dynamics as a simple spring-dashpot-mass model with frequency-independent coefficients. Rigid foundations on the surface and with embedment are considered for all translational and rotational motions. In a practical analysis of soil-structure interaction, this dynamic model of the foundation is coupled directly to that of the structure. The spring-dashpot-mass models are also called lumped-parameter models.

A sufficiently accurate consideration of soil behavior can be obtained if the soil stiffness and damping coefficients of a circular massless foundation on soil strata are evaluated by the frequency independent expressions (Wolf, 1997). The stiffness and damping coefficients of soil medium are expressed by

$$K_h = \frac{8Ga}{2-\nu} \tag{1}$$

$$K_r = \frac{8Ga^3}{3(2-\nu)} \tag{2}$$

$$C_h = \frac{0.58a}{c_s} K_h \tag{3}$$

$$C_r = \frac{a}{C_s} K_h \left[\frac{0.3}{1+\frac{3m(1-\nu)}{8\rho a^5}} \right] \tag{4}$$

where K_h and K_r represent the horizontal and rocking stiffness of soil medium, respectively; C_h and C_r are the horizontal and rocking viscous damping coefficients for radiation soil damping, respectively; G is the soil shear modulus; C_s is the shear wave velocity for soil; a is the radius of circular footing; ν is Poisson's ratio for the soil; and m is the mass moment of inertia of the rotation degree of freedom. The average shear wave velocity values of soil as per National Earthquake Hazards Reduction Program (NEHRP) recommendations are considered to simulate the different soil types (Wair and Dejong, 2012). Accordingly, the soil having average shear wave velocity of 180 to 360 m/s is classified as hard soil/rigid soil. In the present study the shear wave velocity of 300 m/s is considered, since this value is recommended for carrying out ground response analysis with rigid/fixed base (Kramer, 1996).

3. Superstructure Modeling

Figure 1(a) shows the idealized mathematical model of the *N*-storey building considered for the present study; in the example $N = 5$. The building is modeled as a shear type structure with one lateral degree-of-freedom at each floor.

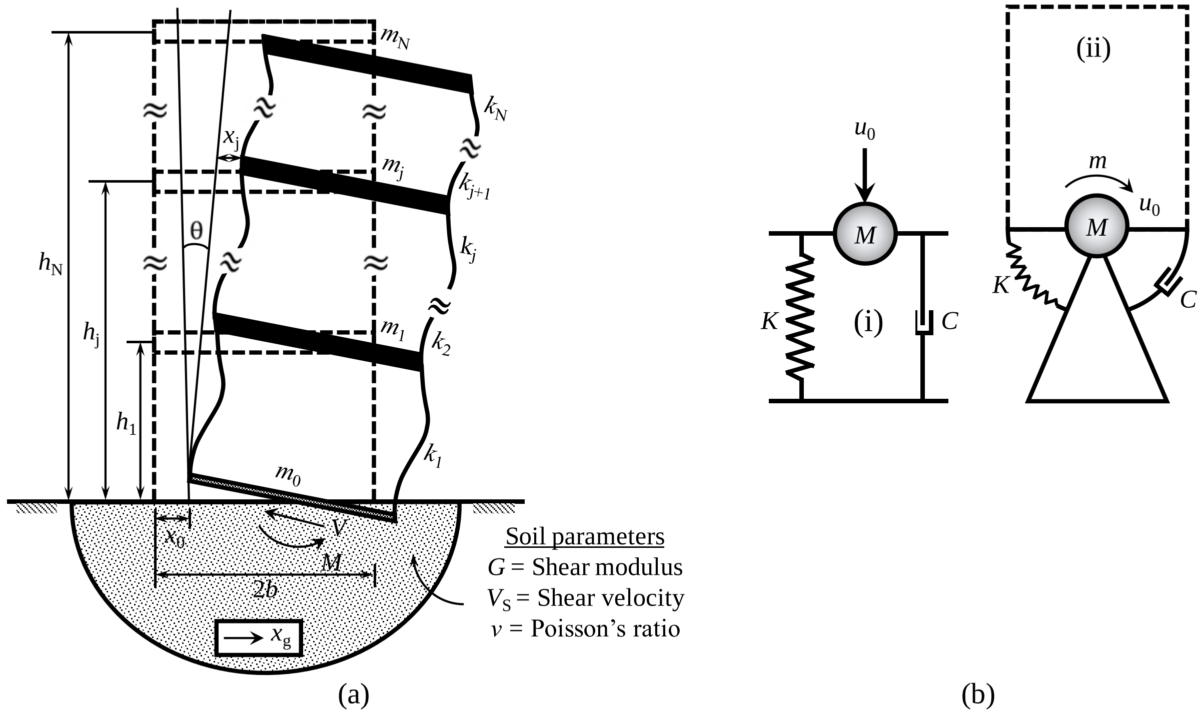


Fig. 1 (a) Mathematical model of *N*-storey structure (Wolf, 1997), (b) spring-dashpot-mass model of foundation for (i) translation and (ii) rotation

The following assumptions are made for the structural system under consideration: (i) the superstructure is considered to remain within the elastic limit during the earthquake excitation; (ii) the floors are assumed rigid in its own plane and the mass is supposed to be lumped at each floor level; (iii) the columns are inextensible and weightless providing the lateral stiffness; and (iv) the system is subjected to single horizontal component of the earthquake ground motion.

4. Governing Equations of Motion

1. General Equation of Motion

The equations of motion for the structure-foundation model illustrated in Figure 1(a) can be expressed as

$$M\ddot{X}^t(t) + C\,\dot{X}(t) + K\,X(t) = 0 \tag{5}$$

where, $X = \{x_j\}$ is the column vector of relative structural displacements; $X^t = \{x^t_j\}$ is the column vector of total structural displacements, $x^t_j = x_j + x_h + h_j\,\theta + x_g$, where x_h is the translational displacement of foundation; x_g is the displacement of ground due to earthquake excitation; h_j is the height of j^{th} floor from foundation; and θ is the rotational displacement of the foundation. Further, M is the mass matrix of structure; C is the viscous damping matrix of structure; and K is the stiffness matrix of structure.

