NUMERICAL INVESTIGATIONS ON SOIL STRUCTURE INTERACTION OF MULTISTOREY FRAMES

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Certificate

This is to certify that the thesis entitled **"NUMERICAL INVESTIGATIONS ON SOIL STRUCTURE INTERACTION OF MULTISTOREY FRAMES"** submitted by Deepa Balakrishnan S. to the Cochin University of Science and Technology, in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy is a bonafide record of research work carried out by her under my supervision. The contents of this thesis have not been submitted and will not be submitted to any other University or Institute for the award of any degree.

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DECLARATION

This is to certify that the thesis entitled **"NUMERICAL INVESTIGATIONS ON SOIL STRUCTURE INTERACTION OF MULTISTOREY FRAMES"** submitted to the Cochin University of Science and Technology, in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy is a bonafide record of research work carried out by me. The contents of this thesis have not been submitted and will not be submitted to any other University or Institute for the award of any degree.

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ABSTRACT

KEY WORDS: *Multistorey frames, Soil structure interaction, Linear static analysis, Shock spectrum analysis.*

Frames are the most widely used structural system for multistorey buildings. A building frame is a three dimensional discrete structure consisting of a number of high rise bays in two directions at right angles to each other in the vertical plane. Multistorey frames are a three dimensional lattice structure which are statically indeterminate. Frames sustain gravity loads and resist lateral forces acting on it.

India lies at the north western end of the Indo-Australian tectonic plate and is identified as an active tectonic area. Under horizontal shaking of the ground, horizontal inertial forces are generated at the floor levels of a multistorey frame. These lateral inertia forces are transferred by the floor slab to the beams, subsequently to the columns and finally to the soil through the foundation system.

There are many parameters that affect the response of a structure to ground excitations such as, shape, size and geometry of the structure, type of foundation, soil characteristics etc. The Soil Structure Interaction (SSI) effects refer to the influence of the supporting soil medium on the behavior of the structure when it is subjected to different types of loads.

Interaction between the structure and its supporting foundation and soil, which is a complete system, has been modeled with finite elements. Numerical investigations have been carried out on a four bay, twelve storeyed regular multistorey frame considering depth of fixity at ground level, at characteristic depth of pile and at full depth. Soil structure interaction effects have been studied by considering two models for soil viz., discrete and continuum. Linear static analysis has been conducted to study the interaction effects under static load. Free vibration analysis and further shock spectrum analysis has been conducted to study the interaction effects under time dependent loads. The study has been extended to four types of soil viz., laterite, sand, alluvium and layered.

The structural responses evaluated in the finite element analysis are bending moment, shear force and axial force for columns, and bending moment and shear force for beams. These responses increase with increase in the founding depth; however these responses show minimal increase beyond the characteristic length of pile. When the soil structure interaction effects are incorporated in the analysis, the aforesaid responses of the frame increases upto the characteristic depth and decreases when the frame has been analysed for the full depth. It has been observed that shock spectrum analysis gives wide variation of responses in the frame compared to linear elastic analysis. Both increase and decrease in responses have been observed in the interior storeys. The good congruence shown by the two finite element models viz., discrete and continuum in linear static analysis has been absent in shock spectrum analysis.

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NOMENCLATURE

A_h	Horizontal seismic coefficient
A_k	Design horizontal acceleration spectrum value
B	Footing width
CQC	Complete quadratic combination
d	Base dimension of the building at the plinth level
$\{d\}$	Global displacement vector
E_c	Modulus of elasticity of concrete
E_f	Modulus of elasticity of footing
E_s	Modulus of elasticity of soil
h	Height of the building
h_i	Height of floor i measured from the base,
I	Importance factor
I_f	Moment of inertia of footing based on cross section
K	Axial spring constant or spring stiffness
[K]	Global Stiffness Matrix
k_s	Modulus of subgrade reaction
n	Number of storeys in the building
Pk	Modal participation factor
Q_i	Design lateral force at floor i,
Q_{ik}	Design lateral force at floor i in mode k
R	Response reduction factor
[R]	Global load vector
RCC	Reinforced Cement Concrete
S_a	Spectral acceleration
S_a / g	Average response acceleration coefficient
S_d	Spectral displacement
SSI	Soil Structure Interaction
S_v	Spectral velocity
T_a	Fundamental natural period of vibration
$\ddot{u},\mathring{u},u$	Nodal acceleration, velocity and displacement vectors

V_B	Design seismic base shear
V_{ik}	Peak shear force acting in storey i in mode k
W	Seismic weight of the building frame
W_i	Seismic weight of floor i,
Z	Zone factor
λ	Peak Response
μ_c	Poisson's ratio for concrete
μ_s	Poisson's ratio for soil
Φik	Mode shape coefficient at floor i in mode k
ω_r	Natural Frequency

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Urbanization with its lustrous and lucrative advantages has been constantly attracting people towards towns and cities. The facilities available in urban areas are a major source of attraction and each one tries, somehow to settle in urban areas. Land availability for providing facilities for residential and commercial activities has become a major problem. The engineering solution to this crisis has been addressed through the construction of multistorey buildings. Besides enjoying the merits of group living, occupants of multistorey buildings save much of the scarce and usable land. There is definite savings in the cost, since the foundation is common to all the floors and the cost being distributed between all the floors. Hence multistorey buildings are economical compared to individual buildings. There are a few disadvantages for this building system; for example, stereo – typed designs and neglect of personal likes or dislikes. Occupant density (persons / unit area) is much higher in multistorey buildings and disaster management in this context has to be addressed as a multi disciplinary engineering problem.

Frames are the most widely used structural system for multistorey buildings. Building frames contains a number of bays and have several storeys. Frames allow great flexibility in space allocation to meet functional requirements. Multistorey frame can be of Reinforced Cement Concrete (RCC), steel or a combination of these two. RCC being durable, popular and being more economical than steel, is widely used in the construction of multistorey frames up to 30 storeys. Frames consist of horizontal and vertical members viz., beams and columns that are integrally built. The space between the beam – column grid may be with in fills of conventional masonry or of other types depending on the functional utility of the building, cost, aesthetics etc. Commonly employed substructures for the multistorey frame are raft slab or piles depending on the soil properties, mainly safe bearing capacity.

Multistorey frames are a three dimensional lattice structure and the transverse and lateral loads acting in any location in the frame is carried by the total frame, rather than the local components; or in other words it is the global identity of the structure that manages the load; not local contributions. A multistorey frame is a statically indeterminate structure[3]. Frames sustain gravity loads and resist lateral forces acting on it. The gravity load on the frame consists of the dead weight of the structural components such as beams, slabs, columns etc. and the live load. The lateral loads consist of wind force and earthquake forces. The analysis of structural frames is governed by the provisions of clause 22.4 of IS 456[19]. The ability of the multistorey frames to resist lateral forces depends upon the rigidity of the beam – column joint[44]. When the connections are fully rigid, the structure as a whole is capable of resisting lateral forces in any direction. At each joint, the structural members meeting there bear the share of the total load acting at that joint in proportion to its relative stiffness.

The design of multistorey RCC frames are done conforming to the specifications given in IS 456 [19] and IS 1893 (part 1) [22]. Most members require compliance with special detailing specification given in IS 13920 [24].

A building frame is a three dimensional discrete structure consisting of a number of high rise bays in two directions at right angles to each other in the vertical plane. The vertical members are common to both sets of plane frames crossing each other. According to clause 6.1.5 of IS 1893 (part 1)[22], for structures having lateral force resisting elements in the two orthogonal directions only, the design lateral force has to be considered along one direction at a time, and not in both directions simultaneously.

Static and dynamic analyses are envisaged for the design of multistorey frames. When the design loads include seismic forces, it becomes mandatory to conduct modal dynamic analysis in the form of response spectrum analysis. In static analysis the loads considered are the gravity loads and lateral loads consisting of the static equivalent of wind or earthquake forces. Earthquake loads are incorporated as static equivalents based on the provisions given in IS 1893 (part 1)[22]. The magnitude of the bending moments in beams and columns depends upon their relative rigidity.

India lies at the north western end of the Indo-Australian tectonic plate and is identified as an active tectonic area. The three chief tectonic sub-regions of India are the Himalayas along the north, the Gangetic plains in the centre and the peninsular region in the south. A number of significant earthquakes occurred in and around India over the past centuries. Some of these occurred in populated and urbanized areas causing great damage. Many went unnoticed as they occurred deep under the Earth's surface or in relatively uninhabited places. Each of these caused disasters, but also made us to learn about earthquakes and to advance in earthquake engineering.

Earthquake causes shaking of the ground in all three directions. So, a building resting on the ground will experience motions at its base. Under horizontal shaking of the ground, horizontal inertial forces are generated at the floor levels of a multistorey frame. These lateral inertia forces are transferred by the floor slab to the beams, subsequently to the columns and finally to the soil through the foundation system.

There are many parameters that affect the response of a structure to ground excitations such as, shape, size and geometry of the structure, type of foundation, soil characteristics etc. When the ground shakes, the base of a building will swing back and forth, resulting in differential displacements. Under gravity loads beams of the frame undergo bending, resulting in stretching and shortening at various locations. Depending on the severity of earthquake, the seismically induced bending moment may be of much higher magnitude than that due to gravity loads.

The load from the superstructure is transferred to the surrounding soil through the foundation which normally is a raft or pile. The Soil Structure

Interaction(SSI) effects refer to the influence of the supporting soil medium on the behavior of the structure when it is subjected to different types of loads. Soil – structure interaction can be static when the structure is subjected to static loads and dynamic, when dynamic loads are acting on the structure.

Even though interaction occurs between the structure, foundation and supporting soil medium for all types of loading, it is more critical in the case of seismic loads. Hence the term soil structure interaction has now become acknowledged along with seismic loads.

The soil structure interaction effects due to seismic loads can be of three types, viz., soil amplification effect, inertial interaction and kinematic interaction[54]. During dynamic excitations, the motion of the site in the absence of the structure and of any excavation (free field response) is modified. In general, the motion is amplified resulting in horizontal displacements that increase towards the free surface of the site. This effect is called soil amplification effect.

The inertial loads applied on the structure will lead to an overturning moment and transverse shear acting at the base. These will cause deformations in the soil and modify the motion at the base. This type of interaction is called the inertial-interaction. Excavating and inserting a rigid base into the site modify free field response, which is the motion of the site in the absence of the structure and of any excavation. During dynamic excitations, the rigid base will experience some average horizontal displacement and a rocking component. This rigid body motion will result in accelerations, which will vary over the height of the structure. This geometric averaging of the seismic input motion is referred to as kinematic-interaction.

The motion experienced by a rigid foundation is clearly different from the free field ground motion[27]. The actual motion may be evaluated in two steps. First, the foundation input motion is computed which is defined as the motion which would be experienced by the foundation if both foundation and the superimposed structure have been massless.

Computed with due provision for the rigidity of the foundation, the foundation input motion includes both horizontal and torsional components even for a purely horizontal free field ground shaking. Kinematic interaction effect refers to the differences in the structure responses for a foundation input motion and free field motion at some reference point on the ground surface. The greater the degree of ground motion incoherence or the plan dimensions of the foundation in comparison to the length of the dominant seismic waves, the more important this effect is likely to be.

The actual motion of the foundation is also influenced by its own inertia, inertia of the structure, and by the interaction or coupling between the two and the supporting soils. For a structure subjected to a purely horizontal free field ground shaking, the horizontal and torsional components of the foundation motion are different from those of the corresponding input motion, and the actual motion may also include rocking components about horizontal axes. When considered along with the overturning tendency of the superstructure, the latter components may be particularly prominent for tall slender structures and for soft soils. These factors are provided for in the second step of the evaluation process.

The term inertial interaction effect refers to the difference in structural responses computed for the actual motion of the foundation and the foundation input motion. The total soil structure interaction is clearly the sum of these three effects.

The soil is a semi-infinite medium, and for static loading, a fictitious boundary at a sufficient distance from the structure, where the response is expected to have died out from the practical point of view, can be introduced. This leads to a finite domain for the soil in three dimensions.

During seismic excitation, the structure will interact with the surrounding soil, and influence the seismic motion at the base. The dynamic response of the structure and the soil have to be studied together, when a specified time varying load acts on a structure embedded in soil medium. It is established that structures can be designed and constructed so as to satisfy various seismic performance criteria, and the most important among these is that of preventing collapse during an exceptionally large earthquake. The response of a structure to ground vibrations is a function of the nature of foundation soil, materials, form, size and mode of construction of structures; and the duration and characteristics of ground motion.

The actual interaction of active components of the soil-structure system is affected by the local soil conditions besides configuration, structural characteristics of the frame and the type of imposed loading. The structure will interact with the soil along the embedment, and modifies the seismic motion of the free field. Kerala lying in the South Western end of peninsular India has been considered as a place of low seismic activities till recently. But the short to medium tremors that are felt in different localities in the state and appearances of geological changes that are very typical of seismic activities, in the past few years, have made Kerala to be recognized as a seismically active region.

There are three types of soil identified for the studies presented here. In general the soils of Kerala are acidic, kaolinitic and gravelly with low water holding capacity. Climate, topography, vegetation and hydrological conditions are the dominant factors of soil formation. On the basis of the morphological features and physico-chemical properties, the soils of the state have been classified into many types. Both static and dynamic interaction studies have been performed on the three widely available types of soils viz., laterite, sand and alluvium.

The results from the soil structure interaction studies can be broadly concluded as (1) effect on the responses of the structure and (2) the effect on the responses of the soil medium. The effect on the responses of the structure includes the variations in the moments, shear, displacements etc. of the structure and the effect on the responses of the soil include the variations in the stresses that may or may not lead to liquefaction, settlements, gap formations etc.

Direct methods or iterative methods are used for soil structure interaction studies. In direct methods the unknowns will be eliminated one by one and hence the given system of equation will be transformed into an equivalent upper triangular system. In iterative methods the solution of the system of given equations is obtained by successive approximations. For large system of equations, iterative methods are faster than direct methods. Iterative methods chosen should be reliable and should converge with uniform accuracy.

The finite element method is a powerful numerical analysis technique that has been widely applied in the response estimation of structures. The method derives its power from the variety of elements such as beams, shells and springs, that can be combined together to represent complex systems[10]. It is a discretization technique whereby the structure is divided into pieces or elements within which the solution is interpolated from nodal degrees of freedom[4]. Interaction between the structure and its supporting foundation and soil, which is a complete system, can also be modeled with finite elements.

Numerical investigations on soil structure interaction of multistorey frames using finite element method have been envisaged in the present study.

1.2 OBJECTIVES OF THE THESIS

The thesis addresses the soil-structure interaction effects on the structural behavior of multistorey frames under different loadings and soil conditions. Static, free vibration and shock spectrum analysis of RCC multistorey frames using a discrete lattice type finite element model, considering the static and dynamic loads stipulated in the IS codes and incorporating the influence of soil structure interaction have been envisaged in the present study. The objectives can broadly be mentioned as:

- To develop necessary finite element model for the structural behavior of RCC multistorey frames with pile foundation and founding soil for linear, free vibration and shock spectrum analysis under different types of loading.
- To study the influence of different types of soil on the structural response of RCC multistorey frames considering soil structure interaction effects.
- To compare the prediction of stress /displacement response by discrete modeling and solid modeling of the soils.
- To study the influence of founding depth in interaction studies for different soils.

1.3 ORGANISATION OF THE THESIS

The present work deals with three major aspects. (1) Modeling of a multistorey frame, its foundation and the surrounding soil relevant for soil-structure interaction studies (2) conducting linear static analysis to study the interaction effects under static loading (3) conducting free vibration and then shock spectrum analysis to study the interaction effects under time dependent loads.

Chapter 1 details the importance of building frames and describes the load carrying mechanism of multistorey frames. The need for the soil-structure interaction studies and the efficiency of finite element methods in such type of studies are addressed. The different types of approaches existing for evaluating the SSI effects are also detailed. The specific tasks are identified and objectives are defined.

Chapter 2 critically reviews the earlier efforts in the related fields in the literature and discusses it with regard to the motivation for the present study.

Chapter 3 presents the analytical model for the multistorey frame and unbounded soil domain. The elements used in the modeling are detailed. The different soil types chosen for the study and their properties are explained. The different types of analysis to be performed and the types of loading for each case are discussed.

Chapter 4 deals with the linear static analysis of the chosen frame. In this study, seismic strength estimates of an earthquake resistant multistorey frame designed after incorporating recommendations for earthquake resistance has been carried out. Earthquake loads are considered and soil structure interaction effects are included by proper modeling of soil.

Chapter 5 deals with the dynamic analysis of the frame- foundation system. Eigenvalue Analysis which is a free vibration analysis type is performed to obtain the natural frequency and eigen vectors which are used in other types of modal dynamic analysis.

Chapter 6 deals with modal dynamic analysis namely Shock Spectrum Analysis. Here the chosen frame and soil system is subjected to a foundation shock spectra and the responses are evaluated.

Chapter 7 summarizes the results and presents the conclusions of the present work. The limitations of this research work and scope for future studies are also included.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Multistorey frames are simple discrete structures and their analysis has been a part of structural engineering ever since. However classical and finite element analysis of multistorey frames incorporating the modeling of soil and its interaction with the structure have been in practice for only a few years. The literature available in this field has been reviewed and presented here.

2.2 SOIL STRUCTURE INTERACTION

Lee and Harrison (1970) have conducted studies on structure – foundation interaction and proposed two analytical methods for the analysis of combined footing and two dimensional raft foundation. The methods take into account the effect of the rigidity of the superstructure on the distribution of forces and moments transmitted to the foundation. In the first method rotations and sways at the column foundation junctions have been treated as unknowns. The superstructure alone has been analysed and the displacements and rotations obtained at each junctions have been equated to the corresponding values obtained by considering the foundation to be a beam on Winkler medium subjected to a system of forces and moments. The second method involved the successive modification of an assumed contact pressure distribution. The superstructure and foundation have been treated as a single compatible unit and column forces and moments were evaluated from a conventional structural analysis. In the next step, the foundation has been isolated from the superstructure and structural analysis repeated with a new estimate of contact pressure distribution. The procedure has been repeated till acceptable accuracy has been achieved.

Lee and Brown (1972) have conducted a comparative study on a three bay multistorey frame resting on raft foundation. Interaction studies have been done using two models (1) the conventional method using the Winkler 'spring' concept assuming the foundation to be rigid (2) the linear elastic model. An advancement on the conventional method called the 'soil - line – method' which considers the stiffness of the foundation relative to the soil in addition to the Winkler model and loading for a rigid foundation, when calculating moments, shearing forces and deflections has also been evaluated. It has been observed that the difference in maximum bending moment in foundation by the use of the Winkler model and linear elastic models have been relatively small, and the maximum moment has decreased when the flexibility of the foundation increased. It has also been observed that for structures with more than three bays, the difference in maximum foundation bending moment is large which necessitates a thorough interaction study.

Krauthammer and Chen (1988) have investigated the relationships between the type and accuracy of the free field input motion generation and the resulting effects on the corresponding structures. The general finite element computer program ADINA has been utilized for obtaining the numerical information. Three types of free field simulations have been employed for the analysis of three typical soil-structure configurations namely no embedment, partial embedment and full embedment. The results have showed that simulation accuracy is a critical factor in such studies

Gazetas et al. (1993) have outlined a general methodology for a complete seismic- soil – pile – foundation – structure interaction analysis. A Beam – on – Dynamic –Winkler foundation simplified model and a Green's function based rigorous method have been utilized in determining the dynamic response of single piles and pile groups. A systematic parametric study has been conducted on the effect of pile group configuration upon dynamic impedances of piles embedded in homogeneous as well as heterogeneous soils. It had been shown that the cross interaction between piles in different rows controls the dynamic response of a rectangular pile group and that increasing the number of piles in a line group has very little effect on the dynamic stiffness and damping factors. It has been demonstrated that the predictions by the static interaction factor method are acceptable only for static and low frequency cases and that they may be very conservative or very unsafe at higher frequencies. It had been concluded that at intermediate and high frequencies it is better to ignore pile to pile interaction altogether than to use static interaction factors.

Viladkar et al. (1994) have analysed a plane frame combined footing soil system subjected to biaxial loading. An isoparametric interface / joint element has been used to model the interface characteristics of the foundation beam and the soil medium. It has been observed that interface elements are essential for understanding the realistic nature of a laterally loaded structure and that bending moments are not only relieved but also reversed due to the interacting behavior of the framed structure footing soil system.

Yang et al. (1996) have demonstrated that the condensation technique in structural mechanics can in reality be employed to formulate the soil-structure interaction problems. The method has been used to calculate the equivalent seismic forces exerted by the far-field soil on the near-field soil.

Wu (1997) has utilized a single – degree – of freedom replacement oscillator to represent an SSI system with SDOF structural model. A methodology is then proposed to determine the equivalent fixed – base models of general multi degree of freedom SSI system using simple system identification techniques in the frequency domain.

Lu (2002) carried out comparative study on the non-linear behaviour of reinforced concrete multistorey structures. Experimental and numerical analysis on a scaled model has showed that the distribution of storey shear over strength is an indicator of the general inelastic behavior of the frames. Regular base frame, discontinuous-column frame, partially masonry infilled frame and a wall-frame system have been used for the study.

Osinov (2003) has presented a mathematical model for the deformation of soil under irregular cyclic loading in the simple shear condition. The model incorporated (1) the possible change in the effective pressure in saturated soil due to the cyclic shearing, (2) the reciprocal influence of the effective pressure on the response of the soil to the shear loading and (3) the pore pressure dissipation due to the seepage of the pore fluid

Kokusho (2003) has focused on the mechanism involved in the void re distribution and water film effects in layered sand deposits to study the lateral flow mechanisms during liquefaction. It has been found that sand deposits in the field consist of sub layers with different particle sizes and permeability; and these readily developed water films by post liquefaction void redistribution at sub layer boundaries.

Takewaki et. al. (2003) have presented a simple and fast evaluation method of soil structure interaction effects of embedded structure via cone model. The cone model has been used to evaluate the impedances and the effective input motion at the bottom of an embedded foundation.

Takewaki(2005) has developed a new critical excitation method for soil-structure interaction system. The input energy to the soil-structure interaction system during an earthquake has been introduced as a new measure of criticality. Two kinds of input energy have been defined, one to the overall soil-structure interaction system and the other to the super-structure only. The differences between these two energies indicate the energy dissipated in the soil or that radiating into the ground.

Tokimatsu et al. (2005) have conducted studies on inertial and kinematic forces on pile stresses based on large shaking table tests on pile – structure models with foundation embedded in dry and liquefiable sand deposits. The horizontal subgrade reaction acting on the pile and the earth pressure acting on the embedded part of the foundation have been treated as kinematic forces. An artificial ground motion called Rinkai, produced as an earthquake in southern Kanto district in Japan, has been used as an input base acceleration to the shaking table. The maximum values of bending moment and displacement of the pile and soil has showed considerable variations for dry and liquefiable sand deposits. The bending moments after liquefaction have been considerably larger than that before. The results have showed that if the natural period of superstructure is less than that of the ground, the kinematic force tend to be in phase with the inertial force from the superstructure, increasing the stresses in the piles and if the natural period of the superstructure is greater than that of the ground, the kinematic force tend to be out of phase with the inertial force, restraining the pile stresses from increasing. Further in the study, a pseudo – static analysis based on Beam – on Winkler – springs method has been conducted to examine its effectiveness in estimating pile stresses in the large shaking table tests. It has been observed that the estimated bending moment and deformation of the pile from the pseudo – static analysis have been in good agreement with the observed values and hence the method has been suggested for estimating pile stresses and deformation mode with accuracy.

Yang et al. (2005) have observed that direct integration of the ground acceleration data is firstly base line – corrected in the time domain using the latest square curve fitting technique, and then processed in the frequency domain using a windowed filter to remove the components that cause long period oscillations in the desired displacement.

Krishna et.al (2006) assessed the liquefaction mitigation of ground treated by granular piles. Pore pressure generation and dissipation accounting for both densification and drainage effects of granular piles have been considered. It has been observed that both the coefficients of volume change and permeability are affected by densification.

Foundation impedance functions provide a simple means to account for soil-structure interaction when studying seismic response of structures. Impedence functions represent the dynamic stiffness of the soil media surrounding the foundation. Impedence functions have been frequency dependent and hence it is difficult to incorporate SSI in standard time-history analysis software. Safak(2006) has introduced a method to convert frequency dependent impedance functions into time domain filters. The method has been based on least-squares approximation of impedance functions by ratios of two complex polynomials. Such ratios are equivalent, in the time domain, to discrete- time recursive filters, which are simple finite difference equations representing the relationship between foundation displacements and forces.

2.3 SEISMIC SOIL STRUCTURE INTERACTION

Hoshiya and Ishii (1983) have used a stochastic model to evaluate the kinematic interaction of embedded rectangular foundations by the random vibration theory. The formulation has been based on the fact that statistical correlation of ground motions at different points decreases as the distance between the points increases when components of high frequency are contained in the ground motion. For the stochastic model, earthquake records at a large scale inground tank and a foundation, made of cement – mixed soil improved – ground has been used as examples of deep and shallow embedded foundations. It has been observed that the foundation slab, which is relatively stiff compared with the soil, constrain the ground motions and hence short period components of the ground motion whose wave length has been less than the dimension of the slab are weakened. Hence the kinematic interaction effect of the slab has been like a low pass filter on the ground motions.

Neuss and Maison (1984) have presented a matrix formulation to account for $p - \Delta$ effects in computer seismic analysis of multistorey buildings. The method has employed a linear solution approach requiring no iteration which can be used for static and dynamic – elastic analyser.

