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Soil-structure interaction and axial force effect in structural vibration

H. Gao† and K. C. S. Kwok‡

School of Civil & Mining Engineering, The University of Sydney, NSW 2006, Australia

B. Samali‡†

Graduate School of Engineering, University of Technology, Sydney, NSW 2007, Australia

Abstract. A numerical procedure for dynamic analysis of structures including lateral-torsional coupling, axial force effect and soil-structure interaction is presented in this study. A simple soil-structure system model has been designed for microcomputer applications capable of reflecting both kinematic and inertial soil-foundation interaction as well as the effect of this interaction on the superstructure response. A parametric study focusing on inertial soil-structure interaction is carried out through a simplified nine-degree of freedom building model with different foundation conditions. The inertial soil-structure interaction and axial force effects on a 20-storey building excited by an Australian earthquake is analysed through its top floor displacement time history and envelope values of structural maximum displacement and shear force.

Key words: soil-structure interaction; kinematic soil-structure interaction; inertial soil-structure interaction; multistorey building; axial force effect; geometric non-linear stiffness.

1. Introduction

It is generally recognised that soil-structure interaction will effect structural vibrations induced by environmental loads such as earthquakes, winds or sea waves. Different soil conditions and different foundation properties will have different effects on structural response. When dealing with earthquake excitation, there are two factors contributing to these effects:

(1) the inability of a relatively rigid foundation to conform to non-uniform, spatially varying ground motion, i.e., so-called averaging reduction of motion by the foundation. This reflects the kinematic part of soil-foundation interaction;

(2) the action and reaction between the soil and the foundation causing soil deformation and foundation motion. This reflects the inertial part of soil-foundation interaction. For wind excitation, only (2) is relevant.

In relation to earthquake engineering, research work on the kinematic part of soil-foundation interaction shows that the response of a massless foundation to incident waves includes not

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† Research Scholar
‡ Associate Professor
‡† Associate Professor

only translational components but also torsional and rocking components because of the spatially varying nature of ground motion (Rutenberg *et al.* 1985, Mohsen *et al.* 1986, Luco *et al.* 1987ab, Li *et al.* 1993). This six-component response of a massless foundation forms the effective seismic input to the soil-structure system when a further analysis of structural response including the inertial part of soil-structure interaction is required.

Research into the inertial part of soil-foundation interaction requires the dynamic properties of soil as a pre-requisite, i.e., the dynamic compliance coefficients (flexibility or stiffness), damping coefficients and equivalent mass coefficients. To obtain these, several models have been used to describe the foundation soil characteristics such as a single-degree-of-freedom lumped-parameter model (for every direction) (Clough, *et al.* 1975, Roesset 1980, Wolf 1988), a two-degree-of-freedom lumped-parameter model (Wolf 1988), and corn models (Meek, *et al.* 1994). A comparison and relevant data pertaining to these models can be found in the works by Wolf (1988), as well as Roesset's review (1980).

A great amount of literature can be found on structural dynamic analyses including soil-structure interaction either theoretically or experimentally with varying assumptions and limitations (Avanessian, *et al.* 1986, Chandler, *et al.* 1987ab, Coyol, *et al.* 1989, Gupta, *et al.* 1991, Luco 1986, Lin, *et al.* 1984, McCallen, *et al.* 1994, Mita, *et al.* 1989, Novak, *et al.* 1988, Sikaroudi, *et al.* 1992, Sivakumaran, *et al.* 1994, Todorovska, *et al.* 1993ab, Tso, *et al.* 1992, Veletsos, *et al.* 1989). The objective of this paper is to focus on the inertial part of soil-structure interaction and its effect on the superstructure response in which the axial force effect is included, and on how this effect varies as soil conditions and foundation properties change. The soil-structure system includes a shear building superstructure (which has $3n$ degrees of freedom: n storeys and each storey with one torsional and two lateral degrees of freedom) and a rigid rectangular foundation base (which has five degrees of freedom: two translational and three rotational) resting on (or embedded in) an elastic half space foundation soil. The geometric non-linearity in superstructure stiffness includes not only the $P-\Delta$ effect but also the axial force and higher modes effects. The axial force effect in the example of this paper is more notable than the $P-\Delta$ effect discussed by Sivakumaran and Balendra (1994). This system is suitable for analyses on a microcomputer and gives a comprehensive description of the structure's dynamic behaviour. The input to the system is the effective input through the base including kinematic soil-structure interaction for earthquakes or external forces acting on individual floors for winds. The output of the system consists of the structural response components relative to the foundation base and the base motion caused by soil reaction. This arrangement simplifies the problem as soil-structure interaction does not influence the structural natural frequencies when considering relative motions. Furthermore, it is the relative structural response that is of practical interest to engineers in analysis and design.

Luco (1986) and Chandler, *et al.* (1987) pointed out in their studies that soil-structure interaction effects are highly dependent on the characteristics of the seismic excitation. In this study, a parametric study was carried out using a nine-degree of freedom building model. The influence of excitation and different parameters on the soil-structure interaction was displayed by the frequency responses under different soil and structure conditions. A 20 storey building subjected to an Australia earthquake excitation was analysed and its top floor displacement response time history as well as envelope values of displacement and shear force were displayed to demonstrate soil-structure interaction and axial force effects.

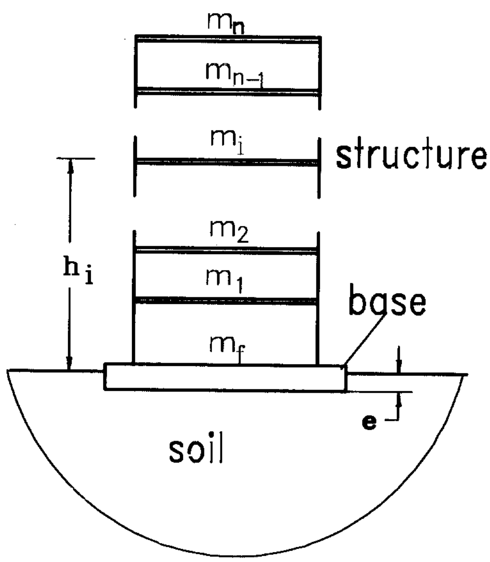


Fig. 1 Soil-structure system.

2. Soil-structure system

A soil-structure system consists of a superstructure, a foundation base and an elastic half space foundation soil as shown in Fig. 1. The mathematical models for these three components are described below.