2. Equations of Motion for the Foundation Alone

The equations of motion for a rigid foundation which undergoes coupled rocking and sliding vibrations under earthquake excitations are

$$m_o\ddot{x}_h + C_h\dot{x}_h + k_h x_h - LC_h\dot{\theta} - LK_h\theta = -m_0\ddot{x}_g \tag{6}$$

$$I_o\ddot{\theta} + (C_r + L^2C_h)\dot{\theta} + (K_r + L^2K_h)\theta - LC_h\dot{x}_h - LK_h x_h = -Lm_0\ddot{x}_g \tag{7}$$

where, L is half of the thickness of the foundation slab; m_o and I_o respectively are the mass and mass moment of inertia of the foundation.

3. Equations of Motion for Foundation with Lumped Superstructure Mass

The foundation undergoes coupled rocking and sliding vibrations under earthquake excitations. The equations of motion for a rigid foundation at which the entire mass of the superstructure is lumped on the foundation considering the superstructure as a rigid mass are

$$(m_o + m_s)\ddot{x}_h + C_h\dot{x}_h + k_h x_h - LC_h\dot{\theta} - LK_h\theta = -(m_o + m_s)\ddot{x}_g \tag{8}$$

$$(I_o + I_s)\ddot{\theta} + (C_r + L^2C_h)\dot{\theta} + (K_r + L^2K_h)\theta - LC_h\dot{x}_h - LK_h x_h = -L(m_o + m_s)\ddot{x}_g \tag{9}$$

where, m_s and I_s respectively are the mass and mass moment of inertia of the superstructure.

4. Equations of Motion for Foundation-Structure System

The equations of motion for a five-storey building and foundation including soil-structure interactions is as given below

$$M\,\ddot{X} + C\,\dot{X} + K\,X = -\bar{M}r\ddot{X}_g \tag{10}$$

where, $X = \{x_1, x_2, x_3, x_4, x_5, x_h, \theta\}^T$ are relative floor displacements, here the numbering of the floors begins from the top, i.e., the top floor is numbered as 1 and the bottom floor is numbered as 5. Further, X_g is the ground motion displacement and r is the influence coefficient vector.

$$M = \begin{bmatrix} m_1 & 0 & 0 & 0 & 0 & m_1 & m_1h_1 \\ 0 & m_2 & 0 & 0 & 0 & m_2 & m_2h_2 \\ 0 & 0 & m_3 & 0 & 0 & m_3 & m_3h_3 \\ 0 & 0 & 0 & m_4 & 0 & m_4 & m_4h_4 \\ 0 & 0 & 0 & 0 & m_5 & m_5 & m_5h_5 \\ m_1 & m_2 & m_3 & m_4 & m_5 & \sum_{i=1}^{5} m_i + m_b + m_o & \sum_{i=1}^{5} m_ih_i \\ m_1h_1 & m_2h_2 & m_3h_3 & m_4h_4 & m_5h_5 & \sum_{i=1}^{5} m_ih_i & \sum_{i=1}^{5} m_i{h^2}_i + I_s + I_o \end{bmatrix} \tag{11}$$

where, m_o, I_o, and I_s are mass of foundation, moment of inertia of the foundation, and total floor moment of inertia of the structure, respectively.

$$K = \begin{bmatrix} k_1 & -k_1 & 0 & 0 & 0 & 0 & 0 \\ -k_1 & k_1+k_2 & -k_2 & 0 & 0 & 0 & 0 \\ 0 & -k_2 & k_2+k_3 & -k_3 & 0 & 0 & 0 \\ 0 & 0 & -k_3 & k_3+k_4 & -k_4 & 0 & 0 \\ 0 & 0 & 0 & -k_4 & k_4+k_5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & K_h & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & K_r \end{bmatrix} \quad (12)$$

$$C = \begin{bmatrix} c_1 & -c_1 & 0 & 0 & 0 & 0 & 0 \\ -c_1 & c_1+c_2 & -c_2 & 0 & 0 & 0 & 0 \\ 0 & -c_2 & c_2+c_3 & -c_3 & 0 & 0 & 0 \\ 0 & 0 & -c_3 & c_3+c_4 & -c_4 & 0 & 0 \\ 0 & 0 & 0 & -c_4 & c_4+c_5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & C_h & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & C_r \end{bmatrix} \quad (13)$$

$$\bar{M} = \begin{bmatrix} m_1 \\ m_2 \\ m_3 \\ m_4 \\ m_5 \\ \sum_{i=1}^{5} m_i + m_o \\ \sum_{i=1}^{5} m_i h_i \end{bmatrix} \quad (14)$$

NUMERICAL SOLUTION PROCEDURE

1. Introduction

Classical modal superposition technique cannot be employed in the solution of equations of motion here because the system is non-classically damped owing to the difference in the damping in soil as compared to the damping in the superstructure. Therefore, the equations of motion are solved numerically using Newmark's method of step-by-step integration, adopting linear variation of acceleration over a small time interval of Δt.

2. Numerical Example

Table 1: System parameters for numerical example

Model	Parameter	Symbol	Value	Unit
Superstructure	Floor mass	m_j, j = 1-5	15000	kg
	Ratio of column stiffness		1.0:1.0:1.0:1.0:1.0	
	Foundation to storey height	h_j, j = 1-5	$3.5 \times j$	m
	Floor moment of inertia	I_j, j = 1-5	15000	kg m^2
	Time period	T_s	0.5	s
Foundation	Half side-width	b	1.75	m
	Mass	m_o	30000	kg
	Moment of inertia	I_o	30000	kg m^2
Soil	Mass density	ρ	1700	kg m^3
	Poisson's ratio	ν	1/3	
	Shear wave velocity	C_s	150	m/s
	Translational stiffness coefficient	K_h	362426400.0	N/m
	Rotational Stiffness coefficient	K_r	1220331671.0	N/m
	Translational damping coefficient	C_h	2766328.0	N s/m
	Rotational damping coefficient	C_r	4817869.42	N s/m

To demonst rate the validity of the computer code developed, a five-storey shear building resting on a homogeneous elastic soil through a rigid square foundation is considered. Table 1 summarizes all the parameters for the superstructure, foundation, and soil. The equivalent radius of the square foundation is calculated to find the stiffness and damping coefficients. The earthquake ground motion selected for the numerical example is N00S component of the 1995 Kobe earthquake recorded at Japan Meteorological Agency (JMA). The peak ground acceleration (PGA) of Kobe earthquake is 0.834*g*, where *g* is gravitational acceleration. The maximum ordinate of the pseudo-acceleration is 3.606*g* occurring at period of 0.36s.