Veletsos and Prasad (1989) have made a study of soil structure interaction for seismically excited simple structures considering both kinematic and inertial interaction effects. The system investigated has been a linear structure which was supported on a circular mat foundation at the surface of a homogeneous elastic half space. The structures have been presumed to have one lateral and one torsional degree of freedom in their fixed base condition and have been excited by obliquely incident, horizontally polarized, incoherent shear waves. The temporal variation of the free field ground motion has been expressed stochastically by a local power spectral density function(psd), and its special variability has been specified by a cross psd function. The response quantities examined included the ensemble means of the peak values of the lateral and torsional components of the foundation input motion and the corresponding structural deformations. It has been observed that like kinematic interaction, inertial interaction may affect significantly the responses of systems in the medium and high frequency spectral regions and that the effects of the latter are more important. It has also been reported that unlike kinematic interaction, which generally reduces lateral response, inertial interaction may increase the corresponding response of tall, slender structures in the high frequency region of the response spectrum. The inertial interaction effects for low frequency structures have been negligible because such systems consider the half space as a very stiff, effectively rigid medium. It has also been observed that reliable estimates of the effects of kinematic interaction on the peak values of structural response may be obtained from the knowledge of the corresponding values of the acceleration, velocity and displacement traces of the foundation input motion. These quantities may be computed from analysis of the response of the massless foundation to the free- field ground motion. Insofar as the mean maximum values of the responses have been concerned, the kinematic interaction effects due to ground motion incoherence are similar to those due to wave passage and the two effects may be interrelated.

Guin and Banerjee (1998) have developed a methodology for the dynamic analysis of soil- pile – structure system using a generalized coupled finite element boundary element formulation for the entire problem domain. The formulation has been done in the frequency domain and the excitation is defined through a rock outcrop motion causing vertically propagating S-waves. Linear dynamic analysis has been conducted on two super structural systems namely, a bridge and a multistory frame. It has been observed that coupling of the problems facilitates in the preparations of transfer functions for various degrees of freedom in the structure, including the effects of interaction.

Wolf and Song (2002) have formulated a criterion for the presence of radiation damping in a site. The procedures for the analysis of dynamic soil structure interaction have been out lined. The procedures have included simple physical model (cones, spring – dashpot – mass representations) for the soil, the damping – solvent extraction method, the rigorous forecasting method and the scaled boundary finite element method.

Spyrakos and Xu (2003) have studied the seismic response of massive flexible strip foundation embedded in layered soils subjected to seismic excitation. The foundation has been treated with a finite element formulation, while the difficulty in modeling the infinite extend of the soil has been overcome by a boundary element formulation. System responses have been investigated with the help of boundary element – finite element coupled formulations by enforcing compatibility and equilibrium conditions at the soil foundation interface.

Davenne et al. (2003) have developed numerical tools for the modeling of reinforced structures for the non linear transient analysis of RC structures. A multifiber beam element has been used to describe the response of structural components and a macro element to account for soil structure interaction. The method has been applied for various boundary conditions and incorporating soil-structure interaction.

Spyrakos and Loannidis (2003) have conducted studies on the effect of soil structure interaction on seismic analysis and design of bridges. The significance of soil structure interaction on a model with geometric stiffness and seismic response of a bridge with integral abutments has been established. It has been reported that the role of soil structure interaction is of great importance for the post tensioned modular integral bridge system.

Gen-shu and Jin-qiao (2005) have examined the seismic force and modification factor R based on elastic-plastic time – history earthquake analysis of single degree of freedom systems. The constitutive hysteresis models that have been used are elastic- perfectly –plastic, elastic –linearlyhardening and bilinear-elastic. It has been concluded that R increases linearly with ductility and energy dissipating capacity in short period ranges.

Anandarajah et al.(2005) have demonstrated that soil parameters needed for simplified dynamic analysis of a single pile may be back calculated from the dynamic response of the pile measured in the field. Two methods have been proposed, the first based on Winkler foundation approach and the second based on the equivalent- linear finite element approach, with non linearity of shear modulus and damping accounted for by employing degradation relationships.

Wegner et al. (2005) have developed a numerical procedure for three-dimensional dynamic-soil-structure interaction analysis. Scaled boundary finite-element method has been used for modeling the unbounded soil and standard finite element method is used for modeling the structure. The dynamic response of tall buildings, with multi-level basements, subjected to seismic excitations including P, SV and SH waves at various angle of incidence have been arrived at.

Takewaki and Kishida (2005) have developed a method for the analysis of pile-group effects on the seismic stiffness and strength of buildings with pile foundations. A continuous model consisting of a dynamic Winkler-type soil element and a set of pile has been used to express the dynamic behavior of the structure-pile-soil system. The pile group effect has been accounted through the influence of coefficients that have been defined for interstorey drifts and pile-head bending moments. Pile group effect has reduced the interstorey drift of buildings and increased the bending moments at the pile head.

2.4 RESPONSE SPECTRUM ANALYSIS

Newmark (1973) has shown that the response of simple systems to ground motion can be represented by idealizing the linear response spectrum into constant acceleration, constant velocity and constant displacement response for a given damping factor. Browning (2001) has presented a simple method for proportioning of regular, moderate-rise reinforced concrete building structures. In this method the member sizes have been selected based on the demand defined by the displacement spectrum and criteria specified in relation to different responses.

Ghiocel and Ghanem (2002) have conducted studies on probabilistic analysis of the seismic soil structure interaction problem. The procedure has accounted for the uncertainties in the free field input motion, local site conditions and structural parameters. The uncertain parameters have been modeled using a probabilistic frame work as stochastic processes. The earthquake ground acceleration has been represented by a probabilistic acceleration response spectrum. The procedure has been then applied to the seismic analysis of a nuclear reactor facility and has been observed to have good co-relation with other deterministic methods of risk assessment of hazardous facilities under dynamic loads.

Ambraseys and Douglas (2003) have presented strong motion attenuation relationships for peak ground acceleration, spectral acceleration, energy density, maximum absolute input energy for horizontal and vertical direction and for the ratio of vertical to horizontal of these ground motion parameters. The equations have been derived using a world wide data set of 186 strong – motion records that have been recorded with in 15 km of the surface projection of earthquakes with magnitudes 5.8 to 7.8.

Yuan et.al. (2003) have studied the effect of asymmetry and irregularity of the input seismic waves on the earthquake – induced differential settlement of the buildings on natural subsoil. It has been concluded that these are necessary factors that has to be considered in the evaluation for differential settlement and other problems that have been related to the soil deformation due to earthquakes.

Chintanapakdee and Chopra (2004) have conducted non-linear response history analysis on vertically regular and irregular frames to study the storey drifts and floor displacements. Drift demands in the upper storeys have been more sensitive to irregularities in the lower storeys than the response of lower storeys due to irregularities in the upper storeys. Irregularity in the base storey or lower storeys has significant influence on the height-wise distribution of floor displacements.

Boore and Bommer (2005) have suggested methods for processing of strong motion accelerograms which have been masked and distorted by noises. It has been important to identify the presence of noise in the digitized time-history and its influence on the parameters for any application of recorded accelerograms in earthquake engineering.

Carniel et al. (2006) have investigated the application of the Singular Spectrum Analysis (SSA) to improve the Nakamura technique. Nakamura technique has been employed to estimate the dynamic characteristics of surface layers by measuring solely the tremor at the surface. The SSA has allowed the time series to be decomposed into different components, like signal itself, various noise components etc.

2.5 COMMENTS

The incorporation of soil structure interaction effects in the analysis and subsequent design of multistorey frames has been the subject of research and, started getting attention in the late seventies. It is observed that research attention has been focused on the soil structure interaction effects of high risk structures like nuclear reactors, bridges etc. However only limited research studies have been carried out on soil structure interaction effects of multistorey building frames, which are common, popular and simple in configuration. Soil structure interaction studies of multistorey frames which generally are provided with pile foundations, is tedious, voluminous and cumbersome due to the possible involvement of large number of nodes and finite elements necessary to model the soil mass. This may be the reason why such analysis are not addressed and reported in considerable numbers. High rise buildings on pile foundations have become part of regular building construction due to population explosion. From the review of the reported studies it has been felt that a complete soil structure interaction analysis of multistorey building frames with pile foundations using appropriate numerical methods is justifiable.

CHAPTER 3

FINITE ELEMENT MODELING OF MULTISTOREY FRAMES WITH SOIL STRUCTURE INTERACTION

3.1 INTRODUCTION

Multistorey frames are subjected to horizontal and vertical loads. Frames resist loads entirely due to the rigidities of the beam-column connections and the moment-resisting capacities of the individual members. The load from the superstructure is transferred to the supporting soil medium through the foundation. Displacements occur in the soil body due to the loading and their magnitude depends on the pressure on the foundation.

Pile foundations have been envisaged in the present study. Piles are structural members used to transmit loads to lower levels in the soil mass. This load transfer may be by vertical distribution of the load along the pile shaft (friction pile) or a direct application of load to a lower stratum through the pile point (end bearing).

For analytical investigations on multistorey frames with soil structure interaction, the chosen frame and the surrounding soil are to be properly modeled.

The finite element method is a powerful numerical analysis technique that has been employed for the analysis presented in this study. The finite element commercial software package NISA [Numerically Integrated elements for System Analysis], a general purpose finite element program developed and marketed by Engineering Mechanics Research Corporation (EMRC) to analyse a wide spectrum of problems encountered in engineering mechanics has been used. This program is composed of different types of finite element analysis modules, which are completely integrated through an interactive graphical interface 'DISPLAY III' (Pre & Post-processing)[37]. The DISPLAY III has been used for the geometric and finite element modeling of the superstructure and substructure. A comprehensive library of finite elements is available in NISA to cover many of the engineering problems. Each element in the library is identified by two variables NKTP and NORDR. NKTP specifies the element types and NORDR specifies the element geometries.

In NISA the wave front technique for the solution of the overall finite element equilibrium equations, which are in the form of simultaneous linear algebraic equations has been used. In the frontal method, the solution time is proportional to the square of the wave front size. The frontal technique uses Gauss elimination method for the solution of the simultaneous linear equations. Unlike in banded solvers, in frontal technique, the numbering of elements determines the wave front size. The node numbering sequence does not have any effects on wave front size. Hence node numbering is of no significance regarding computative effort.

For the SSI analysis of multistorey frames, the frame- structure and the pile foundations are modeled using 3D beam elements and the soil by using discrete elements (springs) or elastic half space continuum elements (solids).

3.2 FINITE ELEMENT MODELING OF RCC FRAMES

Super structure of multistorey frames are 3D lattice structures and the beams and columns constituting the frame are modeled using 3D beam elements. The pile foundations are primarily beam-columns and these are also modeled with 3D beam elements.

The 3D beam element considered in the present study, is a two noded prismatic element with six degrees of freedom per node. The degrees of freedom are three translations and three rotations. The formulation includes stretching and bending effects. Element reference for 3D beam element is given in Table 3.1 and the geometry and kinematics of the beam element are shown in Fig. 3.1.

Table 3.1 Element Reference for 3D beam element [37]

Element Type	NKTP=12, 3D Beam element
Analysis Type	Static, Dynamic
Degrees of freedom	6 per node: UX,UY,UZ,ROTX,ROTY, ROTZ
NORDR	Line: 2nodes (NORDR =1)
Real Constants	A : cross sectional area IYY : moment of inertia about y axis IZZ : moment of inertia about z axis
Material properties Isotropic elastic	Young's modulus, Poisson's ratio, Mass density
Element output	Internal forces (FX,FY,FZ,MX,MY,MZ) at beam ends in global co-ordinate system or in local displacement system and strain energy Resultant forces and moments at beam ends in beam local co ordinate system. Element local stresses, principal stresses and maximum shear stress at specified points.
Dynamic capabilities	Consistent or lumped mass Eigenvalue, shock spectrum analysis
Nodal loading	Concentrated nodal forces in global X,Y and Z directions and concentrated nodal moments about global X,Y and Z axes. Specified non zero nodal displacements UX,UY,UZ and nodal rotations ROTX, ROTY and ROTZ in global directions
Pressure and partially distributed loading	Uniform or non uniform pressure (force/length) on top or bottom face of the element.
Ground motion	Force due to ground motion (support excitation) in the global X,Y and Z directions.

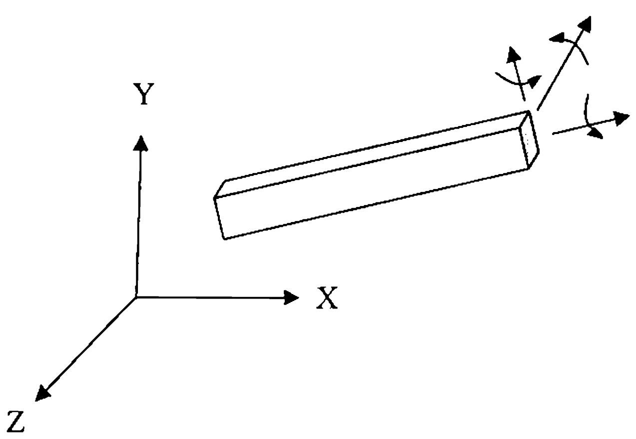


Fig. 3.1 Geometry and kinematics of 3D beam element

3.3 FINITE ELEMENT MODELING OF SOIL

The soil medium in which the piles of multistorey frames are embedded is treated as a semi-infinite domain. Since the purpose of the analysis is to infer the mutual influence of surrounding soil and the pile system, it is preferred to model the soil medium as precise as possible to determine the desired results depicting the interaction behavior. The volume of computation, both in terms of unknowns and storage is large for such investigations.

3.3.1 Soil Types

The details of the homogeneous and layered soil considered in the present study are given in the subsequent sections.

3.3.1.1 Homogeneous Soil

Three types of soil commonly found in Kerala are identified for the analysis. These are laterite, sand and alluvium[59].

Laterites cover about 65% of the total area of the state, occupying a major extent of the midland and mid-upland regions and are the most extensive of the soil groups found in Kerala. The laterite of Kerala is typical Kaolinitic weathering products of gneissic and granitic rocks developed under humid tropical conditions. Heavy rainfall and high temperature prevalent in the state have been conducive to the process of laterisation. The surface soil, which is reddish brown to yellowish red is mostly gravelly loam to gravelly clay loam in texture. The plinthite includes quarriable type that breaks into blocks and also non-quarriable types that breaks into irregular lumps. Laterites are in general poor in available nitrogen, phosphorus and potassium. They have poor water holding capacity. They are generally acidic with pH ranging from 4.5 to 6.2.

Sandy soil, as a group occurs extensively in the State. They have been formed as a result of transportation and sedimentation of materials from adjacent hill slopes and also through deposition by rivers. These exhibit wide variation in physico- chemical properties and morphological features. The development of the soil profiles has occurred under impeded problem with these soils. These are moderately supplied with organic matter, nitrogen and potassium and are deficient in lime and phosphorous.

Three main stretches of alluvial soils are identified in Kerala. They are designated as the Coastal Alluvium, Riverine Alluvium and the Onattukara Alluvium. Coastal Alluvium occurs along the coasts and are results of recent marine deposits. The texture is dominated by sand faction with rapid permeability. These soils are acidic and of low fertility level.

Riverine alluvium occurs mostly along the banks of rivers and their tributaries. It shows wide variation in its physico-chemical properties depending obviously on the nature of alluvium that has been deposited and the characteristics of the catchment area through which the river flows. These are very deep soils with surface texture ranging from sandy loam to clayey loam. These are moderately supplied with organic matter, nitrogen and potassium. These are acidic and poor in phosphorous and lime.

Onattukara Alluvium is confined to the Onattukara region comprising the Karunagapally, Karthikapally and Mavelikara taluks of Kollam and Alappuzha districts. They occur as marine deposits extending to the interior upto the lateritic belt. The soils are, in general, coarse textured with immature profiles. In low-lying areas, the water table is high and drainage is a problem. These soils have very rapid permeability. They are acidic in reaction and are extremely deficient in all the major plant nutrients.

A political map of Kerala is shown in Fig. 3.2 and the summary of the site characteristics of the soils is given in Table 3.2.

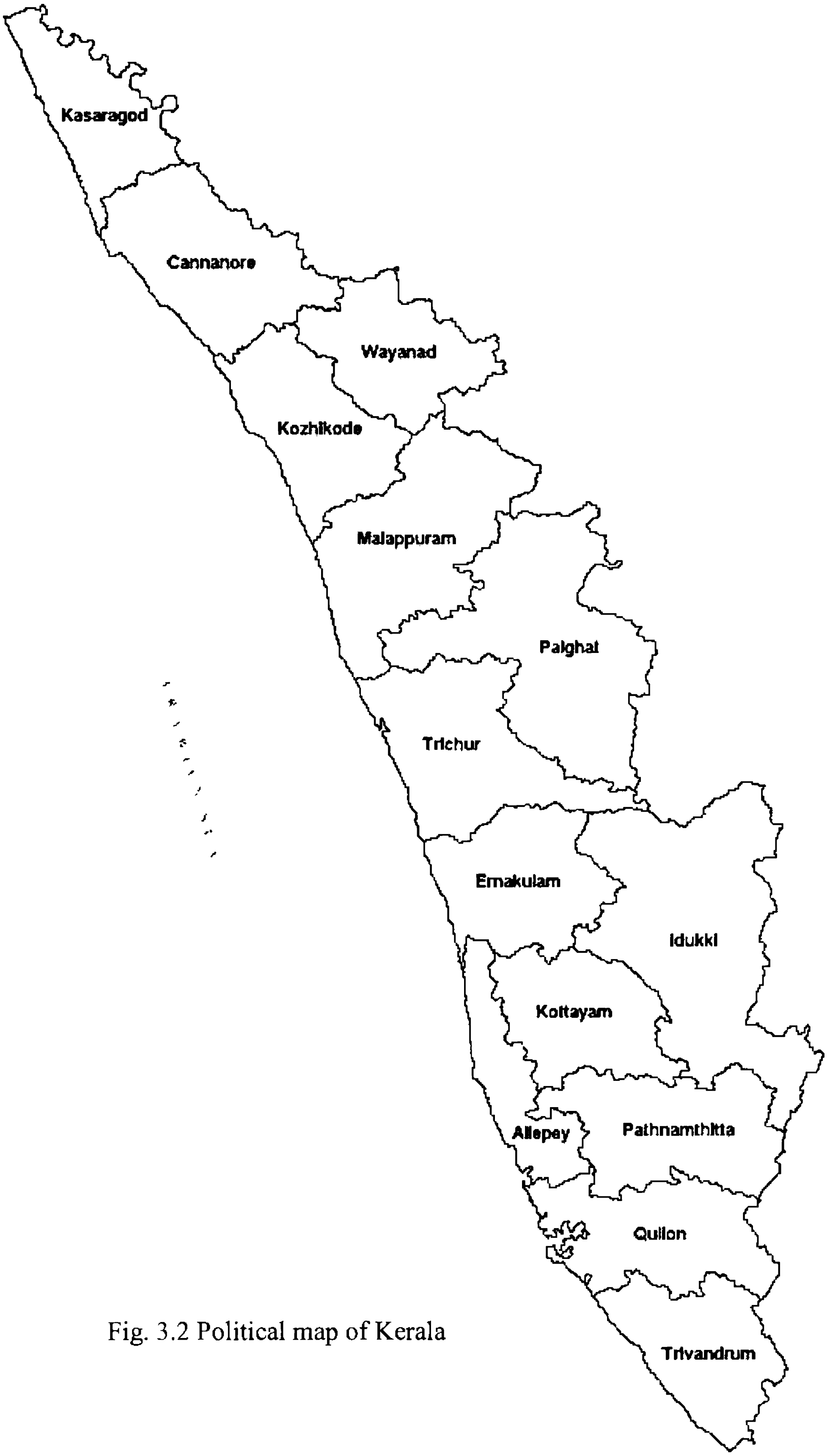


Fig. 3.2 Political map of Kerala

Table 3.2 Site Characteristics of the Soils [59]

District	Type of soil	Details of location
Thiruvananthapuram	• Fairly rich brown loam of laterite • Sandy loam • Rich dark brown loam of granite origin	Middle part of the district Western coastal region Eastern hilly parts of the district
Kollam	• Sandy loam • Laterite Soil	Karunagapally & parts of Kollam Taluk Kottarakkara, Kunnathurand parts of Kollam & Pathanapuram taluks
Pathanamthitta	• Clay soil • Laterite soil	Western and Eastern hilly regions Parts of Ranni and Kozhencheri taluks
Alappuzha	• Sandy loam • Sandy soil • Clay loam with much acidity • Laterite soil	Karthikapally and parts of Mavelikkara taluks. Cherthala and Ambalappuzha taluks. Kuttanad Chengannur and parts of Mavelikkara taluks.
Kottayam	• Laterite soil • Alluvial soil	Parts of Changanacherry and Kottayam taluks and Kanjirappally and Meenachil taluks. Vaikom taluk and parts of Changanacherry and Kottayam taluks.
Idukki	• Laterite soil • Alluvial soil	Peermade and Thodupuzha taluks. Devicolam and Udumbanchola taluks.

Ernakulam	• Laterite • Sandy loam • Alluvial soil	Muvattupuzha, Kothamangalam and parts of Aluva and Kunnathunadu taluks. Parur, Kochi and Kanayannur taluks Parts of Aluva
Thrissur	• Sandy loam • Laterite soil • Clayey soil • Alluvial soil	Parts of Mukundapuram, Thrissur and Chavakkad taluks. Eastern part of Thrissur and western part of Thalappally taluks. Back-water areas of Chavakkad and Mukundapuram taluks Portions of Chavakkad taluk
Palakkad	• Laterite soil • Black soil	Major part of the district North-Eastern part of Chittur taluk
Malappuram	• Laterite soil • Sandy soil	Interior regions of the district Along the coastal belt of the district
Kozhikode	• Laterite soil • Sandy soil	Major part of the district except coastal strip Coastal strip
Wayanad	• Laterite soil • Loamy soil	Major part of the district Valleys in the middle portion of the district
Kannur	• Laterite soil • Sandy soil	Major part of the district except coastal strip Coastal strip
Kasargod	• Laterite soil • Sandy soil	Major part of the district except coastal strip Coastal strip

3.3.1.2 Layered Soil

To study the effect of soil structure interaction in layered soil two different types of non homogeneous soil media and a homogeneous soil media are considered which are shown in Fig. 3.3 [25]. For the layered soil medium LS1, the modulus of elasticity varies from $0.2E_s$ to $0.9E_s$ and for layered soil medium LS2, the modulus of elasticity varies from $0.45E_s$ to $0.9E_s$. The homogeneous soil medium has constant modulus of elasticity E_s. Thus, the considered range of soil properties is varying from soft soil (LS1) to medium soil (LS2) and to hard soil (homogeneous).

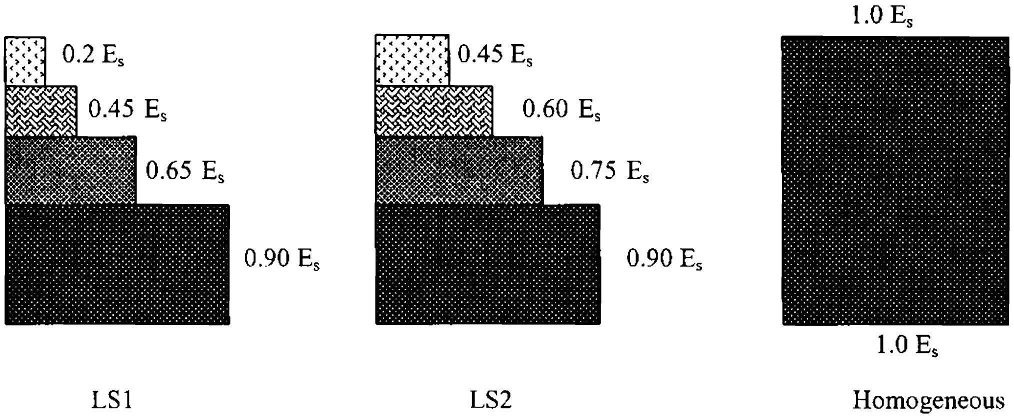


Fig. 3.3 Configuration of the layered soil mediums(LS1 & LS2) and the homogeneous soil medium

3.3.2 Finite Element Models For Soil

The two commonly used models for soil are the discrete model and the elastic continuum model. The theory and finite element formulation of these elements are described subsequently.

3.3.2.1 Discrete Model

In this model, the elastic stiffness characteristics of the soil are represented by discrete springs. These springs have two end connecting nodes and one of them is proposed for attachment to the finite elements constituting the foundation and the other being fixed in the medium. To model an elastic layer of the soil of uniform stiffness, the discrete spring stiffness is calculated based on the spacing of nodes on the foundation surface.

3-D Translational spring elements of NKTP=17 and NORDER=1 are used to model the soil in the present study. The geometry and kinematics of the spring element is shown in Fig. 3.4. The axial displacement is the only degree of freedom of the spring element.

The input parameter for the spring element is the axial spring constant , the value of which depends on the modulus of subgrade reaction (k_s) of the soil medium. Modulus of subgrade reaction is defined as the ratio of the increment in contact pressure to the corresponding change in settlement or deformation.