2.1. Structure model

The structural characteristics of a multistorey building are modelled by a simple plate-beam system described by Gao, *et al.* (1994). The main features of the model are: the rigid floors (with three degrees of freedom each: two lateral and one torsional) connected by columns which have the same degrees of freedom at each end as the floors to which they are attached. The global coordinate system has the $X-Y$ plane lying at the ground level and the Z axis orienting upward. The origin is at the point O_0 which is the position of a vertical member (reference column) that continues right through the entire height of the building. The structure coordinates system and the degrees of freedom of the floor are shown in Fig. 2. Geometrical non-linear stiffness that includes not only the $P-\Delta$ effect but also the axial force and higher modes effects, is used for each column. The stiffness of jth column at ith level, $K_{i,j}$, which corresponds to displacement vector ($u_{i-1,j}$, $v_{i-1,j}$, θ_{i-1}, $u_{i,j}$, $v_{i,j}$, θ_i) can be expressed as:

$$K_{i,j}=K_{i,j}^{L}+K_{i,j}^{P-\Delta}+K_{i,j}^{P-\delta} \tag{1}$$

where $K_{i,j}^{L}$ is the linear stiffness of the column, $K_{i,j}^{P-\Delta}$, the non-linear stiffness caused by $P-\Delta$ effect and $K_{i,j}^{P-\delta}$ the non-linear stiffness caused by the axial force and higher modes deformation. The stiffness coefficients have following forms:

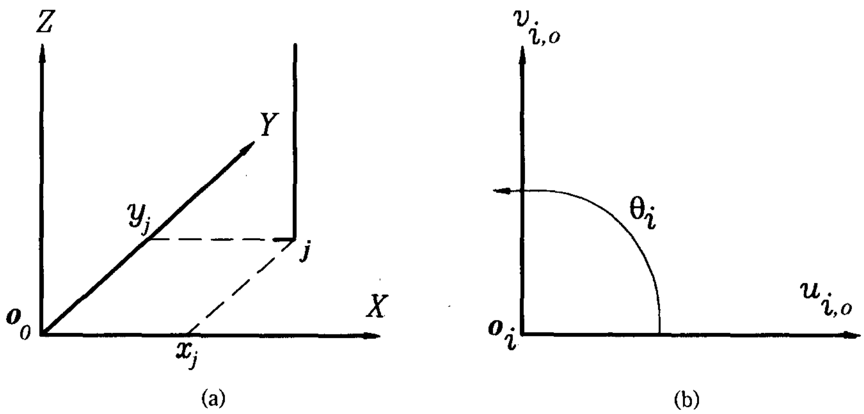


Fig. 2 (a) jth column in structure global coordinate system; (b) Degrees of freedom of ith floor.

$$K_{i,j}^{L}=\begin{bmatrix} \frac{12EI_y}{l^3} & 0 & 0 & -\frac{12EI_y}{l^3} & 0 & 0 \\ 0 & \frac{12EI_x}{l^3} & 0 & 0 & -\frac{12EI_x}{l^3} & 0 \\ 0 & 0 & \frac{GJ}{l} & 0 & 0 & -\frac{GJ}{l} \\ -\frac{12EI_y}{l^3} & 0 & 0 & \frac{12EI_y}{l^3} & 0 & 0 \\ 0 & -\frac{12EI_x}{l^3} & 0 & 0 & \frac{12EI_x}{l^3} & 0 \\ 0 & 0 & -\frac{GJ}{l} & 0 & 0 & \frac{GJ}{l} \end{bmatrix}$$

$$K_{i,j}^{P-\Delta}=\begin{bmatrix} \frac{1}{l} & 0 & 0 & -\frac{1}{l} & 0 & 0 \\ 0 & \frac{1}{l} & 0 & 0 & -\frac{1}{l} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{l} & 0 & 0 & \frac{1}{l} & 0 & 0 \\ 0 & -\frac{1}{l} & 0 & 0 & \frac{1}{l} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} N_{i,j} \qquad K_{i,j}^{P-\delta}=\begin{bmatrix} \frac{1}{5l} & 0 & 0 & -\frac{1}{5l} & 0 & 0 \\ 0 & \frac{1}{5l} & 0 & 0 & -\frac{1}{5l} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{5l} & 0 & 0 & \frac{1}{5l} & 0 & 0 \\ 0 & -\frac{1}{5l} & 0 & 0 & \frac{1}{5l} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} N_{i,j}$$

where $N_{i,j}$ is the axial force in the column (positive in tension and negative in compression). Let m_i denote the mass of the ith floor, $A_{i,j}$ the cross-sectional area of jth column at level i, $\ddot{z}_g$ the vertical ground acceleration and g the gravity acceleration, then, $N_{i,j}$ can be calculated by the following formula:

$$N_{i,j}=-\frac{A_{i,j}}{\sum_j A_{i,j}}\cdot\sum_{i=i}^{n} m_i(g+\ddot{z}_g) \tag{2}$$

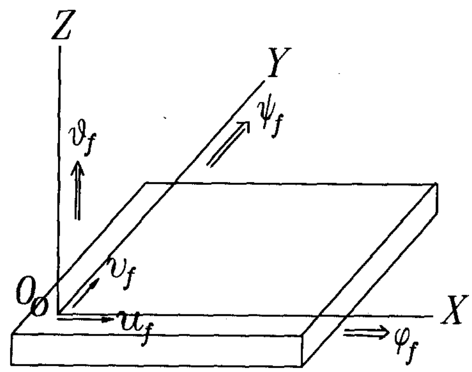


Fig. 3 Degrees of freedom of foundation base.

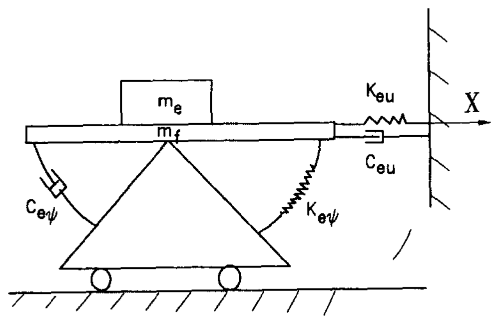


Fig. 4 Standard lumped-parameter model of foundation soil in $X-Z$ plane.

2.2. Foundation base model

The foundation base is considered as a rectangular rigid mat which possesses 5 degrees of freedom as shown in Fig. 3. The motion in the vertical direction is not considered.

2.3. Foundation soil model

A standard one-degree-of-freedom lumped parameter model is used to describe the elastic half space foundation soil in this study. By using this model, the foundation soil is simplified as a lumped mass which is added to the base, with a spring and a dashpot considered, in every direction, as shown in Fig. 4. For a circular foundation, a number of formulae are available to evaluate the stiffness coefficients and they have been compared and reviewed by Roesset (1980). In this study, the square foundation base was approximated as an equivalent foundation disk, and Elsabee and Kausel's soil stiffness formulae (Roesset 1980) were used. The corresponding soil mass and soil damping are described by the following formulae (Wolf 1988):

$$c_e = \frac{a}{c_s} k_e \gamma, \qquad m_e = \frac{a^2}{c_s^2} k_e \mu \tag{3}$$

Table 1 Static stiffness and dimensionless coefficients of standard lumped-parameter model for disk foundation (homogeneous half-space).