Output from the program is described in the following section. Mass matrix of the entire structure-foundation system,

$$M\,(\text{kg}) = 10^4 \begin{bmatrix} 1.5 & 0 & 0 & 0 & 0 & 1.5 & 26.25 \\ 0 & 1.5 & 0 & 0 & 0 & 1.5 & 21.0 \\ 0 & 0 & 1.5 & 0 & 0 & 1.5 & 15.75 \\ 0 & 0 & 0 & 1.5 & 0 & 1.5 & 10.5 \\ 0 & 0 & 0 & 0 & 1.5 & 1.5 & 5.25 \\ 1.5 & 1.5 & 1.5 & 1.5 & 1.5 & 12 & 78.75 \\ 26.25 & 21.0 & 15.75 & 10.5 & 5.25 & 78.75 & 1021.1 \end{bmatrix} \tag{15}$$

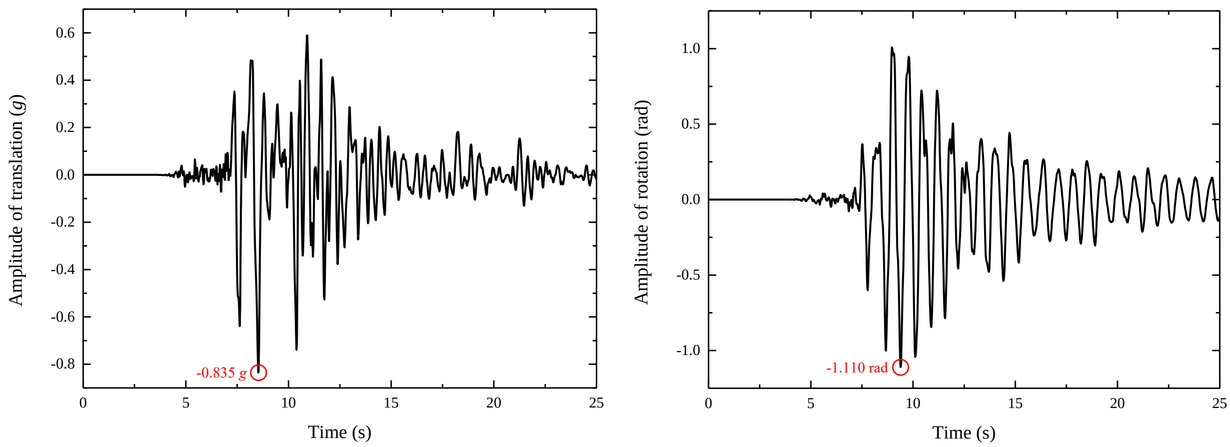
Stiffness matrix of the entire structure-foundation system,

$$K\,(\text{N/m}) = 10^6 \begin{bmatrix} 29.238 & -29.238 & 0 & 0 & 0 & 0 & 0 \\ -29.238 & 58.476 & -29.238 & 0 & 0 & 0 & 0 \\ 0 & -29.238 & 58.476 & -29.238 & 0 & 0 & 0 \\ 0 & 0 & -29.238 & 58.476 & -29.238 & 0 & 0 \\ 0 & 0 & 0 & -29.238 & 58.476 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 362.43 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1220.3 \end{bmatrix} \tag{16}$$

Damping matrix of the entire structure-foundation system,

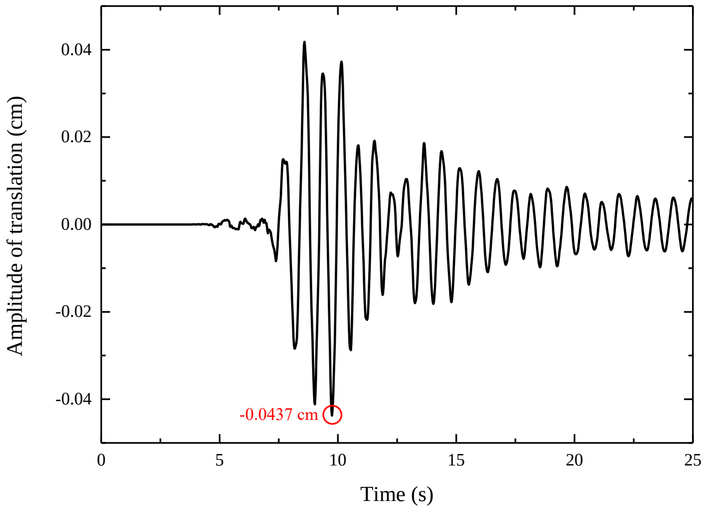
$$C\,(\text{N.s/m}) = 10^3 \begin{bmatrix} 22.719 & -13.244 & -2.9344 & -1.1675 & -0.4544 & 0 & 0 \\ -13.244 & 33.028 & -11.477 & -2.2213 & -0.7131 & 0 & 0 \\ -2.9344 & -11.477 & 33.741 & -11.023 & -1.7669 & 0 & 0 \\ -1.1675 & -2.2213 & -11.023 & 34.196 & -10.310 & 0 & 0 \\ -0.4544 & -0.7131 & -1.7669 & -10.310 & 35.963 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2766.3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 4817.8 \end{bmatrix} \tag{17}$$

The time variation of acceleration in both translation and rotation is shown in Figure 2. From Figure 2a, it is noted that the peak translation acceleration of the foundation is 0.835*g*, which is close to the reported value. This confirms that the numerical code developed is accurate. The time variation of translation displacement and rotation is given in Figure 3. The peak translation displacement of the foundation is 0.437 mm (Figure 3a), and the peak rotation of the foundation is 0.014 radians (Figure 3b).

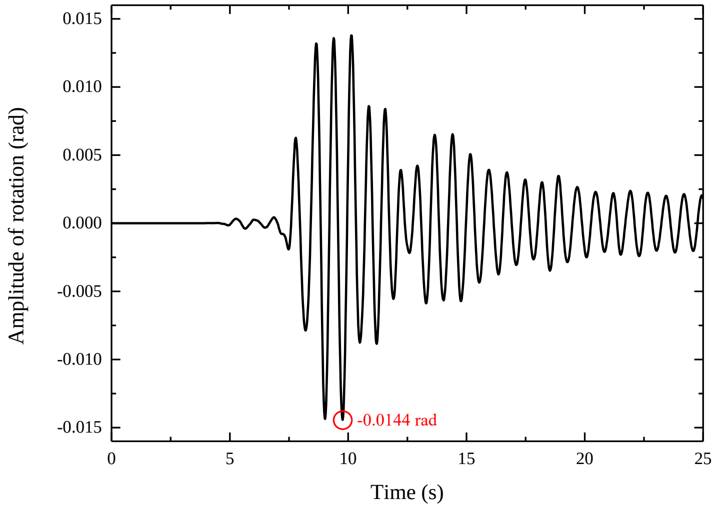


(a) (b)