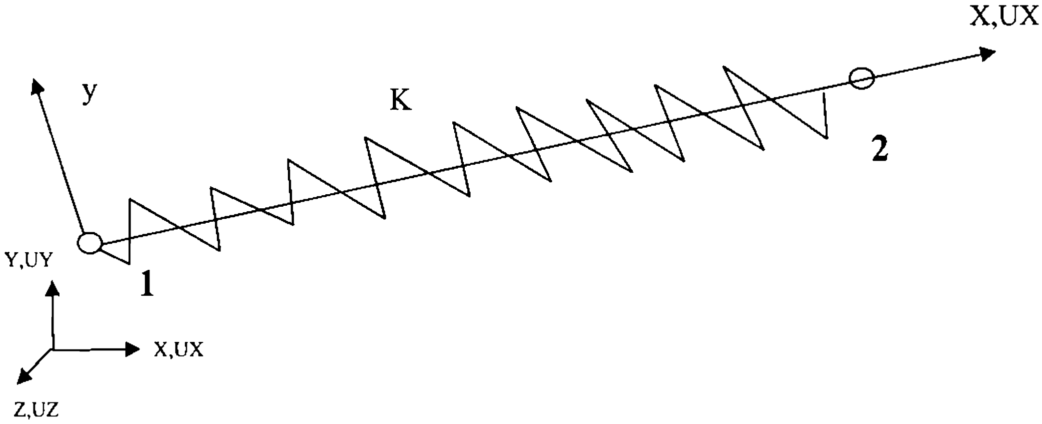


Fig. 3.4 Geometry and kinematics of spring element

Finite element programs using beam elements require concentrating the effect of k_s to the nodes as springs [7]. The concentration method usually used is that suggested by Newmark (1943) [35] for a general parabolic variation of k_s vs length. This method is exact for a parabolic curve and very nearly so for a linear variation of k_s, if the node spacings are not very large.

The stiffness of the springs depends on the modulus of subgrade reaction and it can be computed by using the expression given by Vesić [51].

$$k'_s = 0.65 \sqrt[12]{\frac{E_s B^4}{E_f I_f}} \; \frac{E_s}{1-\mu^2} \quad \text{------------------} \quad (3.1)$$

where

$k'_s = k_s \times B$

E_s – Modulus of soil

E_f – Modulus of footing

B – Footing width

I_f – Moment of Inertia of footing based on cross section

μ - Poisson's ratio

The springs have stiffness obtained from the modulus of subgrade reaction and based on contributory nodal area. According to Bowels [6] the accuracy of results can be improved by doubling the stiffness of end springs. The logic in end spring doubling is that if higher edge pressures are obtained for footings, then this translates into stiffer end soil springs.

The discrete modeling of soil around the pile is shown in Fig. 3.5 and element reference for 3D Translational Spring is given in Table 3.3.

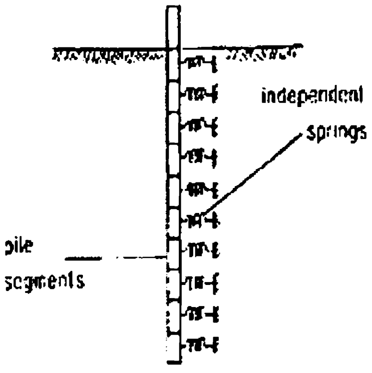


Fig. 3.5 Discrete modeling of soil around the pile

Table 3.3 Element references for 3D Translational Spring

Element Type	NKTP =17, 3- D Translational Spring
Analysis Type	Static, Dynamic
Degrees of freedom	3 per node UX, UY,UZ
NORDR	Line : 2 nodes (NORDR = 1)
Real Constants	K : Axial spring constant
Material properties	None (spring stiffness is treated as a real constant)
Element output	Internal forces (FX,FY,FZ) at the two ends in global coordinate system (or in local displacement system, if defined) and strain energy Axial force (FX)
Dynamic capabilities	Null matrix is assumed. Eigenvalue, shock spectrum analysis
Nodal loading	Concentrated nodal forces in global X,Y and Z direction Specified non-zero nodal displacements UX,UY,UZ in global X,Y and Z direction

3.3.2.2 Elastic Solid Model

The elastic solid modeling of soil is done using 8-noded solid hexahedron (brick) elements. This is an isoparametric 3-D solid element having three degrees of freedom per node, (Ux, Uy, Uz).

The geometry and kinetics of 3-D solid element is shown in Fig. 3.6.

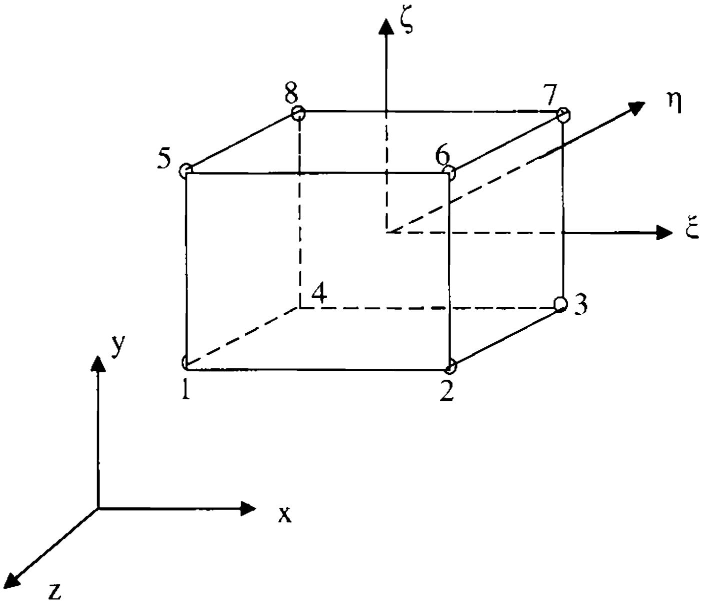


Fig. 3.6 Geometry and kinematics of 3-D solid element

The 3D solid element is an 8 noded isoparametric solid element of NKTP = 4 and NORDR = 1. The element reference for the 3D solid element is given in Table 3.4. The continuum modeling of soil around a pile is shown in Fig. 3.7.

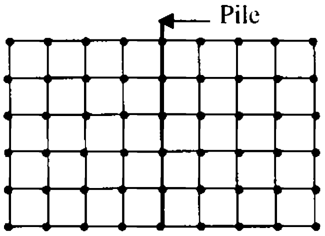


Fig. 3.7 Continuum model of soil around the pile.

Regarding the embedment depth of the pile foundation, two typical depths are considered for the analysis. One is the characteristic depth of fixity as per IS 2911 [23], which is the equivalent length of cantilever that gives the same deflection at ground level as the actual pile and the second one is the full depth of pile. As per clause 5.5.2 and Tables 1 and 2 in Appendix C of IS 2911 the first value is obtained as 5 times diameter of the pile.

Table 3.4 Element references for 3D Solid Element

Element Type	NKTP =4, 3 D Solid element
Analysis Type	Static, Dynamic
Degrees of freedom	3 per node UX, UY, UZ
NORDR	Hexahedron (brick): 8node (NORDR = 1)
Real Constants	None
Material properties Isotropic elastic	Young's modulus, Poisson's ratio, Mass density
Element output	Internal forces (FX,FY,FZ) and strain energy. Element stresses at centroid. Element principal stresses, Von Mises equivalent stress, maximum shear stress at centroid, nodal points etc.
Dynamic capabilities	Consistent or lumped mass Eigenvalue, shock spectrum analysis
Nodal loading	Concentrated nodal forces in global X,Yand Z directions. Specified non-zero nodal displacements UX,UY,UZ in global X ,Yand Z directions.

3.4 ESTIMATION OF LOADS

Analysis of multistorey frames are carried out based on the loads stipulated in the relevant IS codes. The load combinations specified in the codes are considered and the critical among them is used in the investigations. The estimation of static and dynamic loads for static and shock spectrum analyses are given under subsequent sub headings.

3.4.1 Loads For Static Analysis

The loads considered in the analysis are

(a) Dead Load

(b) Imposed Load

(c) Static equivalent of earthquake load

Dead load has been calculated based on the unit weight of the material under consideration as per IS 875 (part I)[20]. For reinforced concrete members, the density of concrete has been taken as 25kN / m^3. The dead load on the beam includes the load from the slab and the self weight of the beam.

In the calculation of live load, the provisions given in IS 875 (part II) [21] considered. The live load is taken as 4 kN /m^2 in the bottom eight storeys and 2 kN /m^2 in the rest of the frame.

The static equivalent of the earthquake loads are calculated based on the provisions in IS 1893 (part 1) 2002 [22].

In static analysis the effects of earthquake are considered as equivalent lateral forces.

The fundamental natural period of vibration (T_a) in seconds as per clause 7.65 for a reinforced frame building without brick infil panels is given as

$$T_a = 0.075\, h^{0.75} \qquad \text{(3.2)}$$

and for all other buildings including moment resisting frame buildings with brick infil panels it is given as,

$$T_a = 0.09\, h / \sqrt{d} \qquad \text{(3.3)}$$

where

d - the base dimension of the building at the plinth level, in m, along the considered direction of the lateral force

h - the height of the building in m.

As per clause 6.4.2 the design horizontal seismic coefficient (A_h) is given by

$$A_h = \frac{Z\, I\, S_a}{2\, R\, g} \text{ --------------------------- } (3.4)$$

where

Z - Zone factor for maximum considered earthquake and service life of structure in a zone.

I - Importance factor, depending upon the functional use of the structure

R - Response reduction factor, depending on the perceived seismic damage performance of the structure

S_a / g - Average response acceleration coefficient.

As per clause 7.5.3 the design seismic base shear (V_B) is given as

$$V_B = A_h . W \text{ -------------------------- } (3.5)$$

where

W - Seismic weight of the building frame calculated by taking appropriate percentages of imposed load specified in Table 8.

The design base shear so calculated is distributed along the height of the frame as per the expression

$$Q_i = V_B \frac{W_i h_i^2}{\sum_{j=1}^{n} W_j h_j^2} \text{ ------------------- } (3.6)$$

where

Q_i - Design lateral force at floor i,

W_i - Seismic weight of floor i,

h_i - height of floor i measured from the base,

n - number of storeys in the building.

3.4.1.1 Load Combinations.

As per IS 1893 [22] for structures which have lateral force resisting elements in the two orthogonal directions only, the design lateral force has to be considered only along one direction at a time. The four load combinations to be considered as per the stipulations of IS code are as follows.

- 1.5 (DL + IL)
- 1.2 (DL + IL ± EL)
- 1.5 (DL ± EL)
- 0.9 DL ± 1.5 EL

where

DL – Dead Load
I L – Imposed Load
EL – Earthquake Load

3.4.2 Loads For Shock Spectrum Analysis

Seismic Loads can be incorporated in the analysis as appropriate time history data of a real earthquake or by using the response spectrum data for the earthquake. The seismic load considered in the analysis is given in the form of a response spectrum. The spectrum specifies the maximum responses that the input will produce on single degree of freedom systems having various natural frequencies and damping ratios[12]. The response spectra for 5% damping as given in IS1893 (part 1)[22] considered in the present study is given in Fig. 3.8.

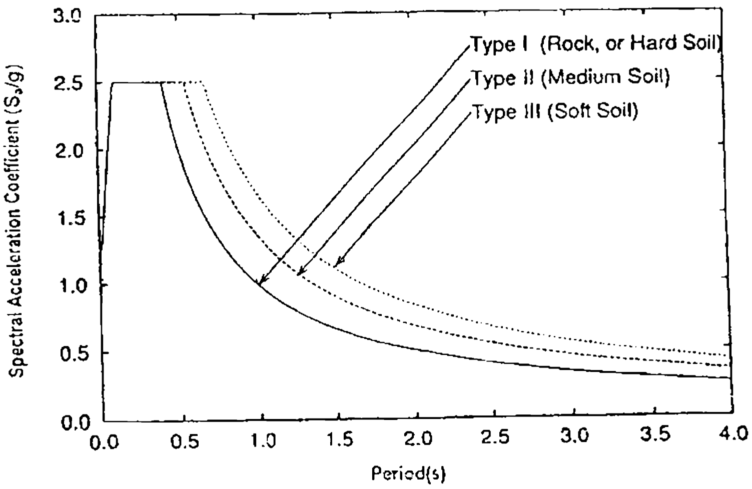


Fig. 3.8 Response Spectra for rock and soil sites for 5% damping

3.5 METHODS OF ANALYSIS

Three basic types of analyses are envisaged in the present study and these are linear static analysis, free vibration analysis and shock spectrum analysis. These are described under subsequent subheadings.

3.5.1 Linear Static Analysis

Linear static analysis involves the computation of responses of a linear system to static loads. This analysis takes into account the dead load, imposed load and the static equivalent of earthquake load. The loads are calculated based on the relevant clauses of the respective codes as given in section 3.4.1. The dead loads and live loads are given as beam loads acting on the elements and the static equivalent of earthquake load is given as lateral forces acting at the nodes.

In linear static analysis, the governing equation is

$$[K]\,\{d\} = [R] \quad \text{...} (3.7)$$

where

$[K]$ - Global Stiffness Matrix

$\{d\}$ - Global displacement vector

$[R]$ - Global load vector

Global stiffness matrix is obtained by assembling the element stiffness matrix and by applying proper boundary conditions. Next the load vector is assembled and then by solving the equation, the displacements are evaluated. Using the displacements, the strains are calculated and further stresses are obtained using constitutive equations.

The output obtained from the linear static analysis includes bending moments, shear force, displacements and rotations.

3.5.2 Free Vibration Analysis

Free vibration analysis or eigenvalue analysis deals with the undamped free vibration of the structure. This analysis does not involve the computation of response due to any loading, but yields the natural frequencies (eigenvalues) and the corresponding mode shapes (eigenvectors) of the structure when there is no dissipation of energy due to damping. A structure with a non-zero initial condition corresponding to any of the mode shapes will exhibit simple harmonic motion at the corresponding natural frequency.

Eigenvalue analysis is carried out to get the vibration characteristics of a structure in terms of its natural frequencies and mode shapes, which may later be used for the computation of the response in the presence of dynamic loads and damping.

Conventional subspace iteration method has been used for eigenvalue extraction. The conventional subspace algorithm uses simultaneous inverse iterations with a set of vectors until the eigenvalues have converged to within a specified tolerance. Each iteration is a reduction using a vector subspace and the reduced eigen problem is solved using the Householder-QR method.

Lumped mass formulation has been used in the analysis. The output from eigenvalue analysis includes the natural frequencies, eigenvectors, modal participation factors, element modal forces and stresses.

3.5.3 Shock Spectrum Analysis

Shock spectrum analysis is a modal dynamic analysis that can be used to estimate the maximum response of a multi-degree freedom structure to an arbitrarily oriented foundation shock spectra input [41]. The input for shock spectrum analysis differs from the other modal dynamic analysis types. The frequency content of the earthquake motion is described locally, at a point on the ground surface either by a response spectrum or a power spectral density function. A response spectrum specification has been assumed in the present study. Here instead of directly specifying the ground motion input, the user has to specify the maximum responses that the input will produce on single degree of freedom systems having various natural frequencies and damping ratios. The maximum responses are given in the form of a spectrum known as the response or shock spectrum. The assumption in this analysis is that the excitation is the same at all support points.

The equation for viscous underdamped system under ground motion $w_j(t)$ in direction j is [37]

$$q_{rj}(t) = \Gamma_{rj} / \omega_r \int_0^t \omega_j (\tau) e^{-\xi r \omega r(t-\tau)} \sin [\omega_r(t-\tau)] d\tau \qquad \text{......................(3.9)}$$

The peak or maximum response is given by

$$(q_{rj})\max = \Gamma_{rj} S_{dj} \qquad \text{...(3.10)}$$

in which S_{dj} is the spectral displacement due to the support excitation given by

$$S_{dj} = \max_{\text{for all } t} \left[1/\omega_r \int_0^t \omega_j (t) e^{-\xi r \omega r(t-\tau)} \sin [\omega_r(t-\tau)] d\tau \right] \qquad \text{............(3.11)}$$

S_{dj} is the maximum response of a single degree of freedom system for the given support excitation. A shock spectrum curve for a certain value of damping may be defined as the maximum responses of all such single degree of freedom systems with the given damping and plotted as a function of natural frequency. Similarly the maximum acceleration S_a and maximum velocity S_v may also be determined. The three spectral quantities of acceleration, velocity and displacement are related as

$$S_{dj} \approx S_{vj} / \omega_r \approx S_{aj} / \omega_r^2 \qquad \text{.................................(3.12)}$$

The analysis has been performed using the acceleration spectrum given in IS 1893 (part 1)[22] for 5% damping. The output generated includes maximum responses of nodal displacements, stresses and reaction forces. Complete quadratic combination (CQC) method has been used to combine the responses of different modes.

The modal participation factor (Pk) of mode k is given by

$$P_k = \frac{\sum_{i=1}^{n} Wi\, \Phi_{ik}}{\sum_{i=1}^{n} Wi\, (\Phi_{ik})^2} \qquad \text{-----------(3.13)}$$

where

Φik - mode shape coefficient at floor i in mode k and

Wi - seismic weight of floor i

The peak lateral force (Qik) at floor i in mode k is given by

$$Qik = A_k\ \Phi_{ik} P_k Wi \qquad \text{..............................(3.14)}$$

where

A_k - design horizontal acceleration spectrum value

(calculated similar to A_h)

The peak shear force (V_{ik}) acting in storey i in mode k is given by

$$V_{ik} = \sum_{j=i+1}^{n} \Phi_{ik} \qquad \text{-----------(3.15)}$$

The peak storey shear force (Vi) in storey i due to all modes considered is obtained by combining those due to each as per Complete Quadratic Combination (CQC) method as

$$\lambda = \sqrt{\sum_{i=1}^{r} \sum_{j=1}^{r} \lambda_i\ P_{ij}\ \lambda_j} \qquad \text{-----------(3.16)}$$

where

r - number of modes being considered

ρ_{ij} - cross- modal coefficient

λ_i - Response quantity in mode i

λ_j - Response quantity in mode j

$$P_{ij} = \frac{8\xi^{2}(1+\beta)\,\beta^{1/5}}{(1+\beta^{2})^{2} + 4\,\xi^{2}\,\beta\,(1+\beta)^{2}} \qquad \text{-----------}(3.17)$$

where

ξ - modal damping ratio, the value of which is to be taken as 5 % of the critical for reinforced concrete buildings

β - frequency ratio (ω_j / ω_i)

ω_i - circular frequency in the ith mode

ω_j . circular frequency in the jth mode

If a building does not have closely – spaced modes, then the peak response quantity (λ) due to all modes considered shall be obtained using square root of the sum of the squares as

$$\lambda = \sqrt{\sum_{k=1}^{r} (\lambda_k)^2} \qquad \text{-----------}(3.18)$$

where

λ - absolute value of quantity in mode k, and

r - number of modes being considered

3.6 SUMMARY

Finite element modeling of the foundation, structure and soil and the three types of soil considered in the present study have been discussed. Provisions for the estimation of loads have been explained and the recommended load combinations are discussed. The three types of analysis envisaged in the present study for the soil – sub structure – structure system have been discussed.

Numerical Investigations on soil structure interaction effects of multistorey frames have been carried out and discussed in the subsequent chapters.

CHAPTER 4

LINEAR STATIC ANALYSIS OF MULTISTOREY FRAMES

4.1 INTRODUCTION

Linear static analysis is concerned with the linear behavior of the elastic continua under prescribed boundary conditions and statically applied loads. The analysis has been carried out on a regular multistorey frame in the present study. Different combinations of dead load, imposed load and seismic load as per the relevant code provisions have been considered and the critical values of stresses and displacements are evaluated. Finite element models have been formulated for the most widely found soil types of Kerala viz., laterite, sand and alluvium for different depth of fixity conditions. Two configurations of nonhomogeneous soil media are considered to study the effect of soil structure interaction in layered soil. The analysis has been repeated with and without considering the subsoil to study the soil structure interaction effects. The details of the analysis are described subsequently.

4.2 DESCRIPTION OF THE STRUCTURE

The frame chosen for the investigations is a four bay twelve storeyed RCC frame. The plan of the structure is shown in Fig. 4.1 and the frame chosen for the analysis has also been marked in this. Fig. 4.2 shows the elevation of the frame.

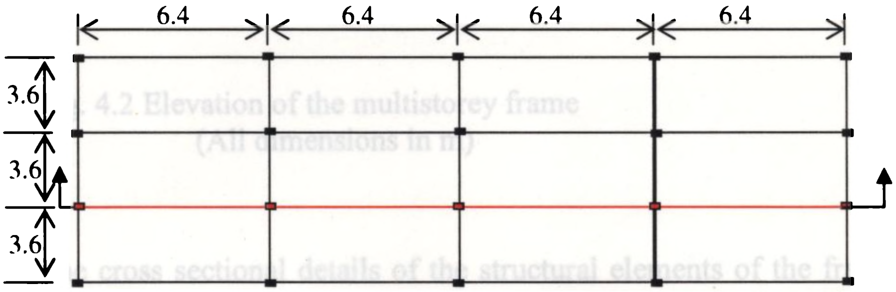


Fig. 4.1 Plan of the twelve storeyed building (All dimensions in m)

The frame selected for analysis is designed as an ordinary moment resisting frame. Floor height has been prescribed as 3.6m for bottom eight floors and as 3.0m for the subsequent four floors. It has five columns of full height at a spacing of 6.4m.The frame has a total height of 40.8m and width 25.6m.

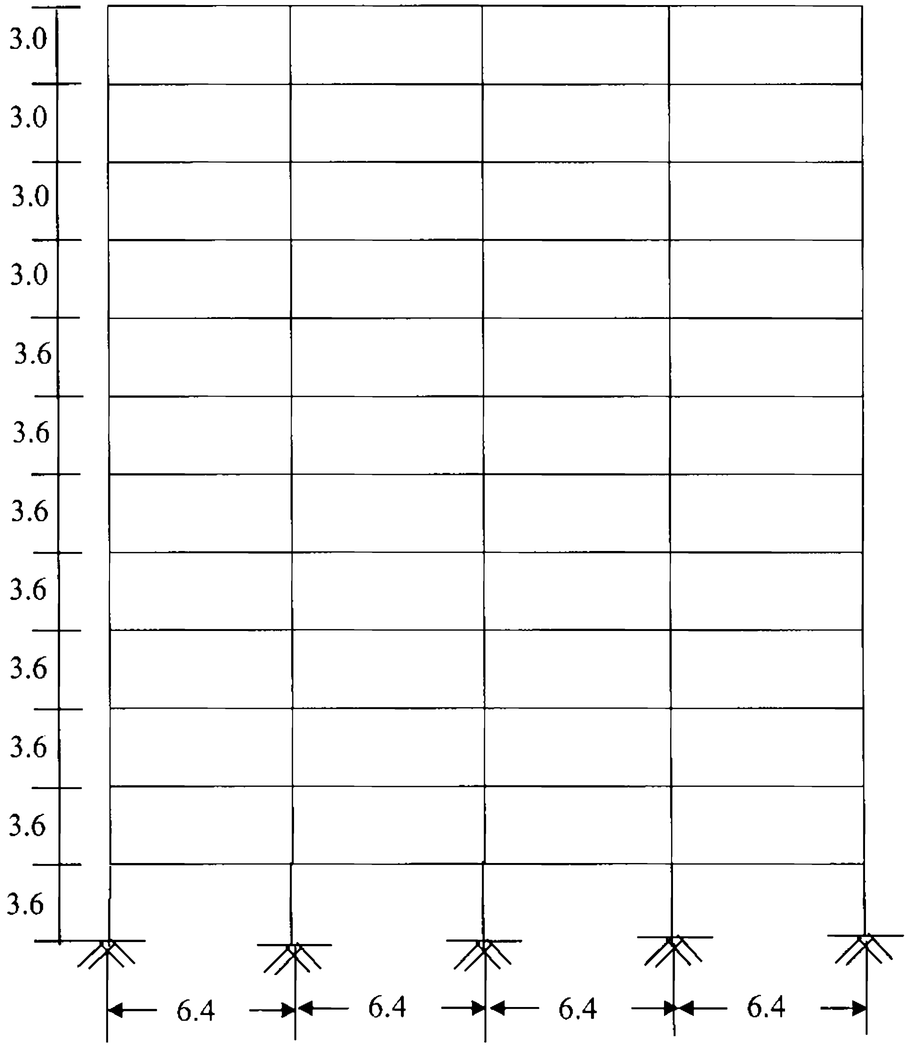


Fig. 4.2 Elevation of the multistorey frame
(All dimensions in m)

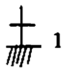
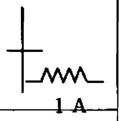
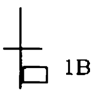
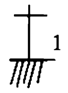
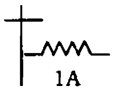
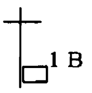
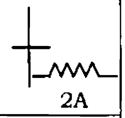
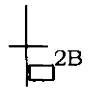
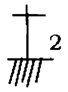
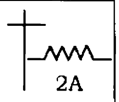
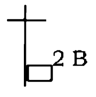
The cross sectional details of the structural elements of the frame are given in Table 4.1. The foundation consists of single bored and cast in situ end bearing piles of depth 20m.

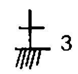
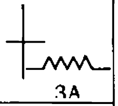
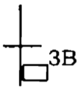
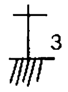
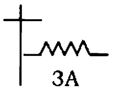
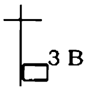
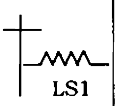
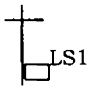
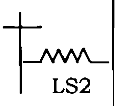
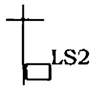
Table 4.1 Cross sectional details of the structural elements.

Structural elements	Sectional dimensions (mm)	Cross section	Material and specification
Beam	230 x 500	Rectangular	Concrete, M_{25}
Column (bottom 4 storeys)	750 x 310	Rectangular	Concrete, M_{30}
Column (storeys 5 – 12)	650 x 300	Rectangular	Concrete, M_{30}
Pile	750	Circular	Concrete, M_{30}

The frame shown in Fig. 4.2 has been analysed for three depths of fixity of piles, for discrete and continuum model of soil, for laterite, sand, alluvium and layered soil. The details of the models are shown in Table 4.2.