D. O. F.	Static stiffness k_e	Dimensionless coefficient γ	Dimensionless coefficient μ
Horizontal	$\frac{8Ga}{2-\nu}\left(1+0.67\frac{e}{a}\right)$	0.58	0.095
Vertical	$\frac{4Ga}{1-\nu}\left(1+0.67\frac{e}{a}\right)$	0.85	0.27
Rocking	$\frac{8Ga^3}{3(1-\nu)}\left(1+2\frac{e}{a}\right)$	$\frac{0.3}{1+\frac{3(1-\nu)m}{8a^5\rho}}$	0.24
Torsional	$\frac{16Ga^3}{3}\left(1+2.67\frac{e}{a}\right)$	$\frac{0.433}{1+\frac{2m}{5a^5\rho}}\sqrt{\frac{m}{a^5\rho}}$	0.045
H-R Coupling	$\frac{1.6Ga}{1-\nu}\left(1+0.47\frac{e}{a}\right)$	–	–

where a is the radius of disk foundation, c_s: shear wave velocity, γ: dimensionless damping coefficient and μ: dimensionless mass coefficient. The stiffness k_e and dimensionless coefficients γ and μ for every degree of freedom are listed in Table 1.

3. Equations of motion for soil-structure system

3.1 Definitions

The structural global displacement is denoted by the vector:

$$\Delta_s=(u_{s1},\ v_{s1},\ \theta_{s1},\ \cdots,\ u_{sn},\ v_{sn},\ \theta_{sn})^T \tag{4}$$

The structural displacement relative to the foundation base is denoted by the vector:

$$\delta_s=(u_1,\ v_1,\ \theta_1,\ \cdots,\ u_n,\ v_n,\ \theta_n)^T \tag{5}$$

The foundation base global displacement is denoted by vector Δ_f which has two components:
(1) the massless base displacement δ_g due to free field motion;
(2) base displacement δ_e due to the reaction of the soil, such that

$$\Delta_f=\delta_g+\delta_e \tag{6}$$

where

$$\left.\begin{aligned}\Delta_f&=(u_f,\ v_f,\ \theta_f,\ \phi_f,\ \psi_f)^T\\ \delta_g&=(u_g,\ v_g,\ \theta_g,\ \phi_g,\ \psi_g)^T\\ \delta_e&=(u_e,\ v_e,\ \theta_e,\ \phi_e,\ \psi_e)^T\end{aligned}\right\} \tag{7}$$

The foundation displacement relative to the first floor of the structure is denoted by the vector:

$$\delta_f=(u_1',\ v_1'.\ \theta_1',\ 0,\ 0)^T \tag{8}$$

Between structural global and relative displacements, the following relationships exist:

$$\begin{cases} u_{si}=u_i+u_f+h_i\,\psi_f \\ v_{si}=v_i+v_f-h_i\,\phi_f \\ \theta_{si}=\theta_i+\theta_f \end{cases} \tag{9}$$

The transformation between structure relative and global displacements is

$$\Delta_s=\delta_s+T_f\Delta_f \tag{10}$$

where

$$T_f=\begin{pmatrix} T_1 \\ T_2 \\ \vdots \\ T_n \end{pmatrix};\qquad T_i=\begin{bmatrix} 1 & 0 & 0 & 0 & h_i \\ 0 & 1 & 0 & -h_i & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \tag{11}$$

Between base global and relative displacements the following relationships exist:

$$\begin{cases} u_f=u_1'+u_{s1}-h_1\,\psi_f \\ v_f=v_1'+v_{s1}+h_1\,\phi_f \\ \theta_f=\theta_1'+\theta_{s1} \end{cases} \tag{12}$$

so does·

$$\Delta_f=\delta_f+T_s\,\Delta_s+R_0\,\Delta_f \tag{13}$$

where

$$T_s=\begin{bmatrix} 1 & 0 & 0 & 0 & \cdots\cdots & 0 \\ 0 & 1 & 0 & 0 & \cdots\cdots & 0 \\ 0 & 0 & 1 & 0 & \cdots\cdots & 0 \\ 0 & 0 & 0 & 0 & \cdots\cdots & 0 \\ 0 & 0 & 0 & 0 & \cdots\cdots & 0 \end{bmatrix};\qquad R_0=\begin{bmatrix} 0 & 0 & 0 & 0 & -h_1 \\ 0 & 0 & 0 & h_1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The transformation between base relative and global displacements is

$$R_1\,\Delta_f=\delta_f+T_s\,\Delta_s \tag{15}$$

where

$R_1=I-R_0$ and I is a unit matrix

3.2. Equilibrium equation of superstructure

The equilibrium equation of superstructure is

$$M_s\ddot{\Delta}_s-C_s\dot{\delta}_s+K_s\,\delta_s=F_w \tag{16}$$

Using Eq. (10) and Eq. (6) and substituting for $\ddot{\Delta}_s$, one obtains

$$M_s\ddot{\delta}_s+C_s\dot{\delta}_s+K_s\delta_s+M_sT_f\ddot{\delta}_e=F_w-M_sT_f\ddot{\delta}_g \tag{17}$$

Where $3n\times3n$ matrices M_s, C_s, K_s are the mass, damping and stiffness matrices of the superstructure respectively, $F_w=(F_{x1},\ F_{y1},\ 0,\ \cdots,\ F_{xn},\ F_{yn},\ 0)^T$ is the wind load vector. Note that either wind or earthquake load will be considered as input to the system and hence one of the terms in the right hand side of Eq. (17) will be zero in real applications.

3.3. Equilibrium equation of foundation base

Because foundation soil was simplified as lumped masses with springs and dashpots attached to the foundation base, the foundation base equilibrium equation can be expressed as

$$(M_e+M_f)\ddot{\Delta}_f+C_f\dot{\delta}_f+K_f\delta_f=F_e+F_s \tag{18}$$

Where M_e is the equivalent soil mass matrix added to the base. M_f, C_f and K_f are the base mass matrix, the base damping and the base stiffness matrices respectively, that are determined by the properties of first level columns.
F_e is the soil reaction force to the base which can be expressed as

$$F_e=-C_e\dot{\delta}_e-K_e\delta_e \tag{19}$$

where C_e and K_e are the equivalent soil damping and stiffness matrices.