Fig. 2 Time variation of soil (a) translation acceleration, and (b) rotation acceleration for a five-storey structure under Kobe, 1995 earthquake



(a)



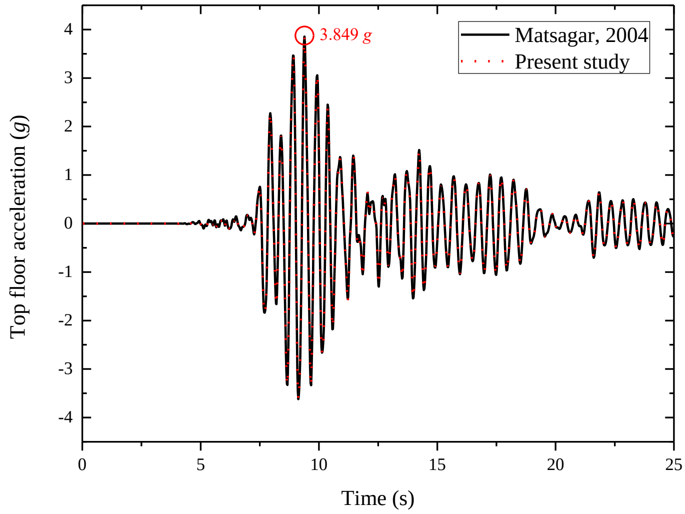
(b)

Fig. 3 Time variation of soil (a) translation displacement, and (b) rotation for a five-storey structure under Kobe, 1995 earthquake

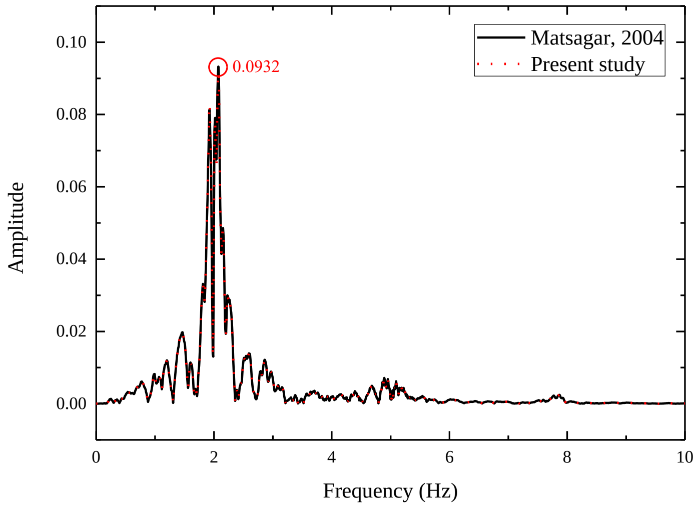
3. Validation of the Code

1. Comparison with Fixed-Base Results

The effect of soil degrees of freedom in the code is nullified by giving very high values for stiffness and negligible values for damping. The top floor acceleration, top floor displacement, and the fast Fourier transform (FFT) of the top floor acceleration are obtained for a five-storey building with time period 0.5 seconds under Kobe earthquake. The results are compared with the standard published results (Matsagar, 2004; Matsagar and Jangid, 2004) for fixed-base structures. Figure 4 shows the comparison of the variation of top floor acceleration in time domain and frequency domain obtained from the developed code and the published results. Figure 5 shows the comparison of the time variation of the top floor displacement obtained from the code and the published results. The comparison of the predicted response parameters is in close agreement with that of the results reported in the literature.



(a)



(b)

Fig. 4 Comparison of the top floor acceleration obtained from the code and the published results: (a) time domain and (b) frequency domain

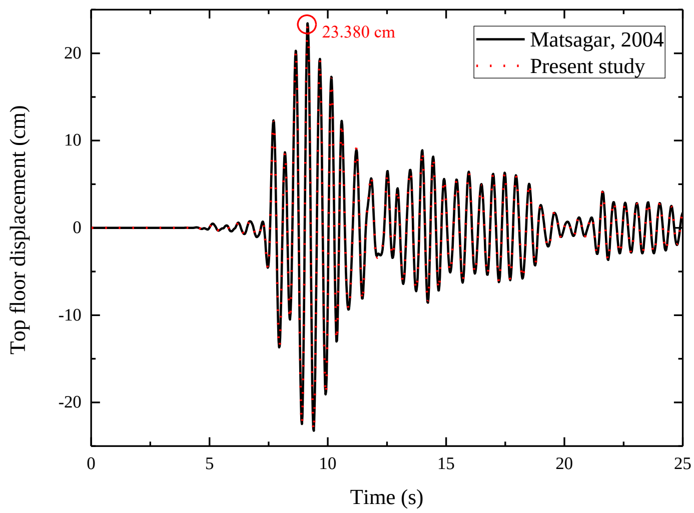


Fig. 5 Comparison of the time variation of top floor displacement obtained from the code and the published results

2. Comparison with Base-Isolated Structure Results

The rotation effect of the foundation is nullified and the translation stiffness and damping of the foundation are given the values of the stiffness and damping of the base-isolators. The results obtained from the code are found to be similar to that of the published results for the base-isolated structure. Figure 6 shows the comparison of the top floor acceleration obtained from the code and the published results in both time domain and frequency domain (Matsagar, 2004; Matsagar and Jangid, 2004). The comparison of results for base-isolated structure indicates that though the top floor acceleration has a reasonable agreement with reported results in time domain, there is a difference (29%) in the peak acceleration in frequency domain.