Table 4.2 Description of the models for Linear Static Analysis

Sl No	Nomenclature	Description	Notation
1	LG1	Frame fixed at GL with loads corresponding to laterite	
2	LPN1	LG1 with pile fixed at characteristic depth without SS1	
3	LPAY1	LG1 with pile fixed at characteristic depth and discrete model for soil	
4	LPBY1	LG1 with pile fixed at characteristic depth and continuum model for soil	
5	LFN1	LG1 with full length of pile without SS1	
6	LFAY1	LG1 with full length of pile and discrete model for soil.	
7	LFBY1	LG1 with full length of pile and continuum model for soil.	
8	LG2	Frame fixed at GL with loads corresponding to sand	
9	LPN2	LG2 with pile fixed at characteristic depth without SSI	
10	LPAY2	LG2with pile fixed at characteristic depth and discrete model for soil	
11	LPBY2	LG2with pile fixed at characteristic depth and continuum model for soil	
12	LFN2	LG2with full length of pile with out SS1	
13	LFAY2	LG2with full length of pile and discrete model for soil.	
14	LFBY2	LG2 with full length of pile and continuum model for soil.	

15	LG3	Frame fixed at GL with loads corresponding to alluvial soil	
16	LPN3	LG3 with pile fixed at characteristic depth with out SSI	
17	LPAY3	LG3with pile fixed at characteristic depth and discrete model for soil	
18	LPBY3	LG3with pile fixed at characteristic depth and continuum model for soil	
19	LFN3	LG3with full length of pile with out SSI	
20	LFAY3	LG3 with full length of pile and discrete model for soil.	
21	LFBY3	LG3with full length of pile and continuum model for soil.	
22	LS1	Frame with type1 layered soil represented by discrete model	
23	LSB1	Frame with type1 layered soil represented by continuum model	
24	LS2	Frame with type2 layered soil represented by discrete model	
25	LSB2	Frame with type2 layered soil represented by continuum model	

4.3 DESCRIPTION OF THE FINITE ELEMENT MODEL

The physical model for the analysis consists of the superstructure, the foundation and the surrounding soil medium. The superstructure consists of beams and columns; and is modeled using 3D beam elements described in section 3.2. The superstructure is defined by a total of 65 nodes and 108 elements and the finite element discretization is shown in Fig. 4.3.

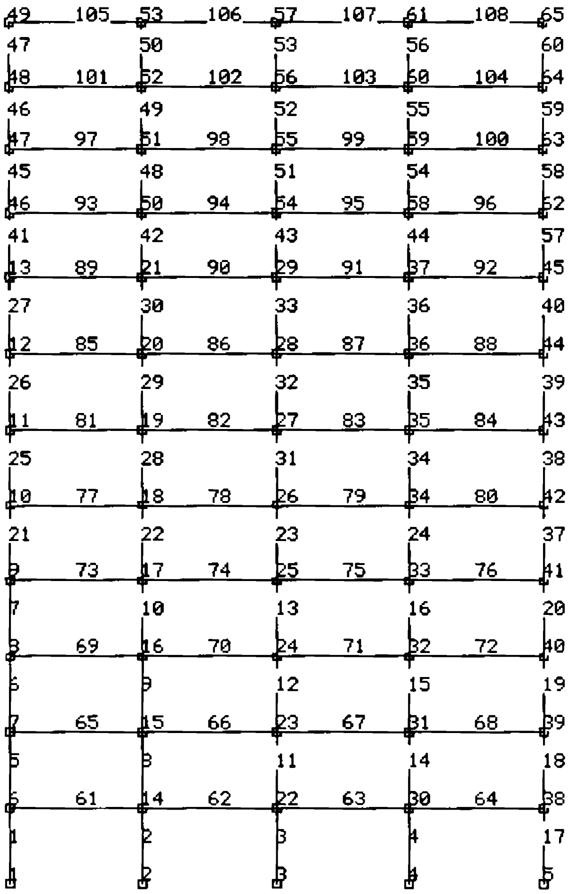


Fig. 4.3 Distribution of nodes and elements in the structural model.

Piles constituting foundation structure are modeled using 3D beam elements. Two types of finite element modeling of the soil has been presented in this study as mentioned in section 3.3.2 using discrete (spring) and continuum (solid) elements. The finite element discretization differs based on the type of finite elements for subsoil modeling.

4.4 LOADS AND LOAD COMBINATIONS

The loads and the load combinations considered in the analysis are described in the subsequent sections.

4.4.1 Load Considerations

For linear static analysis, the dead load, imposed load and static equivalent of earthquake load as described in section 3.4.1. has been considered.

Dead load on beam from 130mm thick slab = 8.409 kN/m
Self weight of beam (230mm x 500mm) = 2.875 kN/m
Imposed load on beams for top four floors (taking load distribution as 2kN/m^2) = 5.175kN/m
Imposed load on beams for bottom seven floors (taking load distribution as 4kN/m^2) = 10.350 kN/m

The total dead load on the beams have been calculated as 11.284 kN/m. The imposed load for the bottom seven floor beams is 10.350 kN/m and for the top four floors, 5.175 kN/m.

The static equivalent of earthquake load has been calculated as per the clause 7.5 of IS 1893 (Part I) [22] as described in section 3.4.1.

The fundamental period of vibration (T_a) in seconds is evaluated using the eqns. 3.2 and 3.3 and the critical one is obtained from eqn. 3.3 and the value is 0.7257sec.

The design horizontal seismic coefficient (A_h) is given by eqn. 3.4. Kerala being in Zone III, the zone factor (Z) as per Table 2, IS 1893 (Part I) has been taken as 0.16 representing moderate seismic intensity. Considering that the upper floors are for residential purposes, the importance factor (I) for the building has been taken as 2. As per Table 7 the response reduction factor (R) for the ordinary moment resisting frame has been taken as 3.

Based on extends of occurrence three soil types have been identified for the analysis. They are Laterite confirming to Type I, Sand confirming to Type II and Alluvial soil confirming to Type III designation of IS 1893(Part I) [22].

The average response acceleration coefficient (S_a / g) and the design horizontal seismic coefficient (A_h) for the three types of soil has been tabulated in Table 4.3.

Table 4.3. Average response acceleration coefficient and design horizontal seismic coefficient for the soil types considered.

Soil Considered	Type as per IS 1893	S_a /g	A_h
Laterite	Type I	1.378	0.07349
Sand	Type II	1.874	0.0999
Alluvium	Type III	2.301	0.1227

The seismic weight (W) of the building frame has been calculated taking appropriate percentages of imposed load specified in Table 8, IS 1893[22]. The distribution of lateral forces to each floor for the soil types considered have been computed and given in Table 4.4.

Table 4.4. Distribution of lateral forces in (kN) to each floor for the soil types considered

Soil Type Floor Level	Laterite	Sand	Alluvium
12	95.6	130.0	159.6
11	82.0	111.5	137.0
10	69.5	94.5	116.0
9	58.0	79.0	97.0
8	47.6	64.7	79.5
7	44.0	60.0	73.5
6	32.0	44.0	54.0
5	22.5	30.5	37.5
4	14.8	20.0	24.5
3	8.0	11.0	14.0
2	3.7	5.0	6.0
1	1.0	1.25	1.5

4.4.2 Load Combinations

The load combinations as given in section 3.4.1.1 have been considered in the analysis.

4.5 INPUT PARAMETERS

The input parameters for the linear static analysis include material properties, boundary conditions, geometric properties and applied loads.

For beams, columns and piles the material properties to be given are the modulus of elasticity, density and Poisson's ratio of concrete. The values used in the present analysis are shown in Table 4.5a.

Table 4.5a. Young's Modulus and Poisson's ratio of concrete used for structural members

Member	E_c (kN/m²)	μ_c
Column	2.738×10^7	0.25
Beam	2.5×10^7	0.25
Pile	2.738×10^7	0.25

For soils, the elastic properties of the medium have been incorporated through the spring stiffness K, which depends on the modulus of elasticity (E_s) and Poisson's ratio (μ_s) using the procedure described in section 3.3.2.1. The values used in the present study are shown in Table 4.5b.

Table 4.5b. Modulus of Elasticity and the Poisson's ratio of the soil types

Soil Type	E_s (kN/m²)	μ_s
Laterite	2.0×10^5	0.3
Sand	0.6×10^5	0.33
Alluvium	0.15×10^5	0.35

For the problem studied herein the soil stiffness is taken constant over the depth not withstanding the fact that it exhibits a parabolic variation. The spring constants calculated for a spacing of 2m for the chosen soil types has been given in Table 4. 5c.

Table 4.5c. Spring constants for the chosen soil types

Soil Type	Spring constant (kN/m)
Laterite	243769.78
Sand	67552.73
Alluvium	15278.84

Geometric properties for the beam elements constituting the finite element model include shape and cross sectional dimensions for the beam, column and foundation, details of which are given in section 4.2.

The applied loads as given in section 4.4 are properly incorporated in the finite element model. Dead loads and imposed loads are given as uniformly distributed loads over the entire span of beams and earthquake loads are incorporated as lateral loads acting on the outer nodes of the frame. Trial runs have been conducted to check the symmetricity of the model by applying the lateral loads from either side and verified that the model is symmetric.

4.6 OUTPUT FEATURES

Linear static analysis has been conducted for all the cases mentioned in Table 4.2 for all load combinations mentioned in section 4.5.2 and the critical values are reported. The output of the linear static analysis includes bending moments, shear forces, axial forces and displacements at all relevant points. The output includes the stresses and reactions for the line elements and stresses and displacements for the continuum elements.

4.7 NUMERICAL INVESTIGATIONS

Linear static analysis has been carried out on the frame shown in Fig. 4.2. for all the cases mentioned in Table 4.2. Lateral loads shown in Table 4.4 has been used in the analysis. Linear elastic analysis has been performed using NISA and the results are reported.

4.8 RESULTS AND DISCUSSIONS

Results obtained from finite element analysis for the frame with depth of fixity at ground level, at full depth of the pile and at characteristic depth, with and without soil structure interaction for different types of soil viz., laterite, sand, alluvium and layered soil are given in subsequent sections.

4.8.1 Effect Of Soil Structure Interaction And Founding Depth In Laterite

The models LG1, LPN1, LPAY1, LPBY1, LFN1, LFAY1 and LFBY1 are analysed to investigate the effect of soil structure interaction and founding depth in laterite. The results are presented and discussed in the subsequent sections. Bending moments, shear forces and axial forces in columns and bending moments and shear forces in beams are compared. Displacements in the frame and bending moments in the pile are compared. Stress distribution in the soil has been studied.

4.8.1.1 Influence of founding depth without SSI

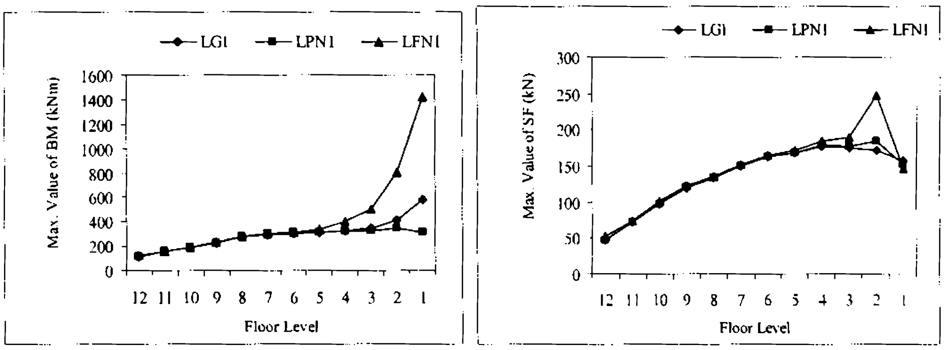
The analytical results of LG1, LPN1 and LFN1 are compared to study the influence of founding depth without SSI with lateral loads corresponding to laterite. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 4.6a. and the percentage variations of maximum responses with respect to LG1 are reported in Table 4.6b. The variations along the floor level is shown in Fig. 4.4

Table 4.6a. Maximum values of bending moments, shear forces and axial forces in **columns** for different depths of fixity without SSI with lateral load corresponding to **laterite**.

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)			Max values of axial force(kN)		
	LG1	LPN1	LFN1	LG1	LPN1	LFN1	LG1	LPN1	LFN1
12	109.27	110.80	118.84	46.69	47.54	52.02	109.38	109.61	111.2
11	151.24	151.93	154.77	72.64	73.09	74.98	217.94	218.42	221.8
10	187.45	188.13	192.94	97.13	97.58	100.56	326.0	326.73	331.8
9	225.52	226.22	230.55	119.76	120.21	123.08	433.84	434.82	441.7
8	278.9	279.67	283.13	133.47	133.84	135.5	541.15	542.38	551.10
7	295.6	296.63	301.71	150.07	150.46	152.49	649.10	649.25	659.7
6	307.66	309.58	318.29	162.16	162.63	164.74	757.27	756.7	768.2
5	310.94	315.81	337.78	167.39	168.03	171.34	894.65	896.02	898.9
4	321.81	329.89	397.3	**176.79**	178.28	184.9	1044.87	1048.1	1058.9
3	352.12	320.43	500.07	175.22	177.46	189.9	1193.8	1201.7	1232.4
2	415.89	**351.89**	808.3	170.84	**183.86**	**247.5**	1335.2	1355.2	1439.3
1	**580.80**	317.40	**1418.6**	157.95	152.05	146.6	**1453.2**	**1506.1**	**1736.8**

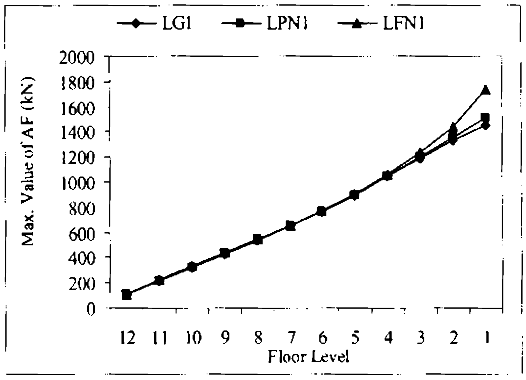
Table 4.6b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 4.6a and % variation with respect to LG1

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG1	580.80	
	LPN1	351.89	-39.4
	LFN1	1418.6	+144.2
Shear force (kN)	LG1	176.79	
	LPN1	183.86	+3.9
	LFN1	247.5	+39.9
Axial force (kN)	LG1	1453.2	
	LPN1	1506.1	+3.6
	LFN1	1736.8	+19.5



a. Bending moment

b. Shear force



c. Axial force

Fig. 4.4 Variation of maximum values of (a)bending moment, (b)shear force and (c)axial force in **columns** for different depths of fixity without SSI with lateral load corresponding to **laterite**.

There is a decrease of 39% for column bending moment when the pile length is taken as characteristic depth and an increase of 144% when pile is treated for full length showing that there is 183% increase in the maximum bending moment in the frame when no soil medium is considered. The corresponding variations in shear force are 4% and 40% showing an increase of 36%. As for axial force it is 4% and 20% giving an increase of 16%. This may be due to the lowering of the support of the frames and the subsequent increase in the cantilever action.

Maximum values of bending moments and shear forces in beams are reported in Table 4.7a and the percentage variations of maximum responses with respect to LG1 are reported in Table 4.7b. The variations along the floor level are shown in Fig. 4.5.

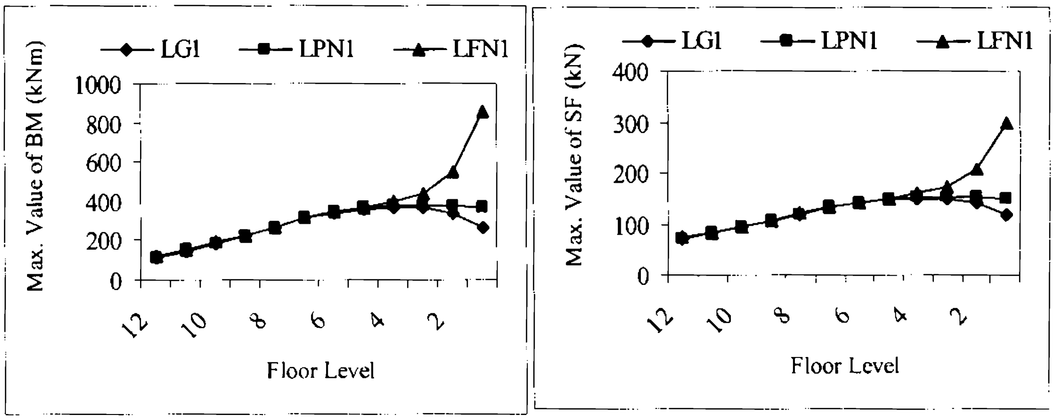
Table 4.7a. Maximum values of bending moments and shear forces in **beams** for different depths of fixity without SSI with lateral load corresponding to **laterite**.

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)		
	LG1	LPN1	LFN1	LG1	LPN1	LFN1
12	112.47	113.11	117.66	71.64	71.87	73.09
11	147.23	148.31	154.0	82.18	82.52	84.29
10	186.57	186.87	191.5	93.87	94.25	95.9
9	225.25	225.54	229.1	106.12	106.20	107.7
8	268.74	269.06	270.3	119.49	119.58	120.6
7	313.43	313.85	314.45	133.18	133.30	133.79
6	341.76	342.53	344.6	141.94	142.17	142.9
5	360.43	362.40	369.79	147.63	148.24	150.5
4	**367.90**	373.99	399.51	**150.21**	152.09	160.23
3	363.31	**378.20**	442.67	148.97	**153.59**	174.05
2	338.96	377.80	550.0	141.37	153.51	207.91
1	263.41	371.32	**852.80**	117.99	150.95	**297.54**

Table 4.7b. Maximum values of bending moments and shear forces in **beams** given in Table 4.7a. and % variation with respect to LG1

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG1	367.90	
	LPN1	378.20	+2.7
	LFN1	852.80	+131.8
Shear force (kN)	LG1	150.21	
	LPN1	153.59	+3.3
	LFN1	297.54	+98.0

The percentage variation of bending moment in beam is 3% when the pile length is taken as characteristic depth and 132% when pile is treated for full length showing that there is 129% increase in the maximum bending moment when no soil medium is considered. The corresponding variations in shear force are 3% and 98% showing an increase of 95%. As in the case of responses in columns this may be due to the lowering of the support of the frames and the subsequent increase in the cantilever action.



a. Bending moment b. Shear force

Fig. 4.5. Variation of maximum values of (a)bending moment and (b)shear force in **beams** for different depths of fixity without SSI with lateral load corresponding to **laterite**.

4.8.1.2 Influence of founding depth with SSI using discrete model for laterite

The analytical results of LG1, LPAY1and LFAY1 are used to study the influence of founding depth with SSI using discrete model for soil. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 4.8a. and the percentage variations of maximum responses with respect to LG1 are reported in Table 4.8b. The variations along the floor level is shown in Fig. 4.6.

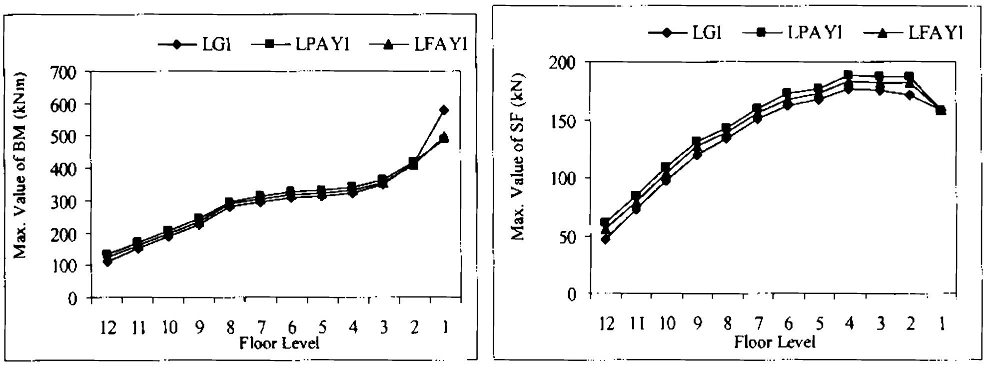
Table 4.8a. Maximum values of bending moments, shear forces and axial forces in **columns** for different depths of fixity with SSI using discrete model for **laterite**

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)			Max values of axial force (kN)		
	LG1	LPAY1	LFAY1	LG1	LPAY1	LFAY1	LG1	LPAY1	LFAY1
12	109.27	135.0	125.82	46.69	61.03	55.92	109.38	112.15	111.13
11	151.24	169.25	161.91	72.64	84.69	79.77	217.94	223.69	221.6
10	187.45	205.02	197.83	97.13	108.96	104.12	326.0	334.57	331.48
9	225.52	243.17	235.95	119.76	131.62	126.76	433.84	445.31	441.17
8	278.9	296.43	289.27	133.47	143.25	139.25	541.15	555.5	550.3
7	295.6	313.49	306.19	150.07	159.94	155.90	649.10	665.04	658.81
6	307.66	326.10	318.67	162.16	172.23	168.11	757.27	775.12	767.14
5	310.94	330.28	322.7	167.39	177.13	173.17	894.65	927.12	913.3
4	321.81	340.22	331.1	**176.79**	**188.39**	**183.7**	1044.87	1082.2	1066.5
3	352.12	362.02	354.8	175.22	186.79	182.2	1193.8	1237.1	1219.3
2	415.89	419.71	411.4	170.84	186.67	181.2	1335.2	1386.6	1366.6
1	**580.80**	**489.46**	**499.56**	157.95	158.98	158.1	**1453.2**	**1519.0**	**1496.1**

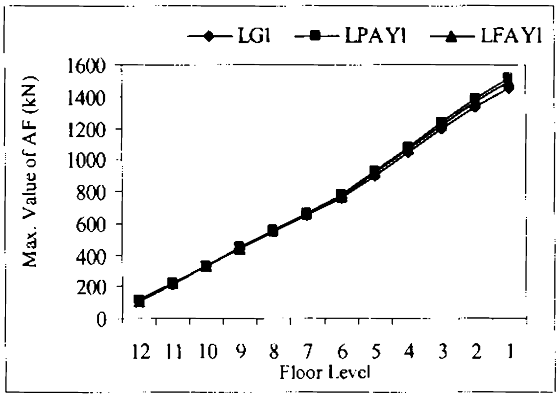
Table 4.8b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 4.8a and % variation with respect to LG1

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG1	580.80	
	LPAY1	489.46	-15.7
	LFAY1	499.56	-13.9
Shear force (kN)	LG1	176.79	
	LPAY1	188.39	+6.5
	LFAY1	183.70	+3.9
Axial force (kN)	LG1	1453.2	
	LPAY1	1519.0	+4.5
	LFAY1	1496.1	+2.9

There is a decrease of 16% for column bending moment when the pile length is taken as characteristic depth and 14% when pile is treated for full length showing that there is 2% increase in the maximum bending moment in the frame when discrete model for soil is considered. The corresponding variations in shear force shows an increase of 7% and 4% showing a decrease of 3%. As for axial force it is 5% and 3% giving a decrease of 2%. The maximum variation in column response is only 3%. This validates the concept of characteristic depth in the design regarding force output.



a. Bending moment b. Shear force



c. Axial force

Fig. 4.6 Variation of maximum values of (a)bending moment, (b)shear force and (c)axial force in **columns** for different depths of fixity with SSI using discrete model for **laterite.**

Maximum values of bending moments and shear forces in beams are reported in Table 4.9a and the percentage variations of maximum responses with respect to LG1 are reported in Table 4.9b. The variations along the floor level are shown in Fig. 4.7.

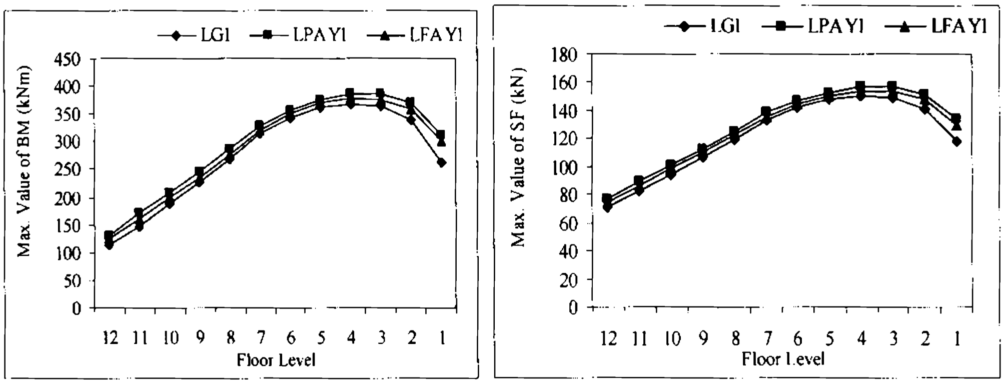
Table 4.9a. Maximum values of bending moments and shear forces in **beams** for different depths of fixity with SSI using discrete model for **laterite**.

Floor Level	Max values of bending moment (kNm)			Max values of shear force(kN)		
	LG1	LPAY1	LFAY1	LG1	LPAY1	LFAY1
12	112.47	130.34	123.0	71.64	76.99	74.65
11	147.23	169.9	160.87	82.18	89.31	86.46
10	186.57	207.28	198.33	93.87	100.91	98.10
9	225.25	244.8	235.83	106.12	112.6	109.84
8	268.74	285.88	276.9	119.49	125.49	122.68
7	313.43	327.56	321.28	133.18	138.52	135.69
6	341.76	355.55	349.7	141.94	147.2	144.36
5	360.43	374.73	368.8	147.63	152.7	150.18
4	**367.90**	385.4	**377.68**	**150.21**	156.58	153.5
3	363.31	**386.37**	375.95	148.97	**156.88**	**153.61**
2	338.96	369.25	357.9	141.37	151.53	147.98
1	263.41	312.88	301.2	117.99	133.92	129.5

Table 4.9b. Maximum values of bending moments and shear forces in **beams** given in Table 4.9a. and % variation with respect to LG1.