F_s is the bending moment exerted on the base by the superstructure and can be calculated as

$$F_s=\begin{pmatrix} 0 \\ 0 \\ 0 \\ \sum(m_i\ddot{v}_{si}-F_{yi})h_i \\ -\sum(m_i\ddot{u}_{si}-F_{xi})h_i \end{pmatrix}=R_2M_s\ddot{\Delta}_s-R_2F_w \tag{20}$$

where R_2 is a $5\times3n$ matrix as follows

$$R_2=\begin{bmatrix} 0,0,0, & \cdots, & \cdots\cdots, & 0,0,0 \\ 0,0,0, & \cdots, & \cdots\cdots, & 0,0,0 \\ 0,0,0, & \cdots, & \cdots\cdots, & 0,0,0 \\ 0,h_1,0, & 0,h_2,0, & \cdots\cdots, & 0,h_n,0 \\ -h_1,0,0, & -h_2,0,0, & \cdots\cdots, & -h_n,0,0 \end{bmatrix} \tag{21}$$

Substituting Eqs. (6), (10), (19) and (20) into (18) yields the equation of motion for the foundation base:

$$\begin{aligned}&(M_e+M_f-R_2M_sT_f)\ddot{\delta}_e+[C_e+C_f(R_1-T_sT_f)]\,\dot{\delta}_e+[K_e+K_f(R_1-T_sT_f)\,\delta_e-C_fT_s\dot{\delta}_s\\&-K_fT_s\delta_s-R_2M_s\ddot{\delta}_s=-R_2F_w-(M_e+M_f-R_2M_sT_f)\,\ddot{\delta}_g-C_f(R_1-T_sT_f)\,\dot{\delta}_g-K_f(R_1-T_sT_f)\,\delta_g\end{aligned} \tag{22a}$$

It is not difficult to prove that $R_1-T_sT_f=0$, so, Eq. (22a) can be simplified as:

$$(M_e+M_f-R_2M_sT_f)\,\ddot{\delta}_e+C_e\dot{\delta}_e+K_e\delta_e-C_fT_s\dot{\delta}_s-K_fT_s\delta_s-R_2M_s\ddot{\delta}_s=-R_2F_w-(M_e+M_f-R_2M_sT_f)\ddot{\delta}_g \tag{22b}$$

3.4 Equations of motion of soil-structure system

Combining Eqs. (17) and (22b), The equations of motion for the soil-structure system can be written as

$$\begin{bmatrix} M_s & M_sT_f \\ -R_2M_s & M_f+M_e-R_2M_sT_f \end{bmatrix}\cdot\begin{pmatrix} \ddot{\delta}_s \\ \ddot{\delta}_e \end{pmatrix}+\begin{bmatrix} C_s & O \\ -C_fT_s & C_e \end{bmatrix}\cdot\begin{pmatrix} \dot{\delta}_s \\ \dot{\delta}_e \end{pmatrix}+\begin{bmatrix} K_s & O \\ -K_fT_s & K_e \end{bmatrix}\cdot\begin{pmatrix} \delta_s \\ \delta_e \end{pmatrix}$$

$$=\begin{bmatrix} I \\ -R_2 \end{bmatrix}F_w-\begin{bmatrix} M_sT_f \\ M_f+M_e-R_2M_sT_f \end{bmatrix}\ddot{\delta}_g \tag{23}$$

Eq. (23) can be used for both earthquake (where $F_w=0$) and wind (where $\ddot{\delta}_g=0$) excitations. Eq. (23) shows that in earthquake situation, the structural relative motion is only explicitly a function of ground acceleration; the ground velocity and displacement do not explicitly effect the relative motion of the structure. Using Eq. (23) in relation to earthquake excitation, the input to the system is a five-component base acceleration which can be calculated by using effective earthquake input theory for every earthquake situation. As for the influence of the vertical component, it can be included through axial force effect. This influence can be neglected when the magnitude of vertical component, in comparison with gravity acceleration g, is small. The output of the system is coupled lateral-torsional superstructure relative responses which are the concern of the design engineer, and the base motions caused by soil deformation which reflect the inertial interaction between soil and foundation.

4. Parametric study

In order to concentrate on soil-structure interaction, a symmetrical nine-degree of freedom model (3 storeys with 3-DOF each) was used to represent an intermediate-height building and a single direction input was used. The influence of relevant parameters of the soil-structure system (not the influence of excitation components which will be studied later) on the response of the structure was examined for two cases: (1) a single lateral base acceleration input; (2) uni-directional external forces exerted at each floor level. To demonstrate the influence of excitation frequency on the soil-structure interaction, a harmonic excitation was used to obtain the frequency responses of the superstructure with various parameters. The base acceleration and the external force have the following forms:

$$\ddot{u}_g=A_g\sin(\omega t); \qquad F_i=A_w\sin(\omega t) \tag{24}$$

The geometric model of the building is shown in Fig. 5. The base is a square mat with a side of $2b$. The foundation soil property data approximated by that of a circular base with equivalent radius $a=1.14b$ (having the same moment of inertia and an approximately equal area to that of the square base). Mita and Luco (1989) achieved reasonable accuracy by using a similar approximation. The foundation soil is an elastic half-space which is mainly characterised by its shear wave velocity. In this study, three different soil types with shear wave velocities of 150 m/s, 300 m/s and 600 m/s respectively are investigated. The lower shear wave velocity corresponded to soft sandy soil while a foundation with shear wave velocity of 600 m/s can be considered as approaching a bedrock. The soil density and Poison's ratio are assumed to be 1800 kg/m^3 and 0.4 respectively.

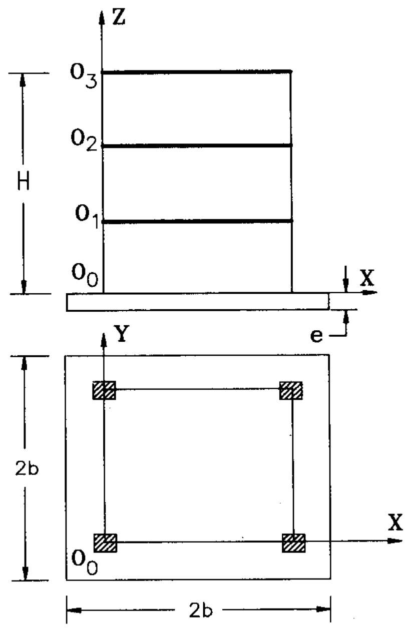
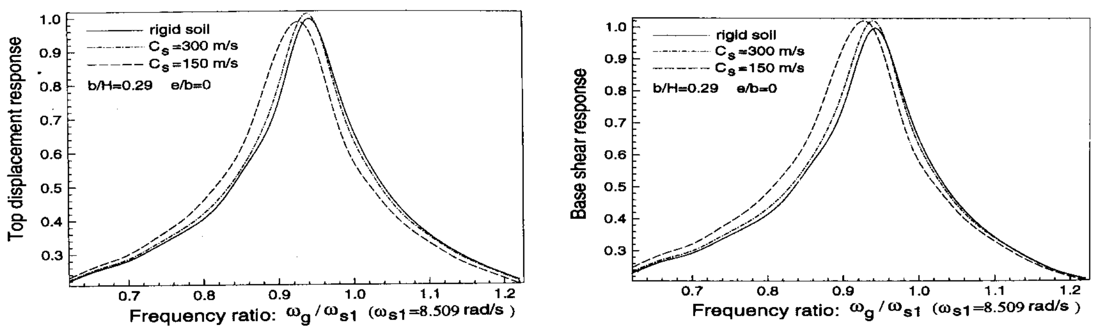


Fig. 5 A nine-degree of freedom building model.