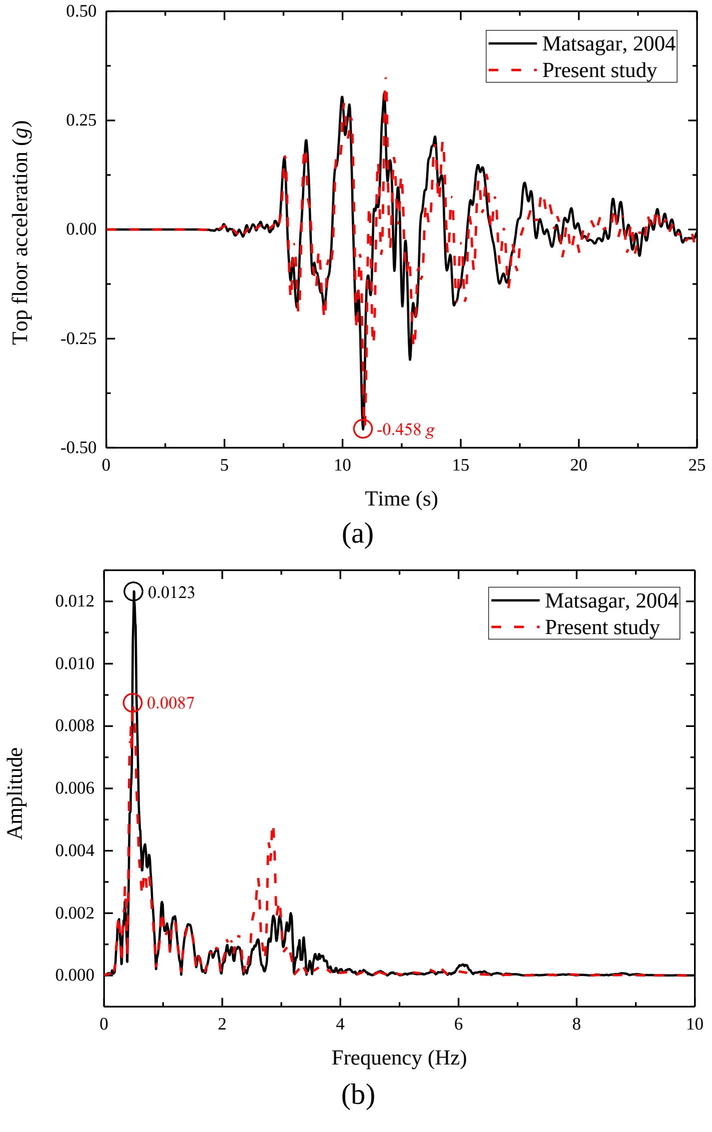


Fig. 6 Comparison of top floor acceleration obtained from the code and the published results for base-isolated structure in (a) time domain and (b) frequency domain

RESULTS AND DISCUSSIONS

By using the formulations described in the previous section various results have been obtained. These results are presented in a systematic way and the trends are discussed. Three different types of buildings are considered. The various parameters for the building, foundation, and the soil are given in the corresponding tables. The thickness of the foundation slab is considered to be 300 mm while calculating the coupled foundation response. The system parameters considered are given in Tables 2 and 3.

Table 2: System parameters for five-storey building

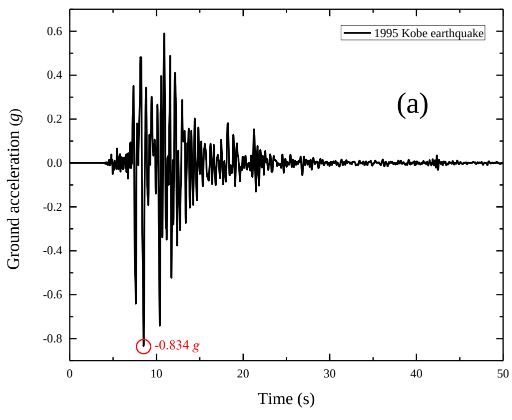
Model	Parameter	Symbol	Value	Unit
Superstructure	Floor mass	m_j, j = 1-5	15000	kg
	Ratio of column stiffness		1.0:1.0:1.0:1.0:1.0	
	Foundation to storey height	h_j, j = 1-5	3.5 × j	m
	Floor moment of inertia	I_j, j = 1-5	15000	kg m^2
	Time period	T_s	0.5	s
Foundation	Half side-width	b	1.75	m
	Mass	m_o	30000	kg
	Moment of inertia	I_o	30000	kg m^2

Table 3: Soil parameters for the different types of soils

Soil Type		Soft Soil	Medium Soil	Hard Soil	
Mass density	ρ	1700	1700	1700	kg m^3
Poisson's ratio	ν	1/3	1/3	1/3	
Shear wave velocity	C_s	100	150	300	m/s
Translational stiffness coefficient	K_h	161078400.0	362426400.0	1449705600.0	N/m
Rotational stiffness coefficient	K_r	542369631.0	1220331671.0	4881326684.0	N/m
Translational damping coefficient	C_h	1844219.0	2766328.0	5532656.0	N s/m
Rotational damping coefficient	C_r	2167309.0	4817869.42	9752891.0	N s/m

1. Response of Foundation with Superstructure Flexibility

The superstructure comprising of five floors with fundamental time period of 0.5 seconds is considered. The system is analyzed for the earthquake excitation of Kobe, 1995 earthquake. The time variation (Figure 7a) of Kobe earthquake ground acceleration and its fast Fourier transform (FFT) (Figure 7b) are plotted. The response of foundation obtained considering the effects of superstructure flexibility is compared with the lumped mass idealization and presented in Figures 8 through 10. Figure 8 presents the time variation of translational acceleration and rotational acceleration response of foundation, whereas Figure 9 presents their corresponding displacement response and the response in frequency domain (FFT) is presented in Figure 10. From the FFT response shown in Figure 10, it is seen that the effects of higher frequencies are not significant on rotational acceleration response when the superstructure flexibility is considered. However, it is noticed from Figure 9 that the translational displacement reduces substantially when the flexibility is considered, but the rotational displacement increases significantly.