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG1	367.90	
	LPAY1	386.37	+5
	LFAY1	377.68	+2.6
Shear force (kN)	LG1	150.21	
	LPAY1	156.88	+4.4
	LFAY1	153.61	+2.2

The percentage variation of bending moment in beam is 5% when the pile length is taken as characteristic depth and 3% when pile is treated for full length showing that there is 2% decrease in the maximum bending moment when discrete model for soil is considered. The corresponding variations in shear force is 4% and 2% showing a decrease of 2%. The maximum variation in beam response is only 2%. As in the case of responses in columns this validates the concept of characteristic depth in the design regarding force output.



a. Bending moment b. Shear force

Fig. 4.7 Variation in maximum values of (a)bending moment and (b)shear force in **beams** for different depths of fixity with SSI using discrete model for **laterite.**

4.8.1.3 Influence of founding depth with SSI using continuum model for laterite

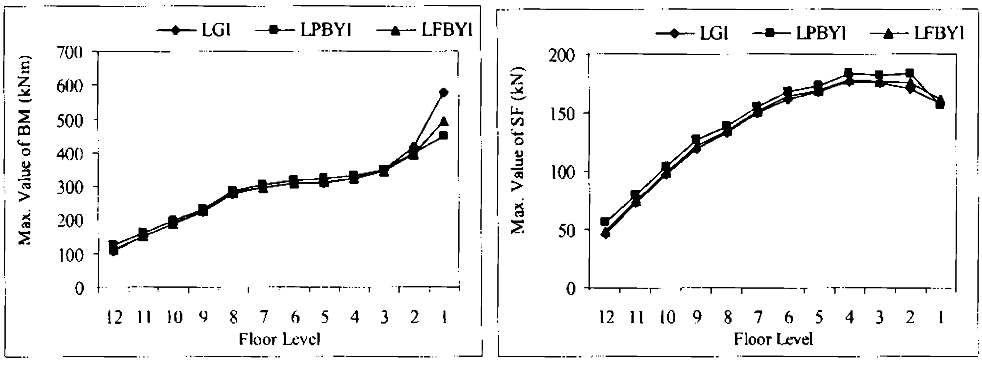
The analytical results of LG1, LPBY1 and LFBY1 are used to study the influence of founding depth with SSI using continuum model for laterite. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 4.10a. and the percentage variations of maximum responses with respect to LG1 are reported in Table 4.10b. The variations along the floor level is shown in Fig. 4.8.

Table 4.10a Maximum values of bending moments,shear forces and axial forces in **columns** for different depths of fixity with SSI using continuum model for **laterite**

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)			Max values of axial force (kN)		
	LG1	LPBY1	LFBY1	LG1	LPBY1	LFBY1	LG1	LPBY1	LFBY1
12	109.27	125.76	113.56	46.69	55.88	49.08	109.38	111.28	110.0
11	151.24	161.45	153.7	72.64	79.46	74.28	217.94	221.9	219.2
10	187.45	197.37	189.85	97.13	103.81	98.74	326.0	331.94	327.9
9	225.52	235.5	227.94	119.76	126.46	121.38	433.84	441.8	436.47
8	278.9	288.84	281.32	133.47	139.0	134.8	541.15	551.1	544.4
7	295.6	305.8	298.14	150.07	155.65	151.42	649.10	659.7	651.75
6	307.66	318.4	310.54	162.16	167.8	163.56	757.27	768.2	758.8
5	310.94	323.04	314.8	167.39	172.9	168.8	894.65	911.6	898.17
4	321.81	333.14	322.3	**176.79**	**183.6**	**178.67**	1044.87	1064.9	1049.4
3	352.12	348.55	344.18	175.22	182.29	177.38	1193.8	1218.3	1200.3
2	415.89	400.17	392.8	170.84	183.37	175.21	1335.2	1367.4	1346.2
1	**580.80**	**449.62**	**493.15**	157.95	157.05	161.5	**1453.2**	**1502.4**	**1475.6**

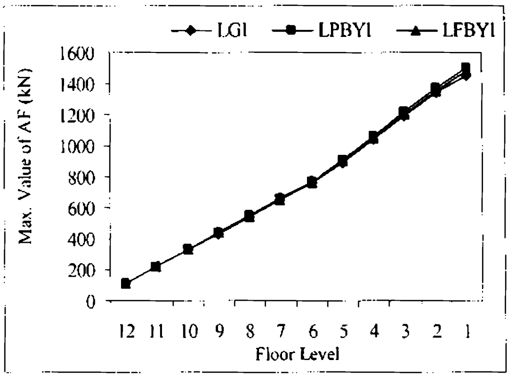
Table 4.10b Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 4.10a and % variation with respect to LG1

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG1	580.80	
	LPBY1	449.62	-22.5
	LFBY1	493.15	-15
Shear force (kN)	LG1	176.79	
	LPBY1	183.6	+3.8
	LFBY1	178.67	+1
Axial force (kN)	LG1	1453.2	
	LPBY1	1502.4	+3.3
	LFBY1	1475.6	+1.5



a. Bending moment

b. Shear force



c. Axial force

Fig. 4.8 Variation of maximum values of(a) bending moment (b)shear force and (c) axial force in **columns** for different depths of fixity with SSI using continuum model for **laterite**

There is a decrease of 23% for column bending moment when the pile length is taken as characteristic depth and 15% when pile is treated for full length showing that there is 8% increase in the maximum bending moment in the frame when continuum model for soil is considered. The corresponding variations in shear force shows an increase of 4% and 1% giving a decrease of 3%. As for axial force it is 3% and 1% giving a decrease of 2%.

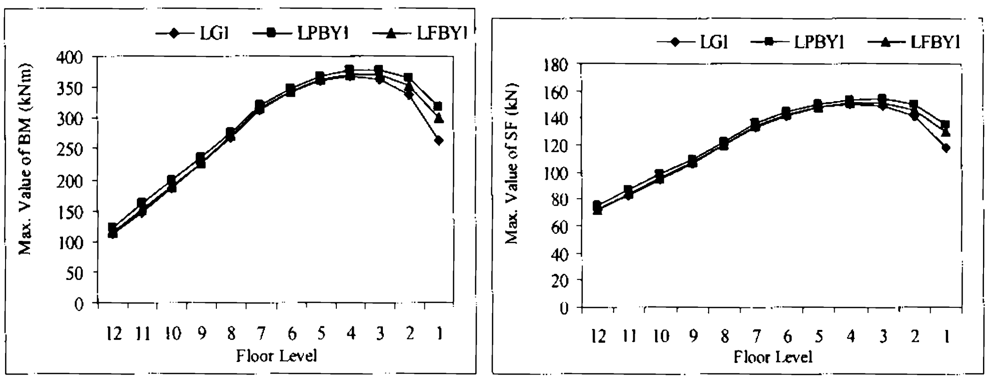
Maximum values of bending moments and shear forces in beams are reported in Table 4.11a and the percentage variations of maximum responses with respect to LG1 are reported in Table 4.11b. The variations along the floor level are shown in Fig. 4.9.

Table 4.11a Maximum values of bending moments and shear forces in **beams** for different depths of fixity with SSI using continuum model for **laterite.**

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	LG1	LPBY1	LFBY1	LG1	LPBY1	LFBY1
12	112.47	122.8	114.8	71.64	74.60	72.16
11	147.23	160.67	150.7	82.18	86.40	83.29
10	186.57	198.13	188.3	93.87	98.04	94.9
9	225.25	235.64	226.6	106.12	109.78	106.7
8	268.74	276.73	270.16	119.49	122.61	119.9
7	313.43	320.5	314.8	133.18	135.64	133.62
6	341.76	349.05	343.3	141.94	144.30	142.41
5	360.43	368.3	362.4	147.63	150.04	148.23
4	**367.90**	377.92	**371.28**	**150.21**	153.75	**151.2**
3	363.31	**378.29**	369.62	148.97	**154.34**	150.9
2	338.96	364.61	353.39	141.37	150.06	145.8
1	263.41	318.97	300.59	117.99	135.34	129.4

Table 4.11b Maximum values of bending moments and shear forces in **beams** given in Table 4.11a and % variation with respect to LG1

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG1	367.90	
	LPBY1	378.29	+2.8
	LFBY1	371.28	+0.9
Shear force (kN)	LG1	150.21	
	LPBY1	154.34	+2.7
	LFBY1	151.2	+0.6



a. Bending moment b. Shear force

Fig. 4.9 Variation of maximum values of (a)bending moment and (b)shear force in **beams** for different depths of fixity with SSI using continuum model for **laterite**.

The percentage variation of bending moment in beam is 3% when the pile length is taken as characteristic depth and 1% when pile is treated for full length showing that there is 2% decrease in the maximum bending moment when continuum model for soil is considered. The corresponding variations in shear force are 3% and 1% showing a decrease of 2%. The maximum variation in beam response is only 2%. As in the case of responses in columns this validates the concept of characteristic depth in the design regarding force output.

4.8.1.4 Influence of SSI of laterite when piles are fixed at characteristic depth

The analytical results of LPN1, LPAY1 and LPBY1 are used to study the influence of SSI using discrete and continuum model for laterite when piles are fixed at characteristic depth. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 4.12a and the percentage variations of maximum responses with respect to LPN1 are reported in Table 4.12b. The variations along the floor level is shown in Fig. 4.10.

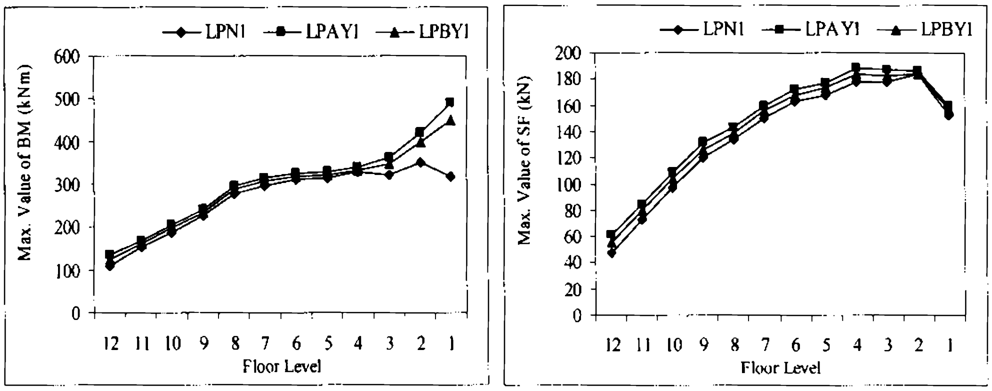
Table 4.12a Maximum values of bending moments, shear forces and axial forces in **columns** for different models for **laterite** when fixed at characteristic depth.

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)			Max values of axial force (kN)		
	LPN1	LPAY1	LPBY1	LPN1	LPAY1	LPBY1	LPN1	LPAY1	LPBY1
12	110.80	135.0	125.76	47.54	61.03	55.88	109.61	112.15	111.28
11	151.93	169.25	161.45	73.09	84.69	79.46	218.42	223.69	221.9
10	188.13	205.02	197.37	97.58	108.96	103.81	326.73	334.57	331.94
9	226.22	243.17	235.5	120.21	131.62	126.46	434.82	445.31	441.8
8	279.67	296.43	288.84	133.84	143.25	139.0	542.38	555.5	551.1
7	296.63	313.49	305.8	150.46	159.94	155.65	649.25	665.04	659.7
6	309.58	326.10	318.4	162.63	172.23	167.8	756.7	775.12	768.2
5	315.81	330.28	323.04	168.03	177.13	172.9	896.02	927.12	911.6
4	329.89	340.22	333.14	178.28	**188.39**	**183.6**	1048.1	1082.2	1064.9
3	320.43	362.02	348.55	177.46	186.79	182.29	1201.7	1237.1	1218.3
2	**351.89**	419.71	400.17	**183.86**	186.67	183.37	1355.2	1386.6	1367.4
1	317.40	**489.46**	**449.62**	152.05	158.98	157.05	**1506.1**	**1519.0**	**1502.4**

Table 4.12b Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 4.12a and % variation with respect to LPN1

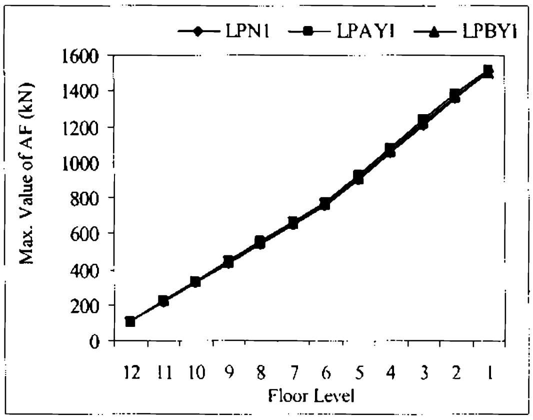
Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LPN1	351.89	
	LPAY1	489.46	+39
	LPBY1	449.62	+27.7
Shear force (kN)	LPN1	183.86	
	LPAY1	188.39	+2.4
	LPBY1	183.6	-0.1
Axial force (kN)	LPN1	1506.1	
	LPAY1	1519.0	+0.8
	LPBY1	1502.4	-0.2

There is an increase of 39% for column bending moment when modeled using discrete elements and 28% using continuum elements showing that there is 11% variation in the maximum bending moment in the frame when two models for soil are considered. The corresponding variations in shear force is an increase of 2% and 0% showing a variation of 2%. As for axial force it is 1% and 0% giving a variation of 1%. This shows that even though both elements are equally good in modeling the properties of soil, discrete model gives upper bound values for column bending moment.



a. Bending moment

b. Shear force



c. Axial force

Fig. 4.10 Variation of maximum values of (a) bending moment, (b)shear force and (c)axial force in **columns** for different models for **laterite** when fixed at characteristic depth.

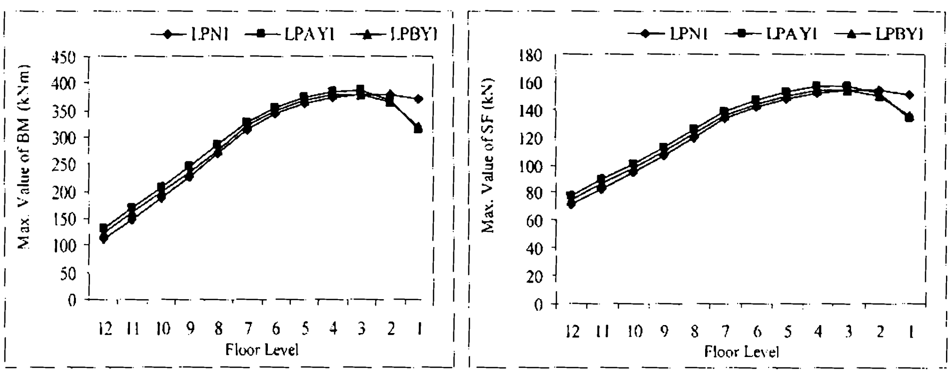
Maximum values of bending moments and shear forces in beams are reported in Table 4.13a and the percentage variations of maximum responses with respect to LPN1 are reported in Table 4.13b. The variations along the floor level are shown in Fig. 4.11.

Table 4.13a Maximum values of bending moments and shear forces in **beams** for different models for **laterite** when fixed at characteristic depth

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)		
	LPN1	LPAY1	LPBY1	LPN1	LPAY1	LPBY1
12	113.11	130.34	122.8	71.87	76.99	74.60
11	148.31	169.9	160.67	82.52	89.31	86.40
10	186.87	207.28	198.13	94.25	100.91	98.04
9	225.54	244.8	235.64	106.20	112.6	109.78
8	269.06	285.88	276.73	119.58	125.49	122.61
7	313.85	327.56	320.5	133.30	138.52	135.64
6	342.53	355.55	349.05	142.17	147.2	144.30
5	362.40	374.73	368.3	148.24	152.7	150.04
4	373.99	385.4	377.92	152.09	156.58	153.75
3	**378.20**	**386.37**	**378.29**	**153.59**	**156.88**	**154.34**
2	377.80	369.25	364.61	153.51	151.53	150.06
1	371.32	312.88	318.97	150.95	133.92	135.34

Table 4.13b. Maximum values of bending moments and shear forces in **beams** given in Table 4.13a and % variation with respect to LPN1

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LPN1	378.20	
	LPAY1	386.37	+2.1
	LPBY1	378.29	0.0
Shear force (kN)	LPN1	153.59	
	LPAY1	156.88	+2.1
	LPBY1	154.34	+0.4



a. Bending moment b. Shear force

Fig. 4.11 Variation of maximum values of(a)bending moment and(b)shear force in **beams** for different models for **laterite** when fixed at characteristic depth.

The percentage variation of bending moment in beam is 2% when modeled using discrete elements and 0% using continuum elements showing that there is 2% variation in the maximum bending moment when two models for soil are considered. The corresponding variations in shear force are 2% and 0% showing a decrease of 2%. The maximum variation in beam response is only 2%. This shows that soil structure interaction does not have significant effects when piles are fixed at characteristic depth.

4.8.1.5 Influence of SSI of laterite considering full depth of piles

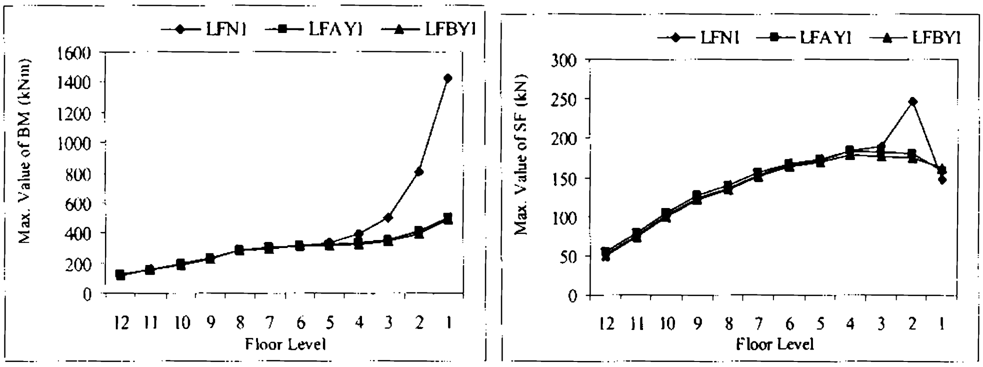
The analytical results of LFN1, LFAY1 and LFBY1 are used to study the influence of SSI using discrete and continuum model for laterite when piles are fixed at full depth. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 4.14a and the percentage variations of maximum responses with respect to LFN1 are reported in Table 4.14b. The variations along the floor level is shown in Fig. 4.12.

Table 4.14a Maximum values of bending moments, shear force and axial force in **columns** for different models for **laterite** when fixed at full depth

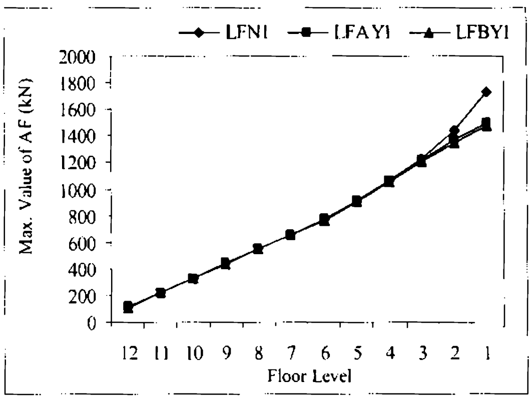
Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)			Max values of axial force (kN)		
	LFN1	LFAY1	LFBY1	LFN1	LFAY1	LFBY1	LFN1	LFAY1	LFBY1
12	118.84	125.82	113.56	52.02	55.92	49.08	111.2	111.13	110.0
11	154.77	161.91	153.7	74.98	79.77	74.28	221.8	221.6	219.2
10	192.94	197.83	189.85	100.56	104.12	98.74	331.8	331.48	327.9
9	230.55	235.95	227.94	123.08	126.76	121.38	441.7	441.17	436.47
8	283.13	289.27	281.32	135.5	139.25	134.8	551.10	550.3	544.4
7	301.71	306.19	298.14	152.49	155.90	151.42	659.7	658.81	651.75
6	318.29	318.67	310.54	164.74	168.11	163.56	768.2	767.14	758.8
5	337.78	322.7	314.8	171.34	173.17	168.8	898.9	913.3	898.17
4	397.3	331.1	322.3	184.9	**183.7**	**178.67**	1058.9	1066.5	1049.4
3	500.07	354.8	344.18	189.9	182.2	177.38	1232.4	1219.3	1200.3
2	808.3	411.4	392.8	**247.5**	181.2	175.21	1439.3	1366.6	1346.2
1	**1418.6**	**499.56**	**493.15**	146.6	158.1	161.5	**1736.8**	**1496.1**	**1475.6**

Table 4.14b Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 4.14a and % variation with respect to LFN1

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LFN1	1418.6	
	LFAY1	499.56	-64.7
	LFBY1	493.15	-65.2
Shear force (kN)	LFN1	247.5	
	LFAY1	183.7	-25.7
	LFBY1	178.67	-27.8
Axial force (kN)	LFN1	1736.8	
	LFAY1	1496.1	-13.8
	LFBY1	1475.6	-15



a. Bending moment b. Shear force



c. Axial force

Fig. 4.12 Variation of maximum values of (a)bending moment, (b)shear force and (c)axial force in **columns** for different models for **laterite** when fixed at full depth.

There is a decrease of 65% for column bending moment when the full depth of pile is considered for the two models of soil showing that there is no variation in the maximum bending moment. The corresponding variations in shear force shows a decrease of 26% and 28% giving a variation of 2%. As for axial force it is 14% and 15% giving a variation of 1%. The maximum decrease in column bending moment is 65%. This may be due to the effect of soil structure interaction which reduced the responses in the frame.

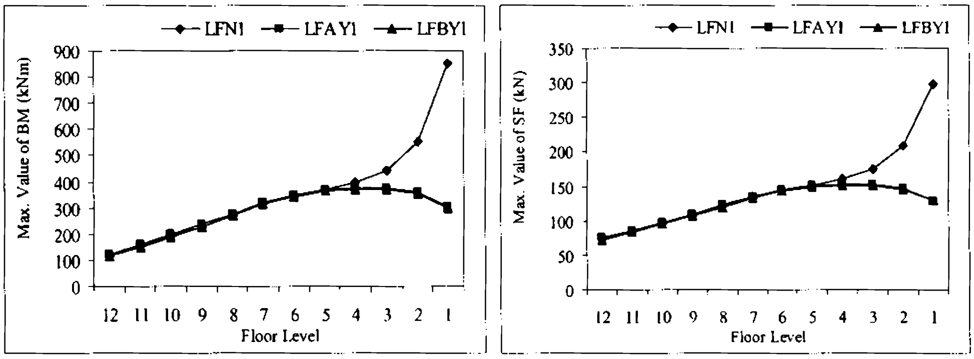
Maximum values of bending moments and shear forces in beams are reported in Table 4.15a and the percentage variations of maximum responses with respect to LFN1 are reported in Table 4.15b. The variations along the floor level are shown in Fig. 4.13.

Table 4.15a Maximum values of bending moments and shear forces in **beams** for different models for **laterite** when fixed at full depth

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	LFN1	LFAY1	LFBY1	LFN1	LFAY1	LFBY1
12	117.66	123.0	114.8	73.09	74.65	72.16
11	154.0	160.87	150.7	84.29	86.46	83.29
10	191.5	198.33	188.3	95.9	98.10	94.9
9	229.1	235.83	226.6	107.7	109.84	106.7
8	270.3	276.9	270.16	120.6	122.68	119.9
7	314.45	321.28	314.8	133.79	135.69	133.62
6	344.6	349.7	343.3	142.9	144.36	142.41
5	369.79	368.8	362.4	150.5	150.18	148.23
4	399.51	**377.68**	**371.28**	160.23	153.5	**151.2**
3	442.67	375.95	369.62	174.05	**153.61**	150.9
2	550.0	357.9	353.39	207.91	147.98	145.8
1	**852.8**	301.2	300.59	**297.54**	129.5	129.4

Table 4.15b Maximum values of bending moments and shear forces in **beams** given in Table 4.15a and % variation with respect to LFN1

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LFN1	852.8	
	LFAY1	377.68	-55.7
	LFBY1	371.28	-56.4
Shear force (kN)	LFN1	297.54	
	LFAY1	153.61	-48.3
	LFBY1	151.2	-49.1



a. Bending moment b. Shear force

Fig. 4.13 Variation of maximum values of (a)bending moment and (b) shear force in **beams** for different models for **laterite** when fixed at full depth

There is a decrease of 56% for beam bending moment when full depth of pile is considered showing that there no variation in the maximum bending moment when two models for soil are considered. The corresponding variations in shear force are 48% and 49% decrease showing a variation of 2%. The maximum variation in beam response is 56%. As in the case of columns this may be due to the effect of soil structure interaction which reduced the responses in the frame.