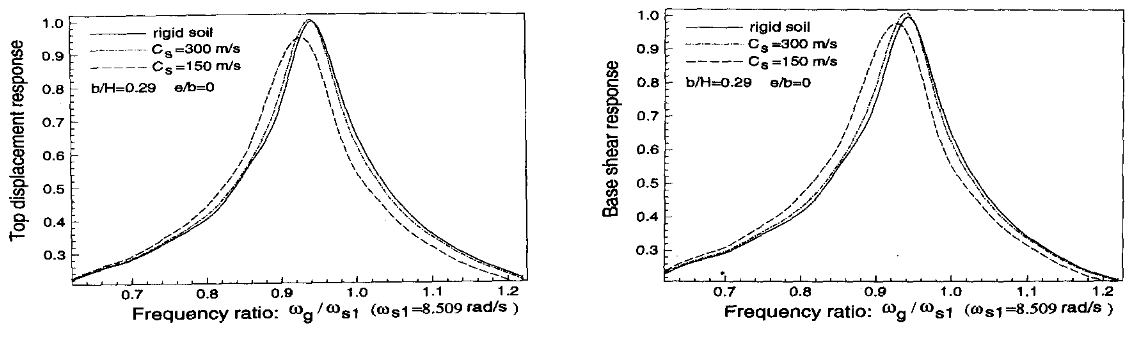
(a) (b)

Fig. 6 Influence of shear wave velocity on lateral response of structure to one lateral base acceleration excitation.

4.1. Influence of soil stiffness, structure stiffness and structure mass

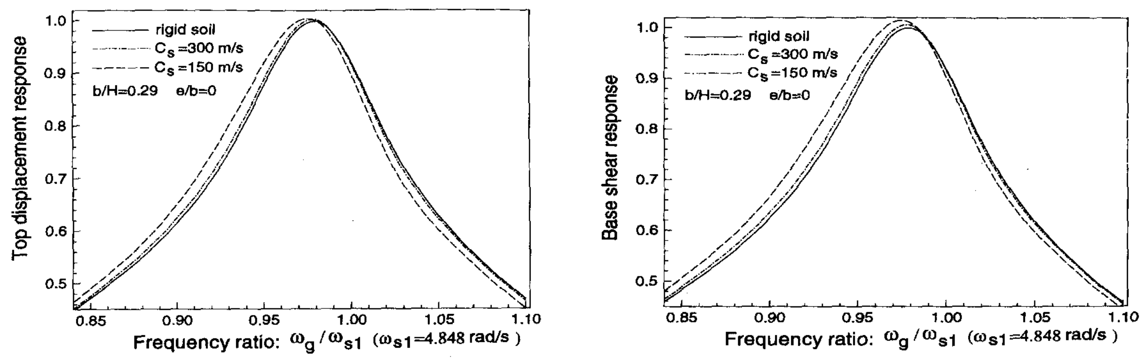
Three structural systems with varied characteristics were investigated. The dimensionless frequency responses are used to display the influence of excitation, structure and soil parameters on the effects of soil-structure interaction. The dimensionless frequency responses are obtained by dividing all frequency responses by the peak response which occurs in a rigid soil condition.

Firstly, the fundamental circular frequency of the building model was tuned at 8.509 rad/s (which is consistent with a building about 50 m in height). Fig. 6 and Fig. 7 show the frequency response of this building in the two excitation cases. From these two figures, one can observe that the effect of soil-structure interaction increases as the soil stiffness decreases (i.e., soil wave



(a) (b)

Fig. 7 Influence of shear wave velocity on lateral response of structure to external load excitation.



(a) (b)

Fig. 8 Influence of shear wave velocity on lateral response of flexible structure to one lateral base acceleration excitation.

velocity decreases). The soil-structure interaction lowered the resonant frequency of the structure compared to that of a structure on a rigid soil. And the peak response is changed after the soil-structure interaction is included.

Secondly, stiffness of the columns were decreased while keeping the geometric and other conditions of the building unchanged. The fundamental circular frequency of the building model was now changed corresponding to 4.848 rad/s. The frequency response of this more flexible building to base acceleration excitation is shown in Fig. 8. Compared with Fig. 6 one can observe that the effect of soil-structure interaction on the stiffer building is more pronounced than on the more flexible building.

Thirdly, increasing mass and stiffness of the building simultaneously while keeping all the other conditions unchanged. The mass and stiffness were increased at the same proportion in order to avoid any change in fundamental frequency. Fig. 9 shows how increasing the building mass by ten times influences the soil-structure interaction and the response of the superstructure to base acceleration excitation. Comparison with Fig. 7, confirms that the building mass has an obvious influence on soil-structure interaction and that soil-structure interaction effects the heavier buildings more significantly. Tordorvska and Trifunac (1993a) obtained similar results from their 2-D building-soil model.

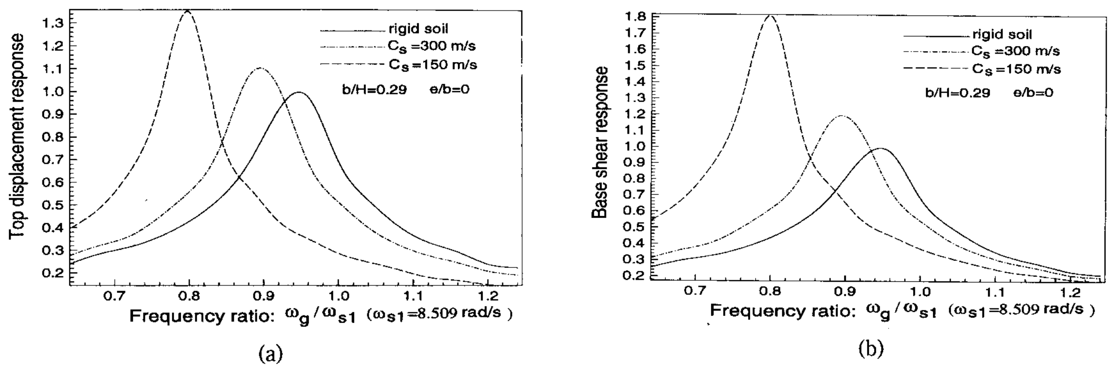


Fig. 9 Influence of shear wave velocity on lateral response of heavy structure to one lateral base acceleration excitation.