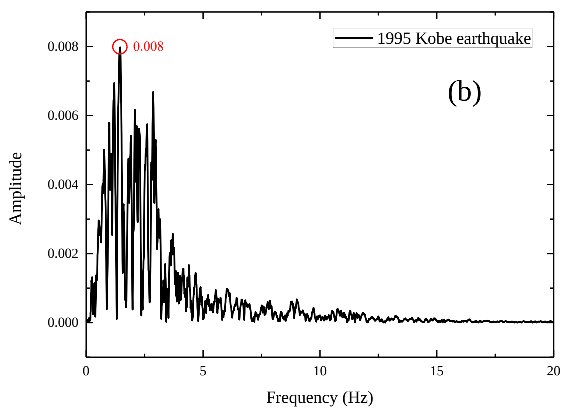
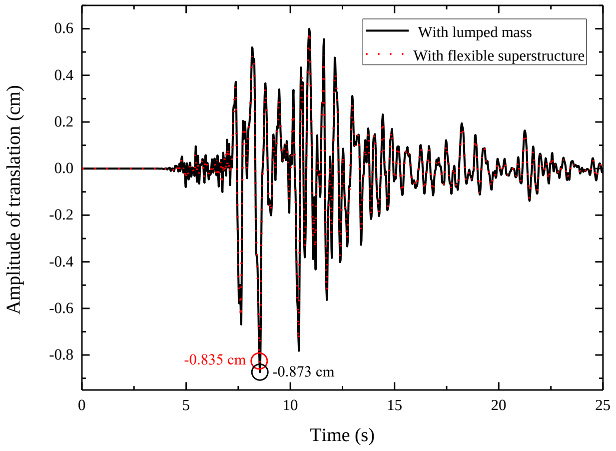
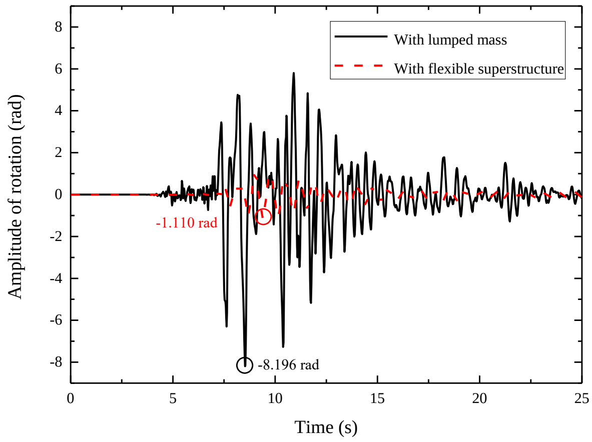


Fig. 7 The variation of the ground acceleration of the Kobe earthquake in (a) time domain and (b) frequency domain

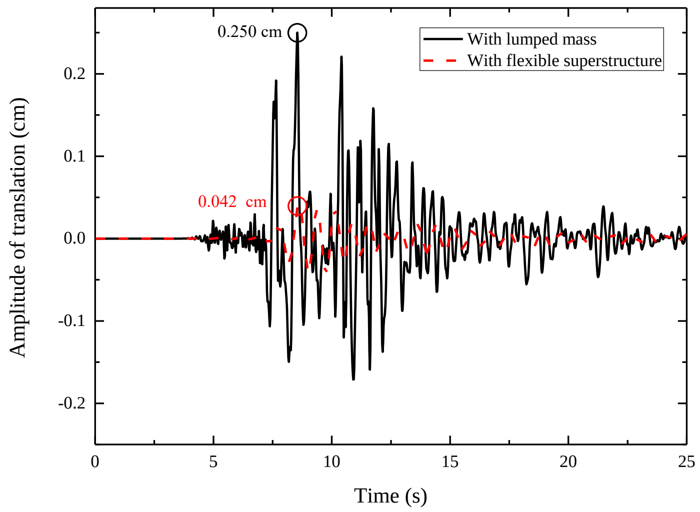


(a)

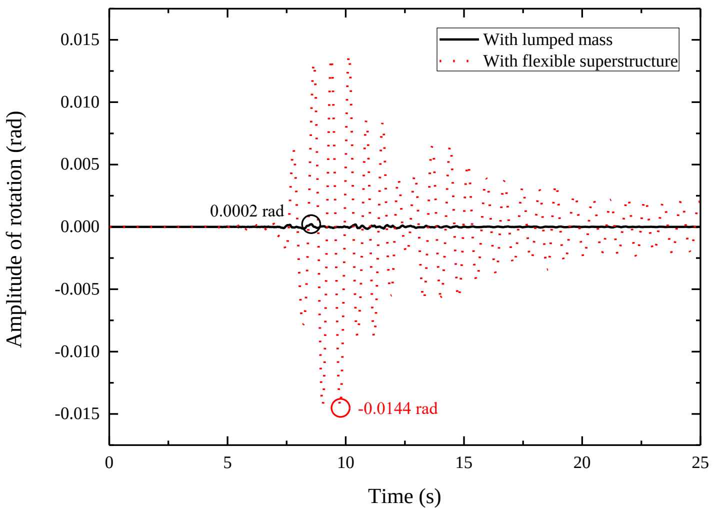


(b

Fig. 8 Effect of flexibility on the soil (a) translation acceleration, and (b) rotation acceleration for a five-storey superstructure



(a)



(b)

Fig. 9 Effect of flexibility on the soil (a) translation displacement, and (b) rotational displacement for a five-storey superstructure

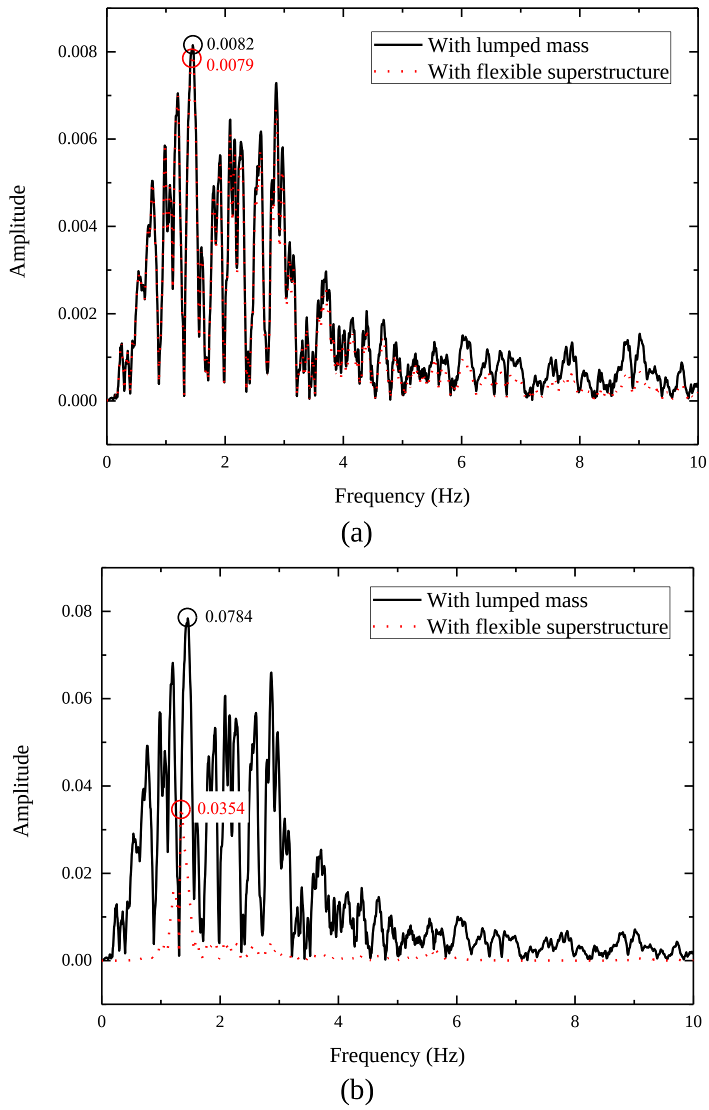
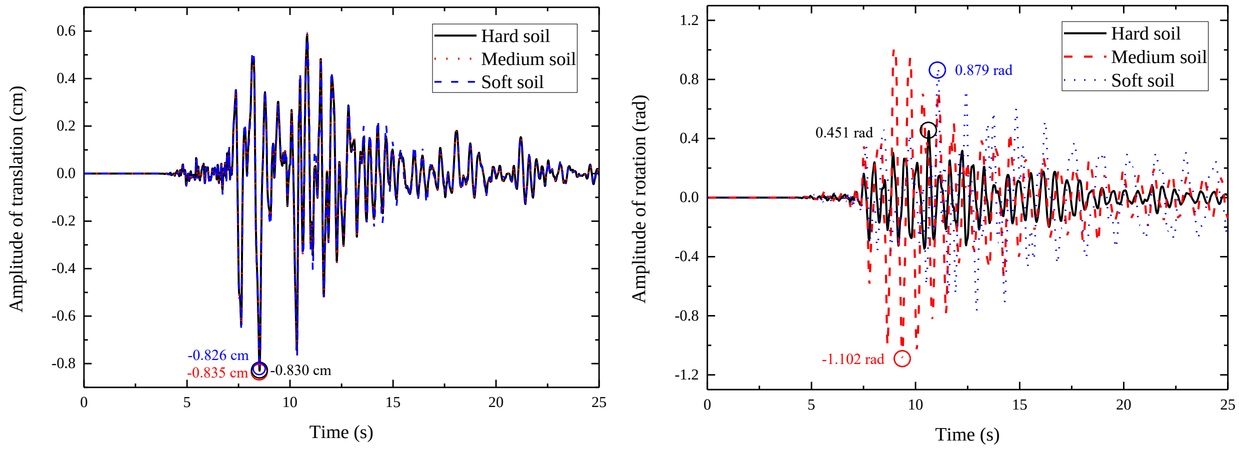