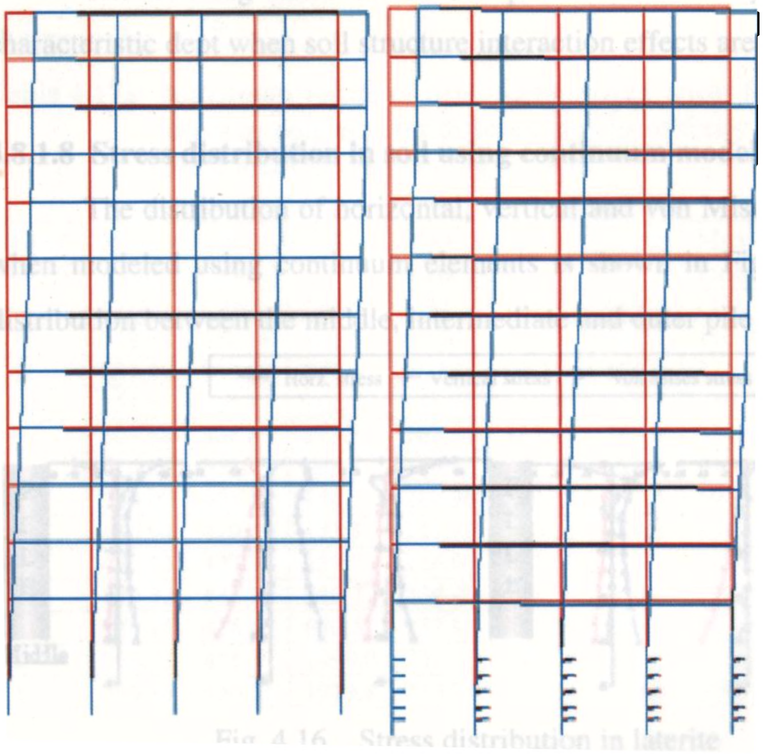
4.8.1.6 Influence of SSI and founding depth on displacements in laterite

The models LG1, LPN1, LPAY1, LPBY1, LFN1, LFAY1 and LFBY1 are analysed to investigate the effect of soil structure interaction and founding depth on displacements in laterite. The maximum values of horizontal and vertical displacements are reported in Table 4.16. Fig. 4.14 shows the deflected shapes when the pile is taken for characteristic length, with and without soil structure interaction.

Table 4.16 Effect of fixity with and without SSI effect of **laterite** on displacements

Depth of fixity			Max values of displacement (m)	
			Horizontal direction	Vertical direction
Ground Level			0.180	0.005
Characteristic depth	Without SSI		0.212	0.0056
	With SSI	Discrete model	0.215	0.022
		Continuum model	0.207	0.013
Full depth	Without SSI		0.792	0.0082
	With SSI	Discrete model	0.201	0.0130
		Continuum model	0.197	0.0084

When displacements are considered, it is observed that the maximum values of displacement both in the horizontal and vertical direction increases with depth of fixity for the two models of soil, compared to when the frame is fixed at the ground level. Maximum displacements with soil structure interaction effects are reported when the pile length is taken as characteristic depth. Decrease in displacements for full depth of fixity is due to the restoring effect caused by the thick soil medium.



a.Without SSI
Max.horizontal displacement:0.212m
Max.vertical displacement :0.005m

b.With SSI (**laterite**)
Max.horizontal displacement:0.215m
Max.vertical displacement :0.022m

Fig. 4.14 Deflected shapes (a)without and (b)with soil structure interaction

4.8.1.7 Influence of SSI of laterite on bending moments in pile

The variation of bending moments in the pile with and without soil structure interaction is shown in Fig. 4.15. Models LPN1 and LPAY1 are compared.

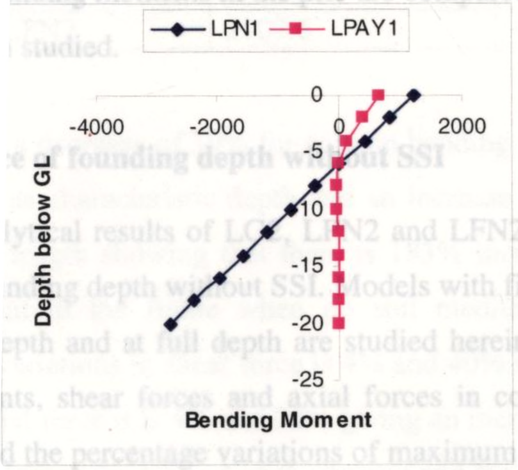


Fig. 4.15 Variation of bending moments in the **pile** with and without SSI

The bending moments in the pile are drastically reduced beyond characteristic dept when soil structure interaction effects are considered.

4.8.1.8 Stress distribution in soil using continuum model.

The distribution of horizontal, vertical and von Mises stress in the soil when modeled using continuum elements is shown in Fig. 4.16. The stress distribution between the middle, intermediate and outer pile are shown.

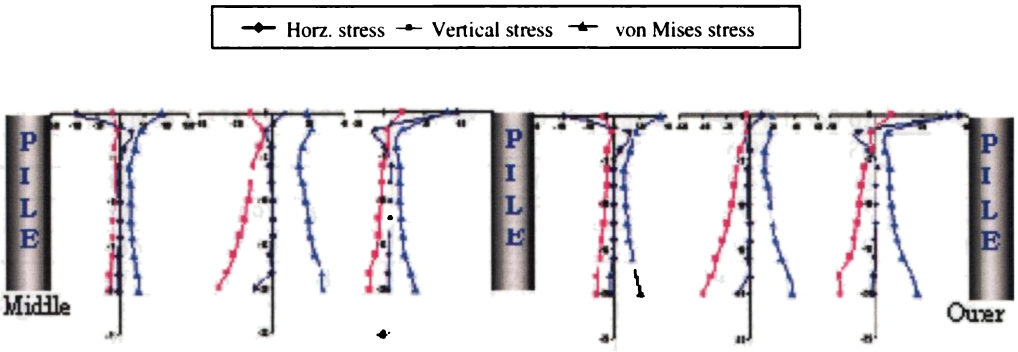


Fig. 4.16 Stress distribution in laterite

4.8.2 Effect Of Soil Structure Interaction And Founding Depth In Sand

The models LG2, LPN2, LPAY2, LPBY2, LFN2, LFAY2 and LFBY2 are analysed to investigate the effect of soil structure interaction and founding depth in sand. The results are presented and discussed in the subsequent sections. Bending moments, shear forces and axial forces in columns and bending moments and shear forces in beams are compared. Displacements in the frame and bending moments in the pile are compared. Stress distribution in the soil has been studied.

4.8.2.1 Influence of founding depth without SSI

The analytical results of LG2, LPN2 and LFN2 are used to study the influence of founding depth without SSI. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 4.17a. and the percentage variations of maximum responses with respect to LG2 are reported in Table 4.17b. The variations along the floor level is shown in Fig. 4.17.

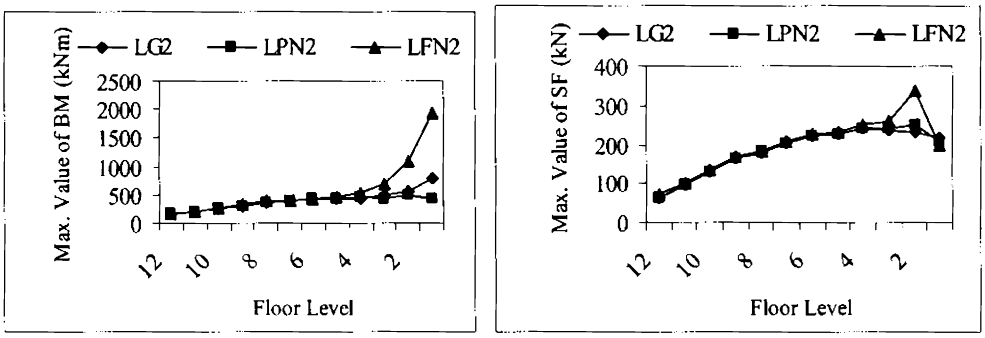
Table 4.17a Maximum values of bending moments, shear forces and axial forces in **columns** for different depths of fixity without SSI with lateral loads corresponding to **sand**.

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)			Max values of axial force (kN)		
	LG2	LPN2	LFN2	LG2	LPN2	LFN2	LG2	LPN2	LFN2
12	148.61	150.68	161.6	63.50	64.66	70.75	110.79	111.21	113.8
11	201.51	202.20	207.5	96.39	97.15	101.1	221.14	222.02	227.4
10	254.62	255.87	262.4	131.63	132.44	136.7	330.76	332.09	340.4
9	305.58	306.87	313.6	162.15	162.99	167.4	439.98	441.77	452.9
8	376.85	378.19	385.1	180.08	180.73	184.3	548.37	550.61	564.6
7	400.09	401.72	410.5	202.96	203.60	207.4	696.92	696.86	693.7
6	416.94	419.31	433.3	219.72	220.23	224.2	869.36	869.48	866.6
5	421.53	427.91	459.7	226.95	227.69	233.2	1049.7	1050.5	1050.2
4	436.82	447.30	540.7	**239.89**	241.79	250.4	1233.8	1237.0	1246.8
3	478.16	436.15	680.5	237.85	241.54	258.5	1416.4	1425.7	1462.0
2	566.03	**479.37**	1099.0	232.41	**249.90**	**336.2**	1588.8	1614.5	1722.8
1	**790.46**	430.53	**1929.8**	214.74	206.73	199.5	**1729.8**	**1800.3**	**2107.6**

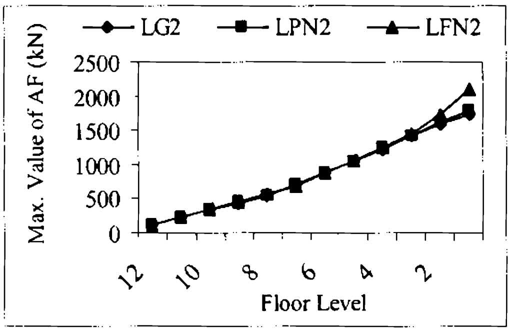
Table 4.17b Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 4.17a and % variation with respect to LG2.

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG2	790.46	
	LPN2	479.37	-39.3
	LFN2	1929.8	+144
Shear force (kN)	LG2	239.89	
	LPN2	249.90	+4.1
	LFN2	336.20	+40.1
Axial force (kN)	LG2	1729.8	
	LPN2	1800.3	+4.0
	LFN2	2107.6	+21.8

There is a decrease of 39% for column bending moment when the pile length is taken as characteristic depth and an increase of 144% when pile is treated for full length showing that there is 183% increase in the maximum bending moment in the frame when no soil medium is considered. The corresponding variations in shear force is 4% and 40% showing an increase of 36%. As for axial force it is 4% and 22% giving an increase of 18%. This may be due to lowering of the support of the frames and the subsequent increase in the cantilever action.



a. Bending moment b. Shear force



c. Axial force

Fig. 4.17.Variation in max values of (a)bending moment, (b)shear force and (c) axial force in **columns** for different depths of fixity without SSI with lateral loads corresponding to **sand.**

Maximum values of bending moments and shear forces in beams are reported in Table 4.18a and the percentage variations of maximum responses with respect to LG1 are reported in Table 4.18b. The variations along the floor level is shown in Fig. 4.18.

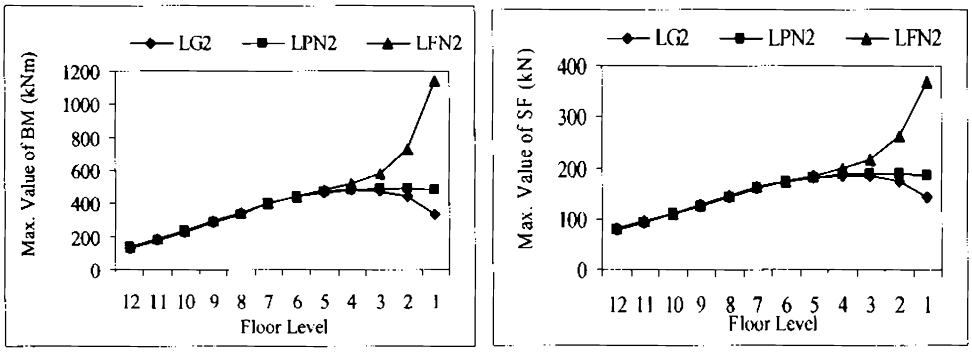
Table 4.18a Maximum values of bending moments and shear forces in **beams** for different depths of fixity without SSI with lateral loads corresponding to **sand**

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	LG2	LPN2	LFN2	LG2	LPN2	LFN2
12	132.17	133.10	139.5	77.85	78.18	79.89
11	179.37	180.80	188.29	92.21	92.66	94.98
10	230.26	231.68	239.13	108.07	108.50	110.8
9	281.38	282.82	290.3	124.05	124.50	126.8
8	340.15	338.80	346.5	141.53	141.99	144.3
7	401.53	401.68	403.9	160.30	160.34	162.3
6	440.78	441.39	444.0	172.44	172.62	174.8
5	466.93	469.16	477.3	180.41	181.10	184.8
4	**477.48**	485.25	519.4	**184.07**	186.48	198.4
3	471.69	491.46	579.3	182.54	188.66	217.2
2	439.39	**491.76**	727.4	172.45	**188.8**	263.3
1	337.58	484.42	**1138.4**	140.93	185.75	**368.6**

Table 4.18b Maximum values of bending moments and shear forces in **beams** given in Table 4.18a and % variation with respect to LG2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG2	477.48	
	LPN2	491.76	+2.9
	LFN2	1138.4	+138.4
Shear force (kN)	LG2	184.07	
	LPN2	188.80	+2.5
	LFN2	368.60	+100

The percentage variation of bending moment in beam is 3% when the pile length is taken as characteristic depth and 138% when pile is treated for full length showing that there is 135% increase in the maximum bending moment when no soil medium is considered. The corresponding variations in shear force is 3% and 100% showing an increase of 97%. As in the case of responses in columns this may be due to the lowering of the support of the frames and the subsequent increase in the cantilever action.



a. Bending moment b. Shear force

Fig. 4.18 Variation of maximum values of(a) bending moment and(b) shear force in **beams** for different depths of fixity without SSI with lateral loads corresponding to **sand**

4.8.2.2 Influence of founding depth with SSI using discrete model for sand

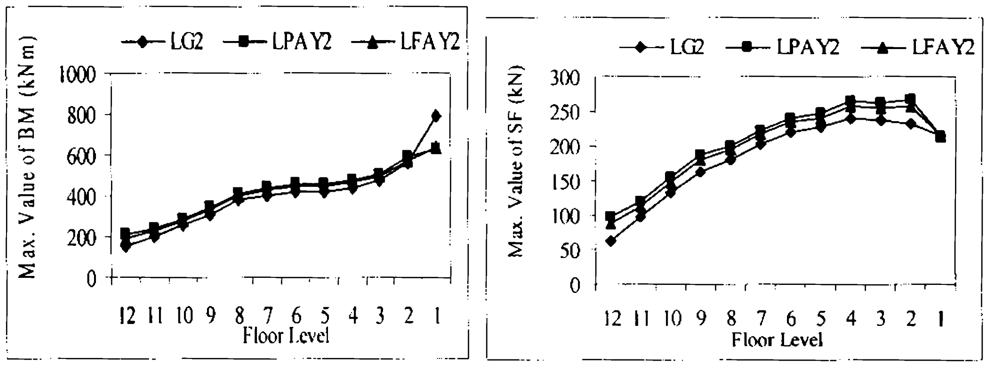
The analytical results of LG2, LPAY2 and LFAY2 are used to study the influence of founding depth with SSI using discrete model for soil. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 4.19a. and percentage variations of maximum responses with respect to LG2 are reported in Table 4.19b. The variations along the floor level is shown in Fig. 4.19.

Table 4.19a. Maximum values of bending moments, shear forces and axial forces in **columns** for different depths of fixity with SSI using discrete model for **sand.**

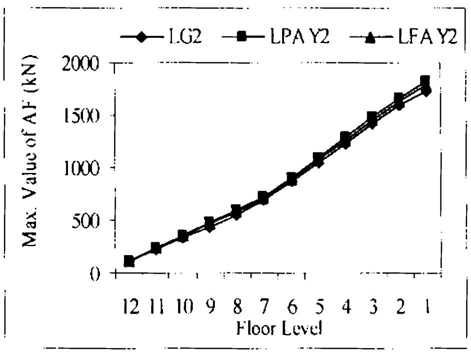
Floor Level	Max values of bending moment(kNm)			Max values of shear force (kN)			Max values of axial force (kN)		
	LG2	LPAY2	LFAY2	LG2	LPAY2	LFAY2	LG2	LPAY2	LFAY2
12	148.61	208.94	191.6	63.50	97.12	87.49	110.79	120.93	118.09
11	201.51	238.68	224.9	96.39	121.17	112.2	221.14	242.23	236.4
10	254.62	290.35	280.14	131.63	155.37	148.52	330.76	362.44	353.7
9	305.58	341.69	331.3	162.15	186.52	179.5	439.98	482.49	470.8
8	376.85	413.09	401.8	180.08	200.37	194.0	548.37	601.77	587.1
7	400.09	437.21	426.5	202.96	223.45	217.4	696.92	732.19	715.8
6	416.94	455.15	443.8	219.72	240.63	234.3	869.36	910.79	891.54
5	421.53	461.33	449.5	226.95	247.13	241.0	1049.7	1097.5	1075.4
4	436.82	479.62	465.5	**239.89**	**264.48**	257.3	1233.8	1288.9	1263.7
3	478.16	501.44	491.7	237.85	261.98	255.2	1416.4	1480.4	1451.9
2	566.03	588.01	573.8	232.41	267.51	**257.9**	1588.8	1665.8	1633.5
1	**790.46**	**632.67**	**642.54**	214.74	213.95	213.8	**1729.8**	**1830.4**	**1793.3**

Table 4.19b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 4.19a. and % variation with respect to LG2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG2	790.46	
	LPAY2	632.67	-19.9
	LFAY2	642.54	-18.7
Shear force (kN)	LG2	239.89	
	LPAY2	264.48	+10.2
	LFAY2	257.9	+7.5
Axial force (kN)	LG2	1729.8	
	LPAY2	1830.4	+5.8
	LFAY2	1793.3	+3.6



a. Bending moment b. Shear force



c. Axial force

Fig. 4.19 Variation of maximum values of (a)bending moment, (b)shear force and (c) axial force in **columns** for different depths of fixity with SSI using discrete model for **sand**.

There is a decrease of 20% for column bending moment when the pile length is taken as characteristic depth and 19% when pile is treated for full length showing that there is 1% increase in the maximum bending moment in the frame when discrete model for soil is considered. The corresponding variations in shear force shows an increase of 10% and 8% giving a decrease of 2%. As for axial force it is 6% and 4% giving a decrease of 2%. The maximum variation in column response is only 2%. This validates the concept of characteristic depth in the design regarding force output.

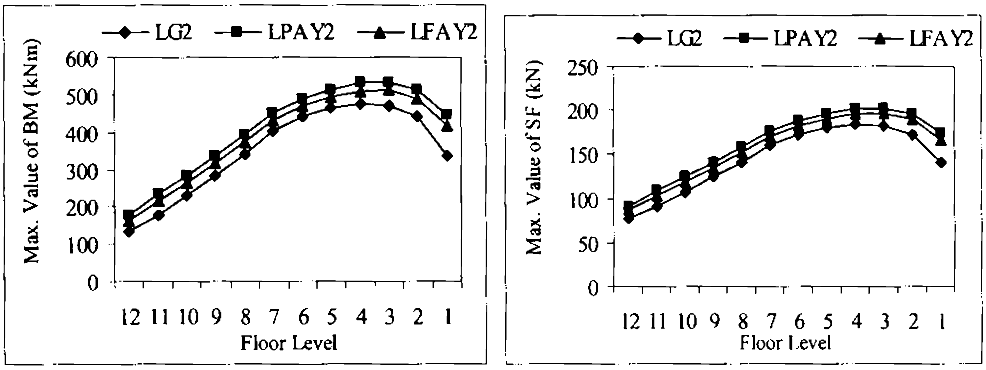
Maximum values of bending moments and shear forces in beams are reported in Table 4.20a and the percentage variations of maximum responses with respect to LG2 are reported in Table 4.20b. The variations along the floor level are shown in Fig. 4.20.

Table 4.20a Maximum values of bending moments and shear forces in **beams** for different depths of fixity with SSI using discrete model for **sand.**

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)		
	LG2	LPAY2	LFAY2	LG2	LPAY2	LFAY2
12	132.17	177.42	162.0	77.85	91.65	86.7
11	179.37	234.09	215.5	92.21	109.37	103.5
10	230.26	284.58	266.1	108.07	125.03	119.2
9	281.38	335.85	317.3	124.05	141.09	135.27
8	340.15	391.89	373.3	141.53	158.59	152.7
7	401.53	448.91	430.2	160.30	176.41	170.5
6	440.78	487.38	468.3	172.44	188.44	182.4
5	466.93	511.98	492.6	180.41	196.13	190.0
4	**477.48**	530.65	510.1	**184.07**	201.95	195.5
3	471.69	**534.08**	**512.28**	182.54	**203.01**	**196.1**
2	439.39	514.76	491.0	172.45	196.99	189.5
1	337.58	444.01	418.83	140.93	174.87	166.6

Table 4.20b. Maximum values of bending moments and shear forces in **beams** given in Table 4.20a and % variation with respect to LG2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG2	477.48	
	LPAY2	534.08	+11.8
	LFAY2	512.28	+7.2
Shear force (kN)	LG2	184.07	
	LPAY2	203.01	+10.2
	LFAY2	196.1	+6.5



a. Bending moment b. Shear force

Fig. 4.20 Variation of maximum values of (a)bending moment and (b) shear force in **beams** for different depths of fixity with SSI using discrete model for **sand.**

The percentage variation of bending moment in beam is 12% when the pile length is taken as characteristic depth and 7% when pile is treated for full length showing that there is 5% decrease in the maximum bending moment when discrete model for soil is considered. The corresponding variations in shear force is 10% and 7% showing a decrease of 3%. The maximum variation in beam response is a decrease of 5%. As in the case of responses in columns this validates the concept of characteristic depth in the design regarding force output.

4.8.2.3 Influence of founding depth with SSI using continuum model for sand

The analytical results of LG2, LPBY2 and LFBY2 are used to study the influence of founding depth with SSI using continuum model for sand. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 4.21a. and the percentage variations of maximum responses with respect to LG2 are reported in Table 4.21b. The variations along the floor level is shown in Fig. 4.21.

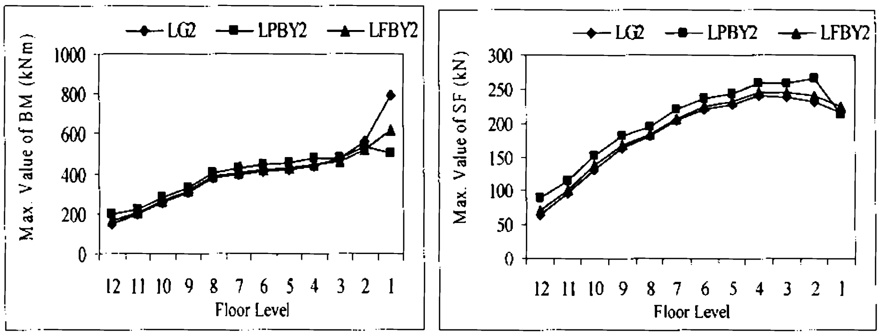
Table 4.21a. Maximum values of bending moments, shear forces and axial forces in **columns** for different depths of fixity with SSI using continuum model for **sand**

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)			Max values of axial force (kN)		
	LG2	LPBY2	LFBY2	LG2	LPBY2	LFBY2	LG2	LPBY2	LFBY2
12	148.61	195.56	161.48	63.50	89.67	70.68	110.79	119.18	113.46
11	201.51	225.99	207.43	96.39	113.69	101.13	221.14	238.69	226.75
10	254.62	282.46	262.26	131.63	150.11	136.69	330.76	357.22	339.24
9	305.58	333.69	313.30	162.15	181.12	167.35	439.98	475.53	451.39
8	376.85	404.13	384.35	180.08	195.33	184.23	548.37	593.05	562.71
7	400.09	429.12	408.08	202.96	218.82	207.24	696.92	714.18	697.8
6	416.94	446.99	425.06	219.72	235.74	223.69	869.36	889.71	870.5
5	421.53	454.38	431.43	226.95	242.58	231.04	1049.7	1073.59	1051.3
4	436.82	476.65	445.45	**239.89**	259.41	**245.21**	1233.8	1262.57	1236.8
3	478.16	476.27	466.59	237.85	258.02	244.73	1416.4	1453.01	1422.57
2	566.03	**537.61**	517.36	232.41	**265.97**	241.37	1588.8	1641.18	1603.49
1	**790.46**	505.25	**616.38**	214.74	213.24	225.52	**1729.8**	**1819.02**	**1767.3**

Table 4.21b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 4.21a. and % variation with respect to LG2

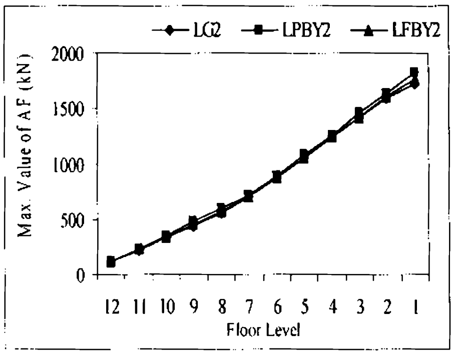
Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG2	790.46	
	LPBY2	537.61	-31.9
	LFBY2	616.38	-22
Shear force (kN)	LG2	239.89	
	LPBY2	265.97	+10.8
	LFBY2	245.21	+2.2
Axial force (kN)	LG2	1729.8	
	LPBY2	1819.0	+5.1
	LFBY2	1767.3	+2.1

There is a decrease of 32% for column bending moment when the pile length is taken as characteristic depth and 22% when pile is treated for full length showing that there is 10% increase in the maximum bending moment in the frame when continuum model for soil is considered. The corresponding variations in shear force is an increase of 11% and 2% showing a decrease of 9%. As for axial force it is 5% and 2% giving a decrease of 3%.



a. Bending moment

b. Shear force



c. Axial force

Fig. 4.21 Variation of maximum values of (a)bending moment, (b) shear force and (c)axial force in **columns** for different depths of fixity with SSI using continuum model for **sand.**

Maximum values of bending moments and shear forces in beams are reported in Table 4.22a and the percentage variations of maximum responses with respect to LG2 are reported in Table 4.22b. The variations along the floor level are shown in Fig. 4.22.