From Figs. 6 to 9, the following observations can be made:

(1) As shear wave velocity of soil increases, the effect of soil-structure interaction on the response of structure (top displacement and base shear) decreases.

(2) The effect of soil-structure interaction on the structural response has two consequences: a change in the peak response and a lowering of the resonant frequency.

(3) Generally, for a building having the same geometric characteristic, the stiffer one (with a higher fundamental frequency) and the heavier one (with a bigger mass) will be more significantly influenced by soil-structure interaction.

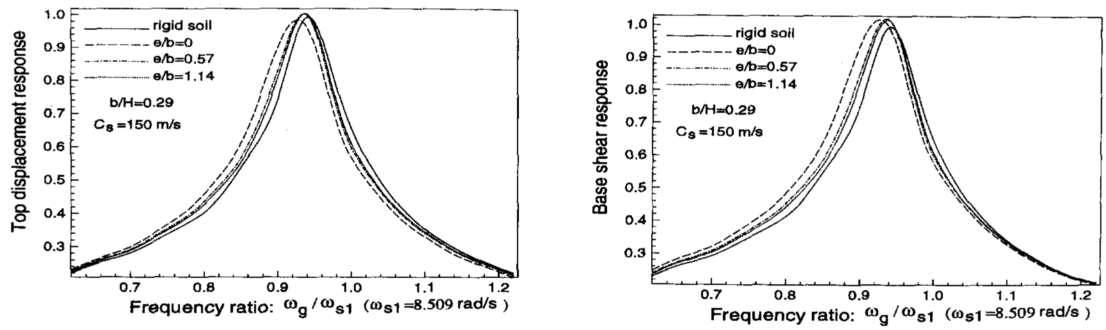
(4) Generally, for an excitation whose dominant frequency is higher (or not much lower) than the structural fundamental frequency, the soil-structure interaction will reduce the maximum structural response. If the excitation frequency is lower than the structural fundamental frequency, the soil-structure interaction may increase the maximum structural response.

(5) In Figs. 6 to 9, the peak response for a rigid soil condition corresponded to a frequency ratio lower than 1. This reflects the coupling effect of the motion in lowering the resonant frequency of the structural response.

4.2. Influence of base embedment, base size and base density

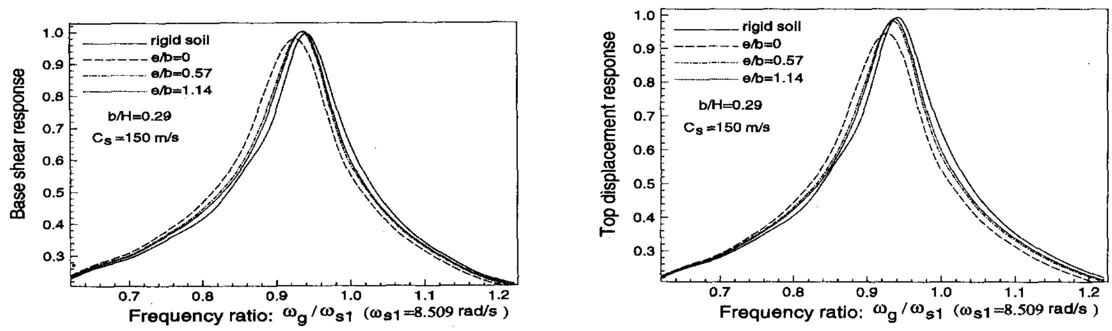
In a soft soil environment, systems with different base embedment were considered. Fig. 10 and Fig. 11 show the influence of embedment on the structure's lateral response to the base acceleration and external load, respectively. A deeply embedded base can help reduce the effect of soil-structure interaction on the lateral response of the superstructure. This is in agreement with other researcher's findings (Avenessian, *et al.* 1986, Chandler, *et al* 1987). Systems with different base sizes were also considered. Fig. 12 and Fig. 13 show the influence of base size on lateral structural responses under different excitations. Increasing the size of the base, like increasing embedment ratio, can reduce the effect of soil-structure interaction on the lateral responses of the superstructure.

The numerical results of the systems with different foundation masses were also obtained and they show that foundation mass has little influence on the effect of soil-structure interaction. This confirms Veletsos and Tang's assumption (1989) that zero base mass is reasonable, but



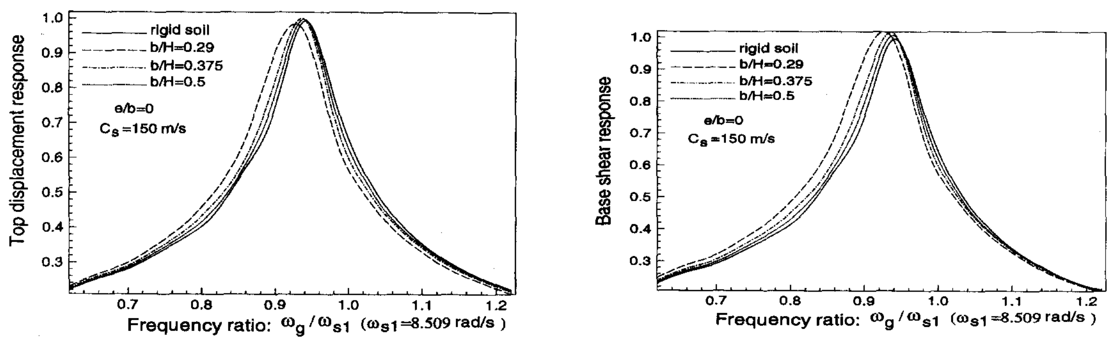
(a) (b)

Fig. 10 Influence of embedment ratio on lateral response of structure to one lateral base acceleration excitation.



(a) (b)

Fig. 11 Influence of embedment ratio on lateral response of structure to external load excitation.



(a) (b)

Fig. 12 Influence of base size on lateral response of structure to one lateral base acceleration excitation.

contradicts Tordorvska's results (1993b). In Tordovska's case, structure mass was set to zero, thereby heightened the influence of base mass. In fact, in a soil-structure system, the base mass is only a small portion of the total mass.