Fig. 10 Effect of flexibility on the FFT response of soil (a) translation acceleration, and (b) rotational acceleration for a five-storey superstructure

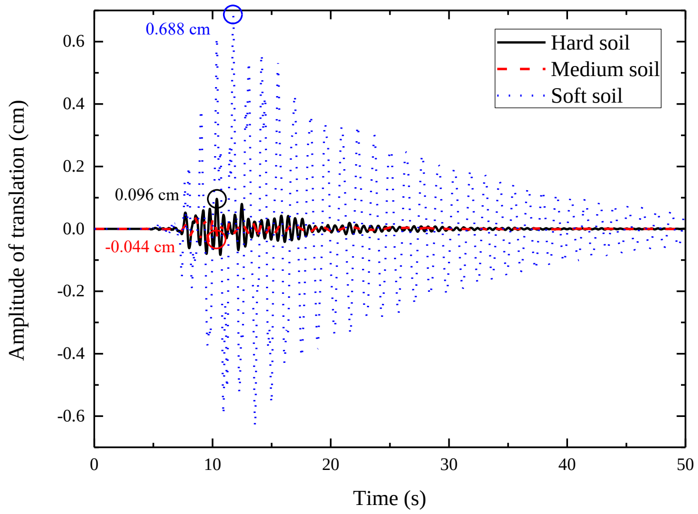
2. Effect of Soil Type on Dynamic Response

The superstructure comprising of five floors with fundamental time period of 0.5 seconds is considered. Three different soil types as described in Table 3 are used for conducting the analysis. Figures 11 through 13 present the effect of soil types on the response of foundation. Figure 11 presents the time variation of translational acceleration and rotational acceleration response of foundation for different soil types, whereas Figure 12 presents their corresponding displacement response. The response in frequency domain (FFT) is presented in Figure 13. As seen in Figure 11a, there is not much difference in the soil translation acceleration, however, the soil rotation acceleration (Figure 11b) varies significantly with the type of soil. This is due to the effect of soil-structure interaction (SSI), i.e., considered flexibility of soil. As the stiffness of the soil decreases, there is an increase in the displacements in both rotation and translation is observed (Figure 12). In addition, a significant shift in the fundamental natural frequency is observed when the soil type is accounted for in the analysis (Figure 13). It is evident from these findings that both soil types and superstructure flexibility have pronounced effects on the response of foundation vibration.

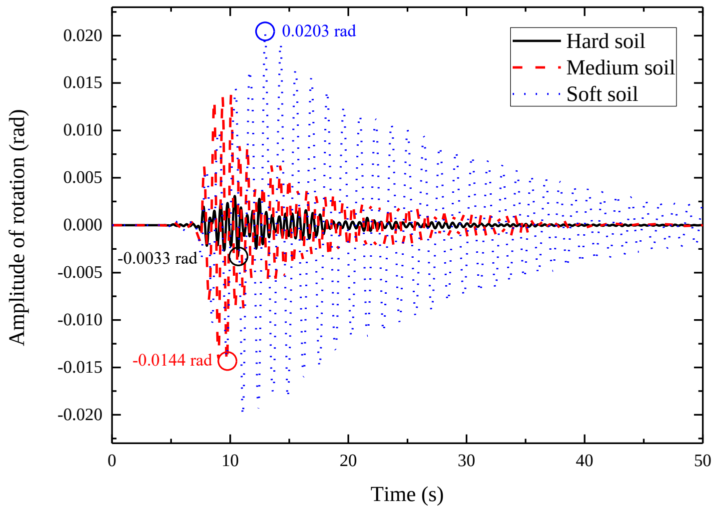


(a) (b)

Fig. 11 Effect of soil types on the foundation response: (a) translation acceleration, and (b) rotation acceleration for a five-storey superstructure



(a)



(b)

Fig. 12 Effect of soil types on the foundation response: (a) translation displacement, and (b) rotation displacement for a five-storey superstructure