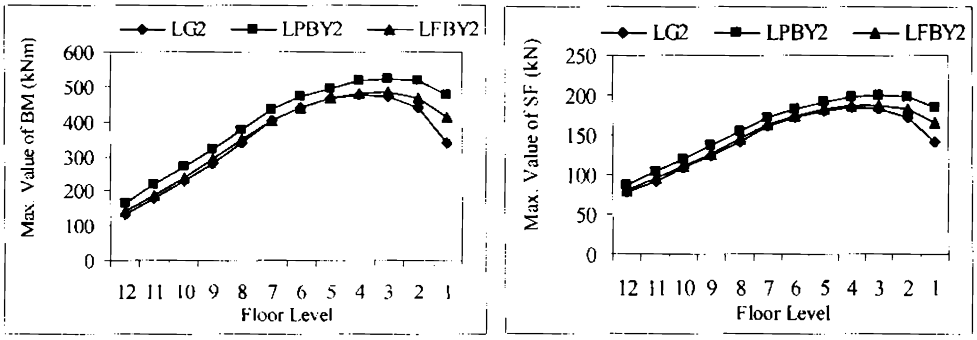
Table 4.22a Maximum values of bending moments and shear forces in **beams** for different depths of fixity with SSI using continuum model for **sand.**

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	LG2	LPBY2	LFBY2	LG2	LPBY2	LFBY2
12	132.17	164.67	140.41	77.85	87.56	79.97
11	179.37	218.53	189.4	92.21	104.46	95.34
10	230.26	269.12	240.2	108.07	120.17	111.16
9	281.38	320.36	291.3	124.05	136.21	127.16
8	340.15	376.40	347.3	141.53	153.71	144.65
7	401.53	433.39	404.1	160.30	171.52	162.40
6	440.78	471.79	441.9	172.44	183.52	174.23
5	466.93	496.77	468.5	180.41	191.33	181.78
4	**477.48**	516.69	483.2	**184.07**	197.55	187.11
3	471.69	**523.87**	**486.1**	182.54	**199.80**	**188.0**
2	439.39	516.61	468.9	172.45	197.53	182.65
1	337.58	477.15	413.62	140.93	185.24	165.43

Table 4.22b. Maximum values of bending moments and shear forces in **beams** given in Table 4.22a and % variation with respect to LG2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG2	477.48	
	LPBY2	523.87	+9.7
	LFBY2	486.10	+1.8
Shear force (kN)	LG2	184.07	
	LPBY2	199.80	+15.73
	LFBY2	188.0	+2.1

The percentage variation of bending moment in beam is 10% when the pile length is taken as characteristic depth and 2% when pile is treated for full length showing that there is 8% decrease in the maximum bending moment when continuum model for soil is considered. The corresponding variations in shear force are 16% and 2% showing a decrease of 14%. The maximum variation in beam response is a decrease of 14%. As in the case of responses in columns this validates the concept of characteristic depth in the design regarding force output.



a. Bending moment b. Shear force

Fig. 4.22 Variation of Maximum values of (a)bending moment and (b)shear force in **beams** for different depths of fixity with SSI using continuum model for **sand**.

4.8.2.4 Influence of SSI of sand when piles are fixed at characteristic depth

The analytical results of LPN2, LPAY2 and LPBY2 are used to study the influence of SSI using discrete and continuum model for sand when piles are fixed at characteristic depth. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 4.23a. and the percentage variations of maximum responses with respect to LPN2 are reported in Table 4.23b. The variations along the floor level is shown in Fig. 4.23.

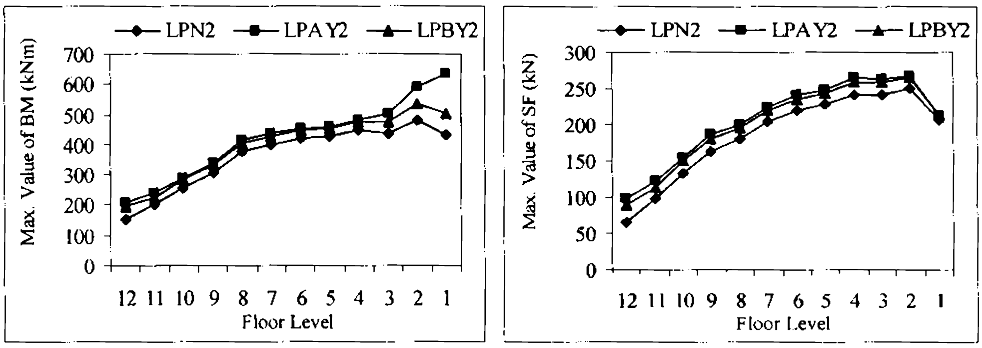
Table 4.23a Maximum values of bending moments, shear forces and axial forces in **columns** for different models for **sand** when fixed at characteristic depth

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)			Max values of axial force (kN)		
	LPN2	LPAY2	LPBY2	LPN2	LPAY2	LPBY2	LPN2	LPAY2	LPBY2
12	150.68	208.94	195.56	64.66	97.12	89.67	111.21	120.93	119.18
11	202.20	238.68	225.99	97.15	121.17	113.69	222.02	242.23	238.69
10	255.87	290.35	282.46	132.44	155.37	150.11	332.09	362.44	357.22
9	306.87	341.69	333.69	162.99	186.52	181.12	441.77	482.49	475.53
8	378.19	413.09	404.13	180.73	200.37	195.33	550.61	601.77	593.05
7	401.72	437.21	429.12	203.60	223.45	218.82	696.86	732.19	714.18
6	419.31	455.15	446.99	220.23	240.63	235.74	869.48	910.79	889.71
5	427.91	461.33	454.38	227.69	247.13	242.58	1050.5	1097.5	1073.59
4	447.30	479.62	476.65	241.79	264.48	259.41	1237.0	1288.9	1262.57
3	436.15	501.44	476.27	241.54	261.98	258.02	1425.7	1480.4	1453.01
2	**479.37**	588.01	**537.61**	**249.90**	**267.51**	**265.97**	1614.5	1665.8	1641.18
1	430.53	**632.67**	505.25	206.73	213.95	213.24	**1800.3**	**1830.4**	**1819.02**

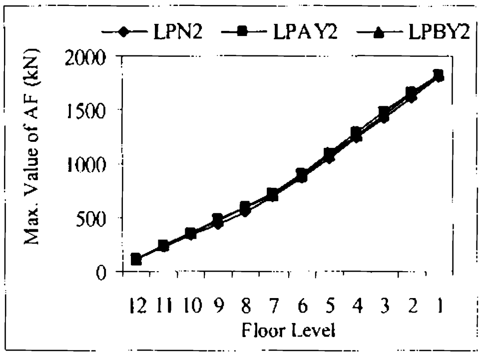
Table 4.23b Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 4.23a and % variation with respect to LPN2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LPN2	479.37	
	LPAY2	632.67	+31.9
	LPBY2	537.61	+12.1
Shear force (kN)	LPN2	249.90	
	LPAY2	267.51	+7.0
	LPBY2	265.95	+6.4
Axial force (kN)	LPN2	1800.3	
	LPAY2	1830.4	+1.6
	LPBY2	1819.02	+1.0

There is an increase of 32% for column bending moment when discrete elements are used and 12% using continuum elements showing that there is 20% variation in the maximum bending moment in the frame when two models for soil are considered. The corresponding variations in shear force are an increase of 7% and 6% showing a variation of 1%. As for axial force it is 2% and 1% giving a variation of 1%. This shows that when the two models are considered in modeling the properties of soil, discrete model gives upper bound values for column bending moment.



a. Bending moment b. Shear force



c. Axial force

Fig. 4.23 Variation of Maximum values of (a)bending moment,(b) shear force and (c)axial force in **columns** for different models for **sand** when fixed at characteristic depth.

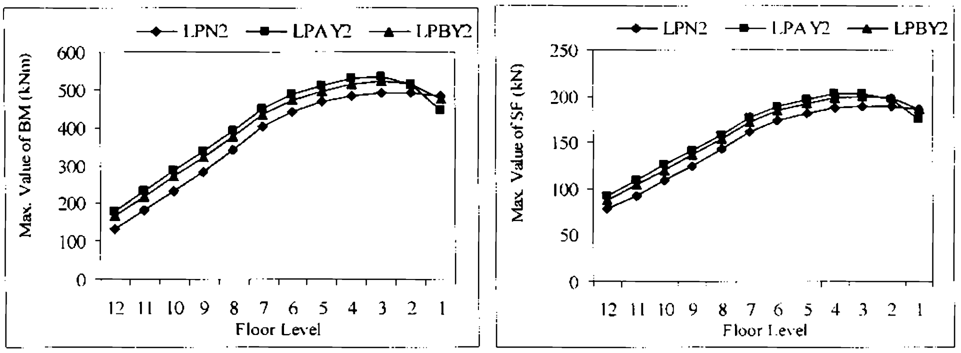
Maximum values of bending moments and shear forces in beams are reported in Table 4.24a and the percentage variations of maximum responses with respect to LPN2 are reported in Table 4.24b. The variations along the floor level are shown in Fig. 4.24.

Table 4.24a Maximum values of bending moments and shear force in **beams** for different models for **sand** when fixed at characteristic depth.

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	LPN2	LPAY2	LPBY2	LPN2	LPAY2	LPBY2
12	133.10	177.42	164.67	78.18	91.65	87.56
11	180.80	234.09	218.53	92.66	109.37	104.46
10	231.68	284.58	269.12	108.50	125.03	120.17
9	282.82	335.85	320.36	124.50	141.09	136.21
8	338.80	391.89	376.40	141.99	158.59	153.71
7	401.68	448.91	433.39	160.34	176.41	171.52
6	441.39	487.38	471.79	172.62	188.44	183.52
5	469.16	511.98	496.77	181.10	196.13	191.33
4	485.25	530.65	516.69	186.48	201.95	197.55
3	491.46	**534.08**	**523.87**	188.66	**203.01**	**199.80**
2	**491.76**	514.76	516.61	**188.8**	196.99	197.53
1	484.42	444.01	477.15	185.75	174.87	185.24

Table 4.24b Maximum values of bending moments and shear forces in **beams** given in Table 4.24a and % variation with respect to LPN2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LPN2	491.76	
	LPAY2	534.08	+8.6
	LPBY2	523.87	+6.5
Shear force (kN)	LPN2	188.80	
	LPAY2	203.01	+7.5
	LPBY2	199.80	+5.8



a. Bending moment b. Shear force

Fig. 4.24 Variation of Maximum values of (a)bending moment and (b)shear force in **beams** for different models for **sand** when fixed at characteristic depth.

The percentage variation of bending moment in beam is 9% when discrete elements are used and 7% using continuum elements showing that there is 2% variation in the maximum bending moment when two models for soil are considered. The corresponding variations in shear force are 8% and 6% showing a decrease of 2%. The maximum variation in beam response is only 2%. This shows that the type of soil model does not have significant effects when piles are fixed at characteristic depth.

4.8.2.5 Influence of SSI of sand considering full depth of piles

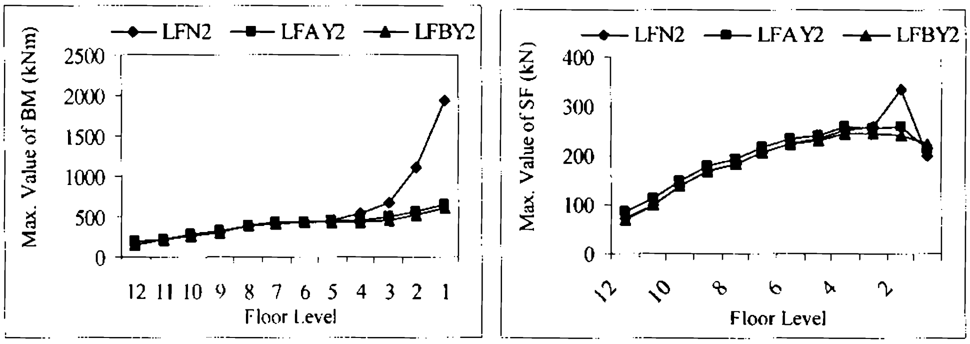
The analytical results of LFN2, LFAY2 and LFBY2 are used to study the influence of SSI using discrete and continuum model for soil when piles are fixed at full depth. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 4.25a. and the percentage variations of maximum responses with respect to LFN2 are reported in Table 4.25b. The variations along the floor level is shown in Fig. 4.25.

Table 4.25a. Maximum values of bending moments, shear forces and axial forces in **columns** for different models for **sand** when fixed at full depth

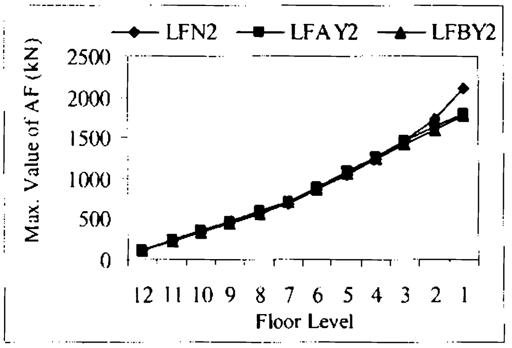
Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)			Max values of axial force(kN)		
	LFN2	LFAY2	LFBY2	LFN2	LFAY2	LFBY2	LFN2	LFAY2	LFBY2
12	161.6	191.6	161.48	70.75	87.49	70.68	113.8	118.09	113.46
11	207.5	224.9	207.43	101.1	112.2	101.13	227.4	236.4	226.75
10	262.4	280.14	262.26	136.7	148.52	136.69	340.4	353.7	339.24
9	313.6	331.3	313.30	167.4	179.5	167.35	452.9	470.8	451.39
8	385.1	401.8	384.35	184.3	194.0	184.23	564.6	587.1	562.71
7	410.5	426.5	408.08	207.4	217.4	207.24	693.7	715.8	697.8
6	433.3	443.8	425.06	224.2	234.3	223.69	866.6	891.54	870.5
5	459.7	449.5	431.43	233.2	241.0	231.04	1050.2	1075.4	1051.3
4	540.7	465.5	445.45	250.4	257.3	**245.21**	1246.8	1263.7	1236.8
3	680.5	491.7	466.59	258.5	255.2	244.73	1462.0	1451.9	1422.57
2	1099.0	573.8	517.36	**336.2**	**257.9**	241.37	1722.8	1633.5	1603.49
1	**1929.8**	**642.54**	**616.38**	199.5	213.8	225.52	**2107.6**	**1793.3**	**1767.3**

Table 4.25b Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 4.25a and % variation with respect to LFN2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LFN2	1929.8	
	LFAY2	642.54	-66.7
	LFBY2	616.38	-68.0
Shear force (kN)	LFN2	336.2	
	LFAY2	257.9	-23.2
	LFBY2	245.21	-27.0
Axial force (kN)	LFN2	2107.6	
	LFAY2	1793.3	-14.9
	LFBY2	1767.3	-16.1



a. Bending moment b. Shear force



c. Axial force

Fig. 4.25 Variation of maximum values of (a)bending moment, (b)shear force and axial force in **columns** for different models for **sand** when fixed at full depth.

There is a decrease of 67% for column bending moment when the full depth of pile is considered using discrete model and 68% using continuum giving 1% variation in the maximum bending moment. The corresponding variations in shear force show a decrease of 23% and 27% giving a variation of 4%. As for axial force it is 15% and 16% giving a variation of 1%. The maximum decrease in column bending moment is 68%. This may be due to the effect of soil structure interaction which reduced the responses in the frame.

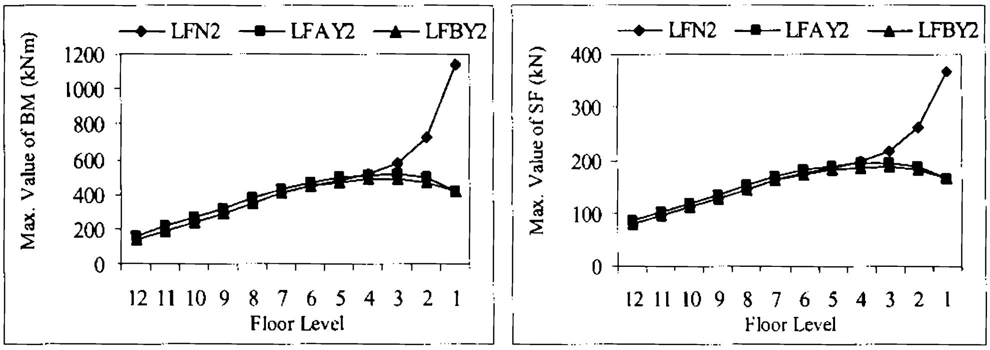
Maximum values of bending moments and shear forces in beams are reported in Table 4.26a and the percentage variations of maximum responses with respect to LFN2 are reported in Table 4.26b. The variations along the floor level are shown in Fig. 4.26.

Table 4.26a Maximum values of bending moments and shear forces in **beams** for different models for **sand** when fixed at full depth

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	LFN2	LFAY2	LFBY2	LFN2	LFAY2	LFBY2
12	139.5	162.0	140.41	79.89	86.7	79.97
11	188.29	215.5	189.4	94.98	103.5	95.34
10	239.13	266.1	240.2	110.8	119.2	111.16
9	290.3	317.3	291.3	126.8	135.27	127.16
8	346.5	373.3	347.3	144.3	152.7	144.65
7	403.9	430.2	404.1	162.3	170.5	162.40
6	444.0	468.3	441.9	174.8	182.4	174.23
5	477.3	492.6	468.5	184.8	190.0	181.78
4	519.4	510.1	483.2	198.4	195.5	187.11
3	579.3	**512.28**	**486.1**	217.2	**196.1**	**188.0**
2	727.4	491.0	468.9	263.3	189.5	182.65
1	**1138.4**	418.83	413.62	**368.6**	166.6	165.43

Table 4.26b Maximum values of bending moments and shear forces in **beams** given in Table 4.26a and % variation with respect to LFN2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LFN2	1138.4	
	LFAY2	512.28	-55.0
	LFBY2	486.1	-57.2
Shear force (kN)	LFN2	368.6	
	LFAY2	196.1	-46.7
	LFBY2	188.0	-48.9



a. Bending moment b. Shear force

Fig. 4.26 Variation of maximum values of (a)bending moment and (b)shear force in **beams** for different models for **sand** when fixed at full depth.

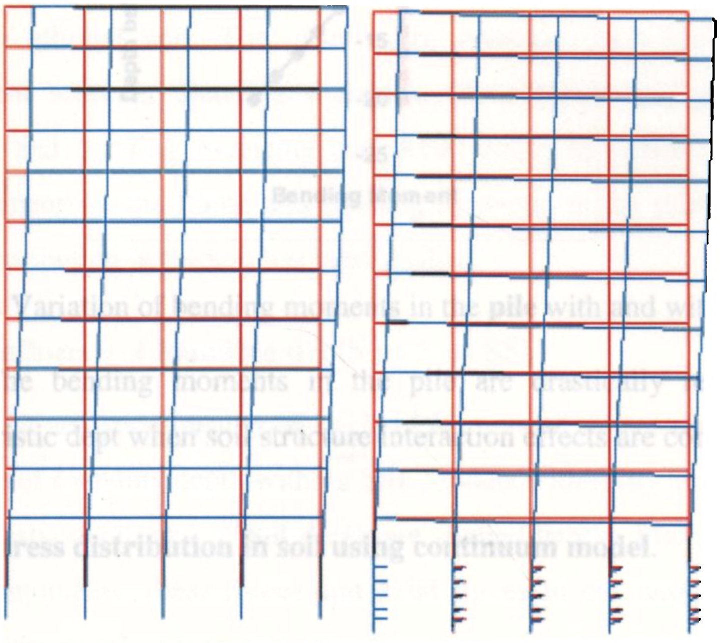
There is a decrease of 55% for beam bending moment when full depth of pile is considered using discrete model and 57% using continuum model showing 2% variation in the maximum bending moment when two models for soil are considered. The corresponding variations in shear force are 47% and 49% decrease showing a variation of 2%. The maximum variation in beam response is a decrease of 56%. As in the case of columns this may be due to the effect of soil structure interaction which reduced the responses in the frame.

4.8.2.6 Influence of SSI and founding depth on displacements in sand

The models LG2, LPN2, LPAY2, LPBY2, LFN2, LFAY2 and LFBY2 are analysed to investigate the effect of soil structure interaction and founding depth on displacement in sand. The maximum values of horizontal and vertical displacements are reported in Table 4.27. Fig. 4.27 shows the deflected shapes when the pile is taken for characteristic length, with and without soil structure interaction.

Table 4.27 Effect of fixity with and without SSI effect of **sand** on displacements

Depth of fixity			Max values of displacement (m)	
			Horizontal direction	Vertical direction
Ground Level			0.24	0.006
Characteristic depth	Without SSI		0.289	0.0066
	With SSI	Discrete model	0.383	0.079
		Continuum model	0.3418	0.0391
Full depth	Without SSI		1.0785	0.0098
	With SSI	Discrete model	0.311	0.035
		Continuum model	0.2967	0.0155



a.Without SSI
Max.horizontal displacement:0.289m
Max. vertical displacement:0.006m

b.With SSI
Max. horizontal displacement:0.383m
Max.vertical displacement: 0.079m

Fig. 4.27 Deflected shapes (a)without and (b)with soil structure interaction in **sand.**

When displacements are considered, it is observed that the maximum values of displacement both in the horizontal and vertical direction increases with depth of fixity for the two models of soil, compared to when the frame is fixed at the ground level. Maximum displacements with soil structure interaction effects are reported when the pile length is taken as characteristic depth. Decrease in displacements for full depth of fixity may be due to the restoring effect caused by the thick soil medium.

4.8.2.7 Influence of SSI of sand on bending moment in piles

The variation of bending moments in the pile with and without soil structure interaction are shown in Fig. 4.28. Models LPN2 and LPAY2are compared.

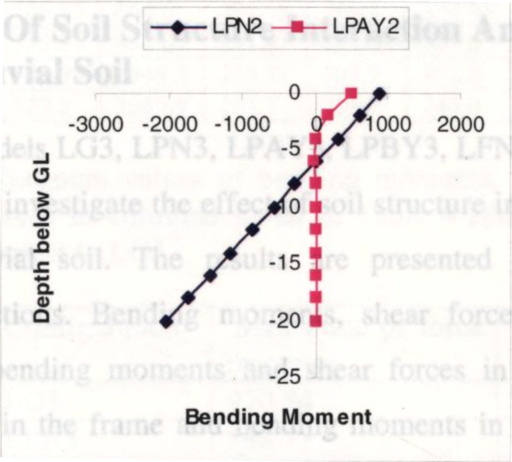


Fig. 4.28 Variation of bending moments in the **pile** with and without SSI

The bending moments in the pile are drastically reduced beyond characteristic dept when soil structure interaction effects are considered.

4.8.2.8 Stress distribution in soil using continuum model.

The distribution of horizontal, vertical and von Mises stress in the soil when modeled using continuum elements is shown in Fig. 4.29. The stress distribution between the middle, intermediate and outer pile are shown.

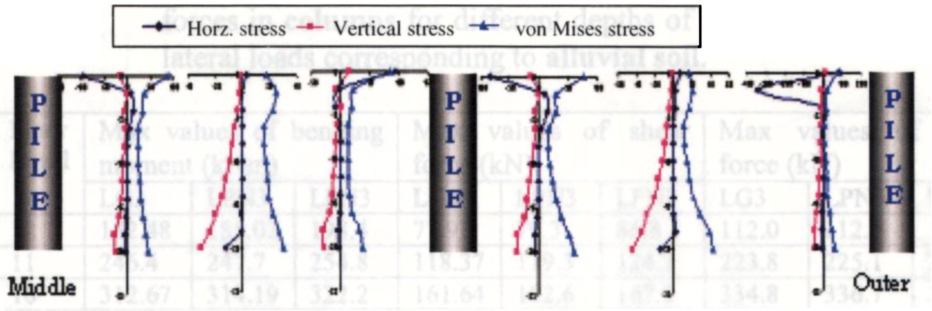


Fig. 4.29 Stress distribution in **sand**

4.8.3 Effect Of Soil Structure Interaction And Founding Depth In Alluvial Soil

The models LG3, LPN3, LPAY3, LPBY3, LFN3, LFAY3 and LFBY3 are analysed to investigate the effect of soil structure interaction and founding depth in alluvial soil. The results are presented and discussed in the subsequent sections. Bending moments, shear forces and axial forces in columns and bending moments and shear forces in beams are compared. Displacements in the frame and bending moments in the pile are compared. Stress distribution in the soil has been studied.

4.8.3.1 Influence of founding depth without SSI

The analytical results of LG3, LPN3 and LFN3 are used to study the influence of founding depth without SSI. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 4.28a. and the percentage variations of maximum responses with respect to LG3 are reported in Table 4.28b. The variations along the floor level is shown in Fig. 4.30.