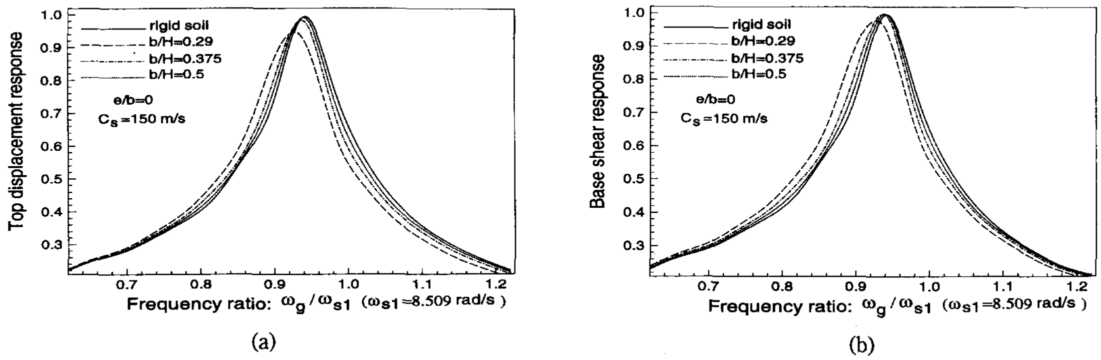


Fig. 13 Influence of base size on lateral response of structure to external load excitation.

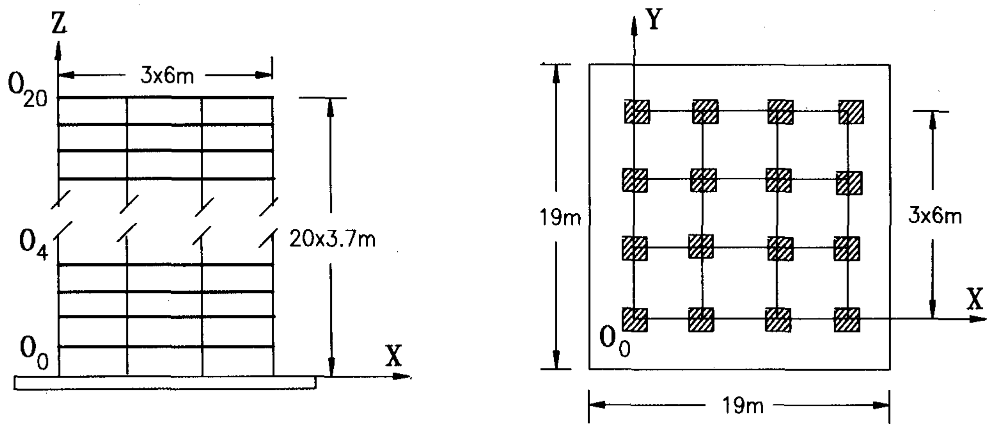


Fig. 14 A 20 storey example building.

Table 2 Structural properties of the 20 storey building.

Storey No.	Floor weight (KN)	Inner column $\frac{I}{I_0}$	Outer column $\frac{I}{I_0}$
1	1423	24	12
2~4	1397	24	12
5~7	1281	20	10
8~10	1263	12	6
11~13	1041	9	4.5
14~16	1005	6	3
17~19	881	3	1.5
20	783	2	1

5. Numerical example

A 20-storey building whose elevation and plan views and relevant data are shown in Fig. 14 and Table 2 was analysed. The building has square columns and dual fundamental frequency

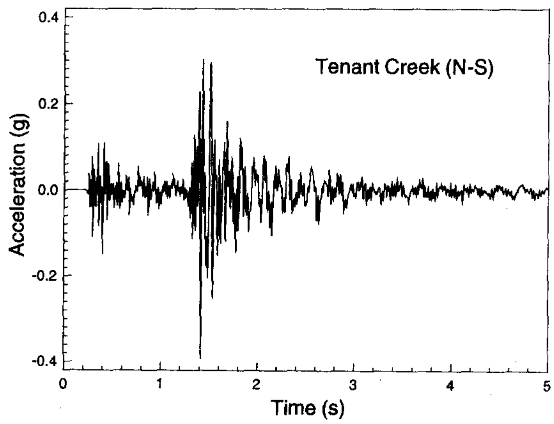
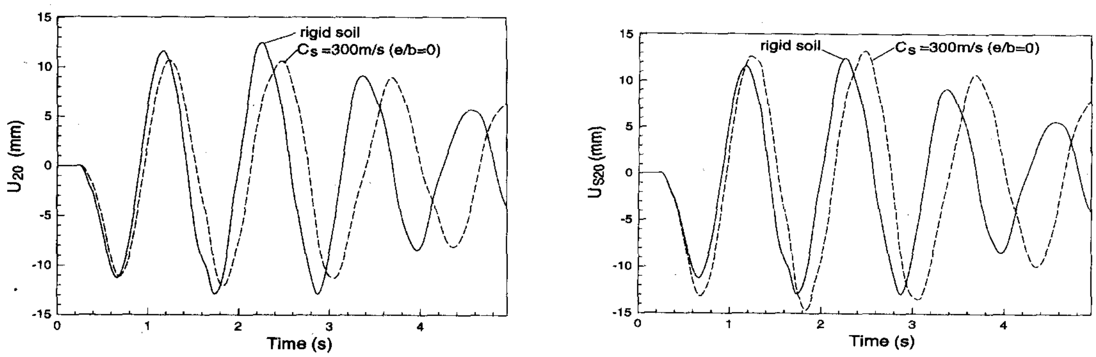


Fig. 15 Record of Tenant Creek earthquake of Australia 1988 (north-south).

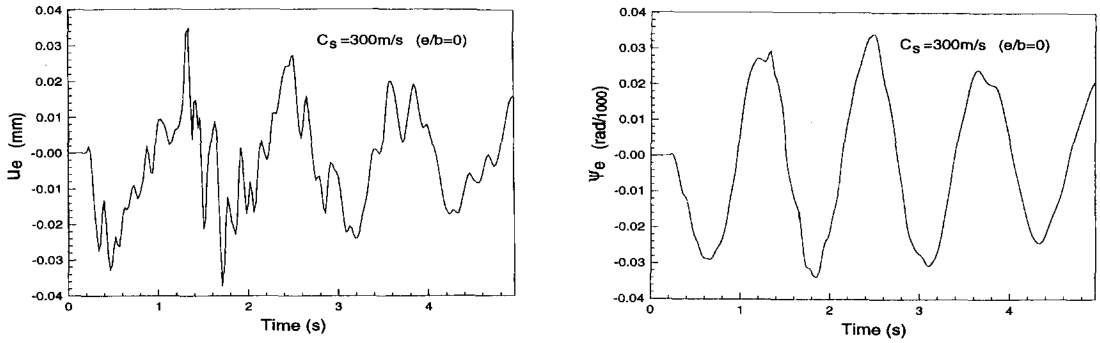


(a) relative (b) global.