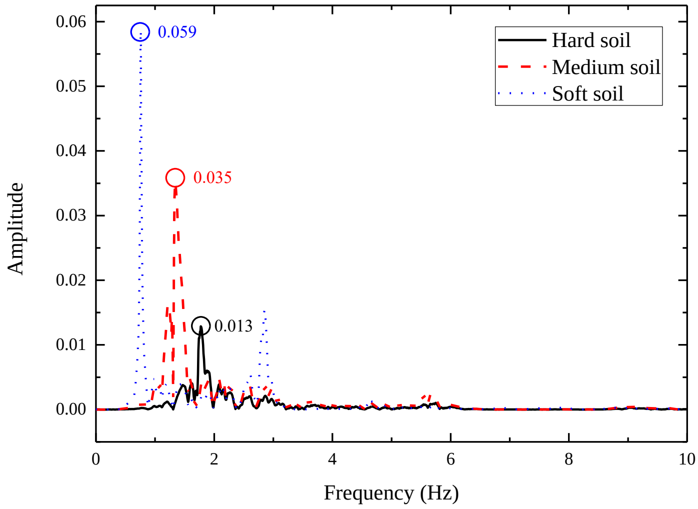


Fig. 13 Effect of soil types on the FFT response of foundation for a five-storey superstructure

CONCLUSIONS

A systematic modeling of dynamic soil-foundation-structure interaction considering superstructure flexibility in various soil/foundation conditions using analytical/numerical approach is presented in this research work. The effect of superstructure flexibility on the dynamic response of the foundation when excited by real earthquake ground motions is studied here. From the present study the following conclusions are drawn:

1. The effect of rotation in the foundation is completely ignored while considering the superstructure mass as a lumped mass on the foundation. This leads to erroneous results as the effect of rotation is of considerable amount when the superstructure flexibility is considered.
2. Superstructure flexibility eliminates the effect of higher frequencies in the foundation vibration response in translation and rotational modes.
3. The response quantities such as the translation and rotation increase with the decrease in the in the shear wave velocity of the soil.
4. The fundamental frequency of the foundation-superstructure system decreases with the decrease in shear wave velocity of the soil.

Overall, the soil flexibility considered in the dynamic soil-structure interaction (SSI) and the flexibility of superstructure have considerable effects on the vibration response quantities. Since the number of parameters (storeys, soil conditions, earthquake characteristics, etc.) considered in the present study are very limited, the results from the present study could not be used to develop semi-empirical equations for quantifying the effect of superstructure flexibility and soil types, as a recommendation. Therefore, it is strongly recommended to consider the site-specific analysis considering the soil types and superstructure flexibility for obtaining the realistic response of foundation/structure.

ACKNOWLEDGMENTS

Institutional support received from Indian Institute of Technology (IIT) Delhi, New Delhi, India and University of the Peloponnese, Patras, Greece is gratefully being acknowledged by all the authors.

REFERENCES

1. Chopra, A.K. (2001). "Dynamics of Structures: Theory and Applications to Earthquake Engineering", *Prentice-Hall, Englewood Cliffs, New Jersey (NJ), USA.*
2. Chopra, A.K. and Gutierrez, J.A. (2007). "Earthquake Response Analysis of Multistorey Buildings Including Foundation Interaction", *Earthquake Engineering and Structural Dynamics*, Vol. 3, No. 1, pp. 65-77.

3. Gupta, V.K. and Trifunac, M.D. (1991). "Seismic Response of Multistoried Buildings Including the Effects of Soil-Structure Interaction", *Soil Dynamics and Earthquake Engineering*, Vol. 10, No. 8, pp. 414-422.
4. Jean, W.Y., Lin, T.W. and Penzien, J. (2006). "System Parameters of Soil Foundations for Time Domain Dynamic Analysis", *Earthquake Engineering and Structural Dynamics*, Vol. 19, No. 4, pp. 541-553.
5. Jianguo, X., Danmin, W. and Tieming, F. (1993). "A Modified Lumped Parametric Model for Nonlinear Soil-Structure Interaction Analysis", *Soil Dynamics and Earthquake Engineering*, Vol. 12, No. 5, pp. 273-282.
6. Kramer, S.L. (1996). "Geotechnical Earthquake Engineering", *Prentice-Hall, New Jersey, USA*.
7. Kutanis, M. and Elmas, M. (2001). "Non-Linear Seismic Soil-Structure Interaction Analysis Based on the Substructure Method in the Time Domain", *Turkish Journal of Engineering and Environmental Science*, Vol. 25, pp. 617-626.
8. Matsagar, V.A. and Jangid, R.S. (2004). "Influence of Isolator Characteristics on the Response of Base-Isolated Structures", *Engineering Structures*, Vol. 26, pp. 1735-1749.
9. Matsagar, V.A. (2004). "Earthquake Behavior and Impact Response Control of Base-Isolated Buildings", *PhD Thesis*, Indian Institute of Technology (IIT) Bombay, Powai, Mumbai, India.
10. Saran, S. (2006). "Soil Dynamics and Machine Foundations", *Galgotia Publications, New Delhi, India*.
11. Shakib, H. and Fuladgar, A. (2004). "Dynamic Soil-Structure Interaction Effects on the Seismic Response of Asymmetric Buildings", *Soil Dynamics and Earthquake Engineering*, Vol. 24, pp. 379-388.
12. Takewaki, I., Takeda, N. and Uetani, K. (2003). "Fast Practical Evaluation of Soil-Structure Interaction of Embedded Structures", *Soil Dynamics and Earthquake Engineering*, Vol. 23, pp. 195-202.
13. Wair, B.R. and Dejong, J.T. (2012). "Guidelines for Estimation of Shear Wave Velocity Profiles", *Pacific Earthquake Engineering Research Center, California, USA*.
14. Wolf, J.P. (1988). "Soil Structure Interaction Analysis in Time Domain". *Prentice-Hall, Englewood Cliffs, New Jersey (NJ), USA*.
15. Wolf, J.P. (1994). "Foundation Vibration Analysis Using Simple Physical Models". *Prentice-Hall, Englewood Cliffs, New Jersey (NJ), USA*.
16. Wolf, J.P. (1997). "Spring-Dashpot-Mass Models for Foundation Vibrations", *Earthquake Engineering and Structural Dynamics*, Vol. 26, No. 9, pp. 931-949.
17. Wu, W.H. and Chen, C.Y. (2001). "An effective Fixed Base Model with Classical Normal Modes for Soil-Structure Interacting Systems", *Soil Dynamics and Earthquake Engineering*, Vol. 21, No. 8, pp. 689-698.
18. Wu, W.H. and Smith, H.A. (2006). "Efficient Modal Analysis for Structures with Soil-Structure Interaction", *Earthquake Engineering and Structural Dynamics*, Vol. 24, No. 2, pp. 283-299.