Fig. 16 Top floor lateral displacement time history of 20-storey building under Tenant Creek earthquake excitation.

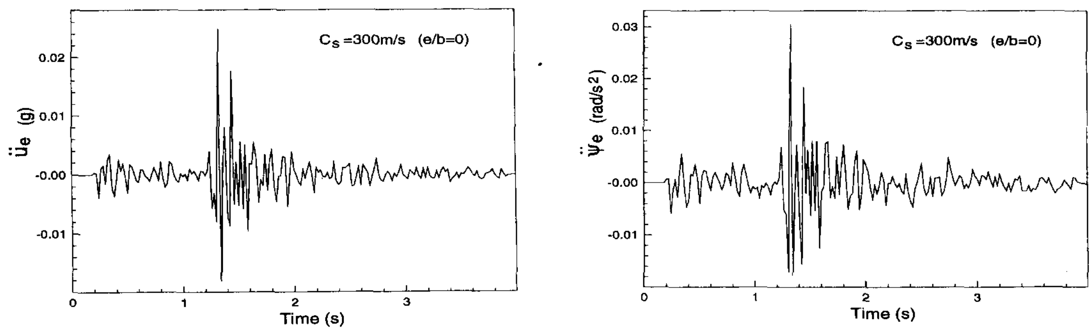
of 8.51 rad/s (period=1.08s) in X and Y directions. The foundation base is a 19 m×19 m mat. The excitation was a single direction base acceleration adopted from an Australian earthquake record (Tenant Creek 1988) as shown in Fig. 15 with a time step of 0.02 seconds. The responses of the building under different soil conditions were calculated and the results discussed in the following (kinematic soil-structure interaction is not considered here):

The top floor displacement response time histories, both relative and global are shown in Fig. 16. According to an analysis by Samali, *et al.* (1994) the dominant frequency of the Tenant Creek earthquake 1988 is within the range of 15 to 314 rad/s which is higher than the superstructure fundamental frequency. The soil-structure interaction suppresses the structural relative vibration in this case. The base displacement responses in both lateral and rocking are shown in Fig. 17. The relationship $u_{si}=u_i+u_e+h_i\psi_e$ exists between the global and relative displacements. It is through base acceleration response (which is shown in Fig. 18) that soil-structure interaction influences the superstructure response. The base accelerations, $\ddot{u}_e$ and $\ddot{\psi}_e$ together with $\ddot{u}_g$ become the actual excitation to the relative motion of the superstructure in soft soil situations. Figs. 19 and 20 give the envelope values of structure displacement and shear force. To show the influence of axial force on the response of this building, the calculations were carried out twice:



(a) Displacement (b) Rocking

Fig. 17 Base response time histories under Tenant Creek earthquake excitation.



(a) Lateral (b) Rocking

Fig. 18 Base acceleration response time histories under Tenant Creek earthquake excitation.

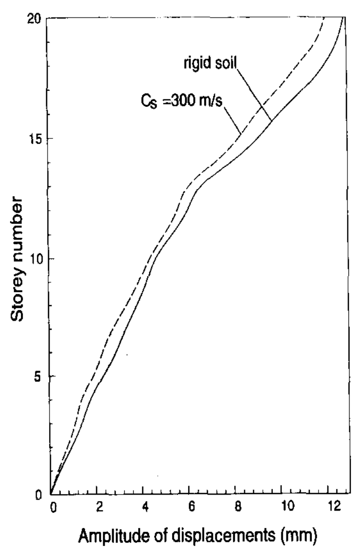


Fig. 19 Envelope values of maximum displacement of the 20-storey building under Tenant Creek earthquake excitation

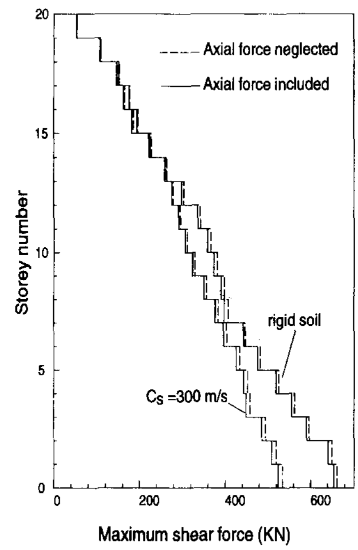


Fig. 20 Envelope values of maximum shear force of the 20-storey building under Tenant Creek earthquake excitation.

by including and then excluding the axial force effect. The numerical results show that the presence of axial force slightly increases top displacement and decreases base shear. As this building has a non-uniform distribution in stiffness and mass along its height, axial force effects appear more notable on shear force than on displacement. The effect of soil-structure interaction on building response is not a monotonous increase (or decrease) along the building height. This may be the result of the soil-structure interaction influencing the higher modes in the building motion. Both Figs. 19 and 20 show that the axial force effects the higher modes of the building motion.

6. Conclusions

A numerical procedure for structural seismic analysis which includes torsional-lateral coupling, axial force effect and soil-structure interaction has been presented. The soil-structure system can give a direct display of inertial soil-foundation interaction as well as the effect of this interaction on the superstructure responses by a microcomputer. It can be used for wind response analysis where the input of the system consists of wind loads on every floor. It also can be used in earthquake analysis where a procedure is needed to calculate effective five-dimensional base input. In the example of this study, only single lateral base acceleration input was used to obtain the features of inertial soil-structure interaction. The effect of multi-directional excitation input on structural response will be studied later on. From the above analyses and discussion, the following conclusions can be drawn:

(1) The effect of inertial soil-foundation interaction will change the structure's peak response of relative displacement and lower its resonant frequency. For an excitation whose dominant frequency is higher or not much lower than the structural frequency, the soil-structure interaction suppresses the structural vibration. For an excitation whose dominant frequency

is lower than the structural frequency, the effect of soil-structure interaction may worsen the structural vibration.

(2) The inertial soil-structure interaction will significantly affect those relatively stiff (short-period) and slender structures. For those tall buildings which have these two competing features, a specific analysis is required to identify the dominant feature.

(3) The building's total weight has some influence on the effect of soil-structure interaction. The heavier buildings are more adversely affected by soil-structure interaction.

(4) As the foundation soil gets softer (shear wave velocity decreasing), the effect of inertial soil-foundation interaction is more pronounced.

(5) The embedment of the base will weaken the inertial soil-foundation interaction and the mass of the base has little influence on the interaction.

(6) The effect of lateral-torsional coupling is to lower the resonant frequency of structure responses.

(7) For the 20-storey example building analysed, the axial forces slightly decrease base shear force while their effect on top displacement is negligible.

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