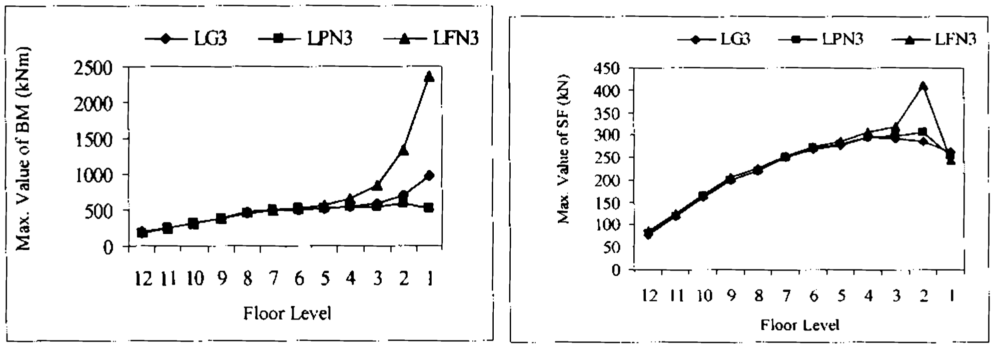
Table 4.28a Maximum values of bending moments, shear forces and axial forces in **columns** for different depths of fixity without SSI with lateral loads corresponding to **alluvial soil.**

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)			Max values of axial force (kN)		
	LG3	LPN3	LFN3	LG3	LPN3	LFN3	LG3	LPN3	LFN3
12	182.48	185.02	198.4	77.97	79.3	86.8	112.0	112.5	116.0
11	246.4	247.7	254.8	118.37	119.3	124.2	223.8	225.1	232.3
10	312.67	314.19	322.2	161.64	162.6	167.9	334.8	336.7	347.7
9	375.24	376.8	385.1	199.1	200.1	205.59	445.2	447.7	462.5
8	462.74	464.4	472.9	221.09	221.9	226.3	592.3	591.8	586.7
7	491.02	493.18	504.1	249.07	249.9	254.7	775.9	775.4	769.6
6	510.87	514.53	532.0	269.10	270.0	275.3	974.6	974.19	968.3
5	516.47	524.88	564.5	278.12	279.5	286.3	1183.1	1183.5	1180.4
4	535.50	548.55	664.0	**294.10**	296.3	307.5	1396.3	1399.5	1408.5
3	586.56	535.65	836.0	291.87	296.6	317.6	1607.7	1618.3	1659.5
2	695.19	**588.77**	1349.3	285.39	**307.2**	**412.6**	1806.9	1837.5	1966.7
1	**970.84**	527.8	**2369.9**	263.7	253.7	245.0	**1967.6**	**2053.2**	**2426.6**

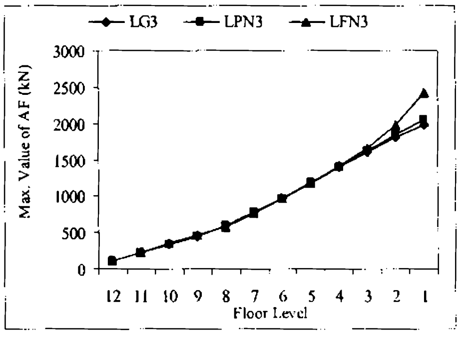
Table 4.28b Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 4.28a and % variation with respect to LG3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG3	970.84	
	LPN3	588.77	-39.4
	LFN3	2369.9	+144.1
Shear force (kN)	LG3	294.10	
	LPN3	307.2	+4.4
	LFN3	412.6	+40.2
Axial force (kN)	LG3	1967.6	
	LPN3	2053.2	+4.3
	LFN3	2426.6	+23.3

There is a decrease of 39% for column bending moment when the pile length is taken as characteristic depth and an increase of 144% when pile is treated for full length showing that there is 183% increase in the maximum bending moment in the frame when no soil medium is considered. The corresponding variations in shear force is 4% and 40% showing an increase of 36%. As for axial force it is 4% and 23% giving an increase of 19%. This may be due to the lowering of the support of the frames and the subsequent increase in the cantilever action.



a. Bending moment b. Shear force



c. Axial force

Fig. 4.30 Variation of maximum values of (a)bending moment, (b)shear force and (c)axial force in **columns** for different depths of fixity without SSI with lateral loads corresponding to **alluvial soil.**

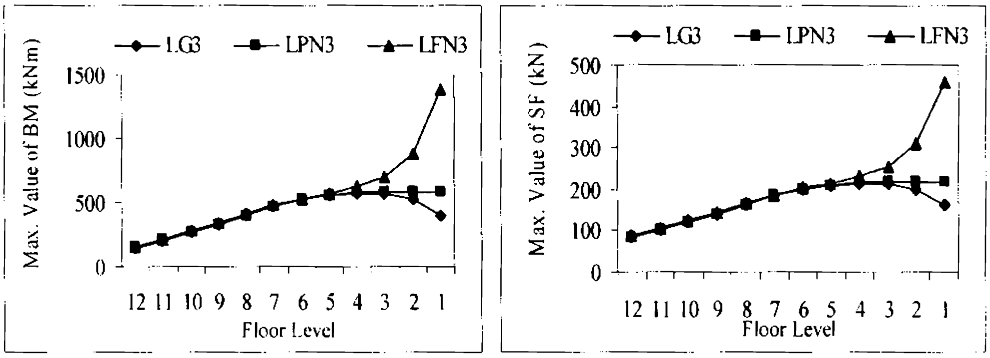
Maximum values of bending moments and shear forces in beams are reported in Table 4.29a and the percentage variations of maximum responses with respect to LG3 are reported in Table 4.29b. The variations along the floor level are shown in Fig. 4.31.

Table 4.29a Maximum values of bending moments and shear forces in **beams** for different depths of fixity without SSI with lateral load corresponding to **alluvial soil.**

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	LG3	LPN3	LFN3	LG3	LPN3	LFN3
12	149.13	150.5	158.4	83.21	83.6	85.7
11	207.06	208.7	217.8	100.85	101.3	104.19
10	269.42	271.1	280.1	120.29	120.8	123.5
9	332.27	334.0	343.1	139.94	140.47	143.2
8	401.61	402.7	412.1	161.4	161.9	164.8
7	477.3	477.2	482.6	183.62	183.76	186.8
6	525.82	526.29	531.9	198.63	198.7	202.2
5	558.34	560.8	571.0	208.55	209.3	214.5
4	**571.6**	580.8	624.5	**213.14**	216.0	231.2
3	564.86	588.81	698.1	211.4	218.8	254.3
2	525.77	**589.79**	880.2	199.19	**219.2**	311.0
1	401.39	581.72	**1384.2**	160.67	215.6	**459.9**

Table 4.29b. Maximum values of bending moments and shear forces in **beams** given in Table 4.29a. and % variation with respect to LG3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG3	571.6	
	LPN3	589.79	+3.1%
	LFN3	1384.2	+142.1
Shear force (kN)	LG3	213.14	
	LPN3	219.2	+2.8%
	LFN3	459.9	+115.7%



a. Bending moment b. Shear force

Fig. 4.31 Variation of maximum values of (a)bending moment and (b)shear force in **beams** for different depths of fixity without SSI with lateral load corresponding to **alluvial soil.**

The percentage variation of bending moment in beam is 3% when the pile length is taken as characteristic depth and 142% when pile is treated for full length showing that there is 139% increase in the maximum bending moment when no soil medium is considered. The corresponding variations in shear force are 3% and 116% showing an increase of 113%. As in the case of responses in columns this may be due to the lowering of the support of the frames and the subsequent increase in the cantilever action.

4.8.3.2 Influence of founding depth with SSI using discrete model for alluvial soil

The analytical results of LG3, LPAY3 and LFAY3 are used to study the influence of founding depth with SSI using discrete model for alluvial soil. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 4.30a. and the percentage variations of maximum responses with respect to LG3 are reported in Table 4.30b. The variations along the floor level is shown in Fig. 4.32.

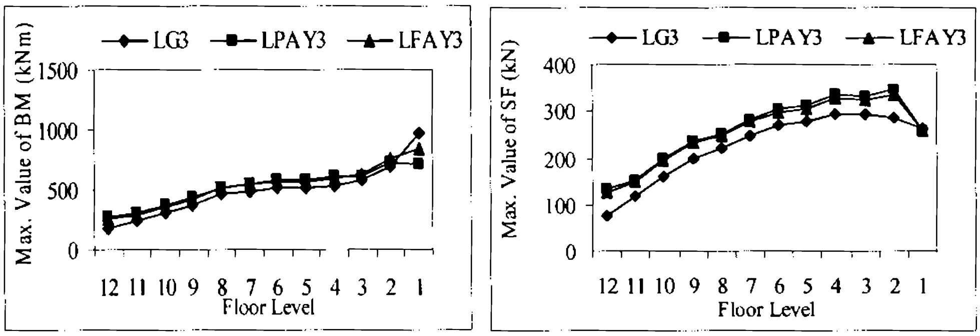
Table 4.30a. Maximum values of bending moments, shear forces and axial forces in **columns** for different depths of fixity with SSI using discrete model for **alluvial** soil.

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)			Max values of axial force(kN)		
	LG3	LPAY3	LFAY3	LG3	LPAY3	LFAY3	LG3	LPAY3	LFAY3
12	182.48	278.72	265.5	77.97	131.61	124.2	112.0	131.06	128.37
11	246.4	299.58	290.0	118.37	153.85	148.98	223.8	263.5	258.02
10	312.67	369.74	361.9	161.64	199.52	194.33	334.8	394.58	386.29
9	375.24	432.85	424.9	199.1	238.0	232.6	445.2	525.4	514.36
8	462.74	518.60	510.9	221.09	252.46	248.15	592.3	655.43	641.4
7	491.02	550.45	542.1	249.07	281.77	277.2	775.9	814.7	804.9
6	510.87	572.84	563.8	269.10	303.02	298.3	974.6	1020.1	1008.5
5	516.47	581.15	570.5	278.12	310.70	306.12	1183.1	1235.7	1222.2
4	535.50	611.26	593.4	**294.10**	334.09	328.25	1396.3	1457.5	1441.2
3	586.56	618.02	626.2	291.87	330.82	324.6	1607.7	1680.5	1660.1
2	695.19	**726.30**	750.7	285.39	**346.19**	**333.7**	1806.9	1898.9	1870.1
1	**970.84**	707.38	**833.5**	263.7	257.73	257.8	**1967.6**	**2099.3**	**2051.3**

Table 4.30b Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 4.30a and % variation with respect to LG3

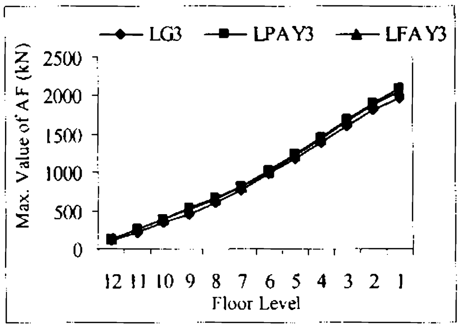
Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG3	970.84	
	LPAY3	726.30	-25.1
	LFAY3	833.50	-14.1
Shear force (kN)	LG3	294.10	
	LPAY3	346.19	+17.7
	LFAY3	333.70	+13.4
Axial force (kN)	LG3	1967.6	
	LPAY3	2099.3	+6.6
	LFAY3	2051.3	+4.2

There is a decrease of 25% for column bending moment when the pile length is taken as characteristic depth and 14% when pile is treated for full length showing that there is 11% increase in the maximum bending moment in the frame when discrete model for soil is considered. The corresponding variations in shear force shows an increase of 17% and 13% showing a decrease of 4%. As for axial force it is 7% and 4% giving a decrease of 2%. The maximum variation in column response is 11% increase in bending moment. This may be due to the fact that alluvial soil is weaker than laterite and sand; and the concept of characteristic depth cannot by strictly followed in this case.



a. Bending moment

b. Shear force



c. Axial Force

Fig. 4.32 Variation of maximum values of (a)bending moment,(b) shear force and (c)axial force in **columns** for different depths of fixity with SSI using discrete model for **alluvial** soil.

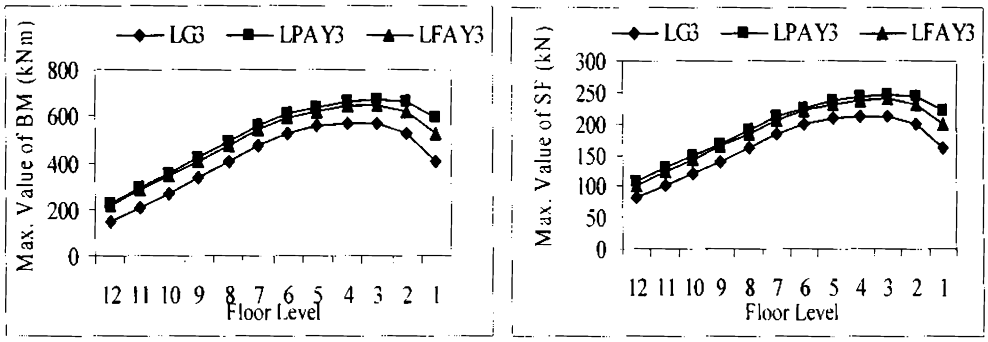
Maximum values of bending moments and shear forces in beams are reported in Table 4.31a and the percentage variations of maximum responses with respect to LG1 are reported in Table 4.31b. The variations along the floor level are shown in Fig. 4.33.

Table 4.31a Maximum values of bending moments and shear forces in **beams** for different depths of fixity with SSI using discrete model for **alluvial** soil

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	LG3	LPAY3	LFAY3	LG3	LPAY3	LFAY3
12	149.13	223.14	210.9	83.21	105.85	101.99
11	207.06	295.06	280.5	100.85	128.41	123.85
10	269.42	356.8	342.3	120.29	147.5	143.03
9	332.27	419.98	405.4	139.94	167.34	162.79
8	401.61	488.93	474.38	161.4	188.87	184.31
7	477.3	559.2	544.5	183.62	210.83	206.21
6	525.82	607.0	591.8	198.63	225.78	221.02
5	558.34	638.1	622.1	208.55	235.49	230.47
4	**571.60**	663.6	644.7	**213.14**	243.45	237.5
3	564.86	**671.97**	**647.8**	211.4	**246.07**	**238.52**
2	525.77	658.40	620.7	199.19	241.85	230.07
1	401.39	591.16	521.6	160.67	220.81	199.05

Table 4.31b. Maximum values of bending moments and shear forces in **beams** given in Table 4.31a. and % variation with respect to LG3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG3	571.60	
	LPAY3	671.97	+17.5
	LFAY3	647.80	+13.3
Shear force (kN)	LG3	213.14	
	LPAY3	246.07	+15.4
	LFAY3	238.52	+12



a. Bending moment b. Shear force

Fig. 4.33 Variation of maximum values of(a) bending moment and (b)shear force in **beams** for different depths of fixity with SSI using discrete model for **alluvial** soil

The percentage variation of bending moment in beam is 18% when the pile length is taken as characteristic depth and 13% when pile is treated for full length showing that there is 5% decrease in the maximum bending moment when discrete model for soil is considered. The corresponding variations in shear force is 15% and 12% showing a decrease of 3%. The maximum variation in beam response is 5%. As in the case of responses in columns this may be due to the fact that alluvial soil is weaker than laterite and sand; and that the concept of characteristic depth cannot by strictly followed in this case.

4.8.3.3 Influence of founding depth with SSI using continuum model for alluvial soil

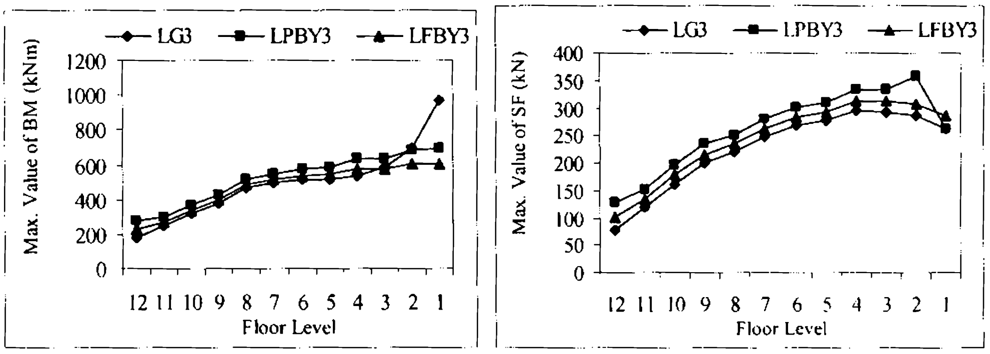
The analytical results of LG3, LPBY3 and LFBY3 are used to study the influence of founding depth with SSI using continuum model for alluvial soil. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 4.32a. and the percentage variations of maximum responses with respect to LG1 are reported in Table 4.32b. The variations along the floor level is shown in Fig. 4.34.

Table 4.32a Maximum values of bending moments, shear forces and axial forces in **columns** for different depths of fixity with SSI using continuum model for **alluvial** soil

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)			Max values of axial force (kN)		
	LG3	LPBY3	LFBY3	LG3	LPBY3	LFBY3	LG3	LPBY3	LFBY3
12	182.48	275.54	224.5	77.97	129.83	101.3	112.0	131.7	122.0
11	246.4	295.36	268.5	118.37	152.67	133.8	223.8	265.0	244.9
10	312.67	367.86	337.5	161.64	198.27	178.1	334.8	397.0	366.6
9	375.24	431.0	400.4	199.1	236.7	216.0	445.2	528.8	488.1
8	462.74	516.92	487.2	221.09	251.4	234.7	592.3	659.7	608.4
7	491.02	549.04	517.3	249.07	280.7	263.3	775.9	794.6	769.3
6	510.87	572.7	539.1	269.10	302.0	283.9	974.6	996.7	966.9
5	516.47	585.5	548.6	278.12	310.1	292.6	1183.1	1209.5	1174.8
4	535.50	630.55	575.3	**294.10**	334.0	312.2	1396.3	1430.3	1389.1
3	586.56	631.10	574.6	291.87	333.1	**312.5**	1607.7	1656.4	1605.3
2	695.19	681.79	602.1	285.39	**358.7**	308.5	1806.9	1889.4	1820.1
1	**970.84**	**697.14**	**607.8**	263.7	261.2	286.8	**1967.6**	**2135.3**	**2025.6**

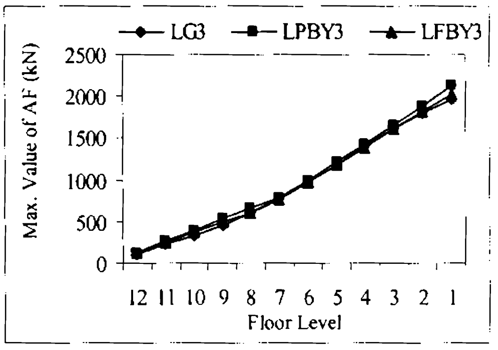
Table 4.32b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 4.32a. and % variation with respect to LG3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG3	970.84	
	LPBY3	697.14	-28.1
	LFBY3	607.80	-37.3
Shear force (kN)	LG3	294.10	
	LPBY3	358.70	+21.9
	LFBY3	312.50	+6.2
Axial force (kN)	LG3	1967.6	
	LPBY3	2135.3	+8.5
	LFBY3	2025.6	+2.9



a. Bending moment

b. Shear force



c. Axial force

Fig. 4.34 Variation of Maximum values of (a)bending moment, (b)shear force and (c)axial force in **columns** for different depths of fixity with SSI using continuum model for **alluvial** soil

There is a decrease of 28% for column bending moment when the pile length is taken as characteristic depth and 37% when pile is treated for full length showing that there is 9% increase in the maximum bending moment in the frame when continuum model for soil is considered. The corresponding variations in shear force are an increase of 22% and 6% showing a decrease of

16%. As for axial force it is 9% and 3% giving a decrease of 6%. When the soil medium is modeled using continuum elements the responses in the columns have reduced when the depth of pile is taken from characteristic depth to full depth. This may be due to the fact that continuum elements are more suitable to describe the concept of characteristic depth in alluvial soil.

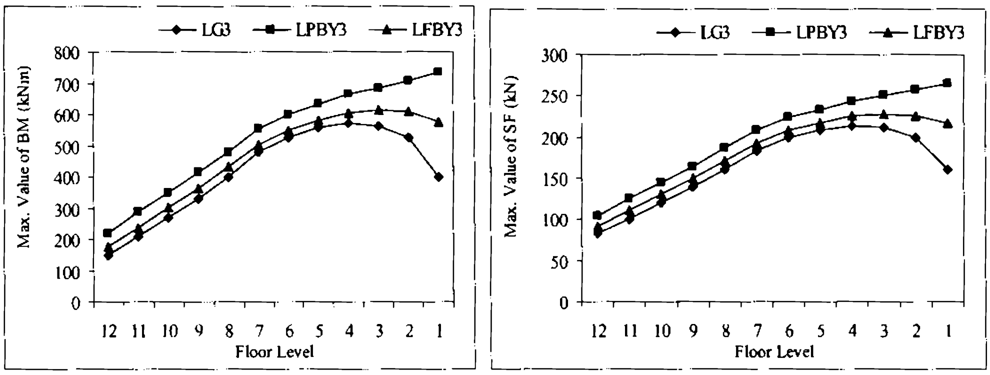
Maximum values of bending moments and shear forces in beams are reported in Table 4.33a and the percentage variations of maximum responses with respect to LG1 are reported in Table 4.33b. The variations along the floor level are shown in Fig. 4.35.

Table 4.33a Maximum values of bending moments and shear forces in **beams** for different depths of fixity with SSI using continuum model for **alluvial** soil

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	LG3	LPBY3	LFBY3	LG3	LPBY3	LFBY3
12	149.13	216.84	176.8	83.21	103.7	91.1
11	207.06	286.98	239.2	100.85	125.8	110.8
10	269.42	348.7	301.3	120.29	144.9	130.1
9	332.27	411.97	364.3	139.94	164.7	149.9
8	401.61	480.99	433.2	161.4	186.3	171.4
7	477.3	551.43	503.2	183.62	208.3	193.2
6	525.82	599.66	550.3	198.63	223.4	207.9
5	558.34	632.43	581.0	208.55	233.6	217.5
4	**571.6**	663.50	605.2	**213.14**	243.3	225.1
3	564.86	684.65	**614.6**	211.4	249.9	**228.1**
2	525.77	707.79	607.8	199.19	257.2	225.9
1	401.39	**733.20**	576.1	160.67	**265.2**	216.2

Table 4.33b. Maximum values of bending moments and shear forces in **beams** given in Table 4.33a and % variation with respect to LG3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LG3	571.60	
	LPBY3	733.20	+28.2
	LFBY3	614.60	+7.5
Shear force (kN)	LG3	213.14	
	LPBY3	265.20	+24.2
	LFBY3	228.10	+7.0



a. Bending moment b. Shear force

Fig. 4.35 Variation of maximum values of (a)bending moment and (b)shear force in **beam** for different depths of fixity with SSI using continuum model for **alluvial** soil.

The percentage variation of bending moment in beam is 28% when the pile length is taken as characteristic depth and 8% when pile is treated for full length showing that there is 20% decrease in the maximum bending moment when the depth of pile is taken from characteristic depth to full depth. The corresponding variations in shear force are 24% and 7% showing a decrease of 17%. The minimum variation in beam response is a decrease of 17%. As in the case of responses in columns this validates the concept of characteristic depth in the design regarding force output.

4.8.3.4 Influence of SSI of alluvial soil when piles are fixed at characteristic depth

The analytical results of LPN3, LPAY3 and LPBY3 are used to study the influence of SSI using discrete and continuum model for alluvial soil when piles are fixed at characteristic depth. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 4.34a. and the percentage variations of maximum responses with respect to LPN3 are reported in Table 4.34b. The variations along the floor level is shown in Fig. 4.36.

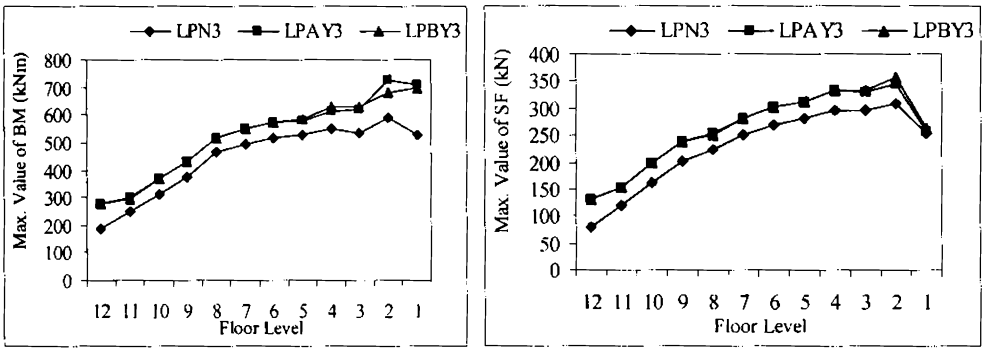
Table 4.34a. Maximum values of bending moments, shear forces and axial forces in **columns** for different models for **alluvial** soil when fixed at characteristic depth

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)			Max values of axial force(kN)		
	LPN3	LPAY3	LPBY3	LPN3	LPAY3	LPBY3	LPN3	LPAY3	LPBY3
12	185.02	278.72	275.54	79.3	131.61	129.83	112.5	131.06	131.7
11	247.7	299.58	295.36	119.3	153.85	152.67	225.1	263.5	265.0
10	314.19	369.74	367.86	162.6	199.52	198.27	336.7	394.58	397.0
9	376.8	432.85	431.0	200.1	238.0	236.7	447.7	525.4	528.8
8	464.4	518.60	516.92	221.9	252.46	251.4	591.8	655.43	659.7
7	493.18	550.45	549.04	249.9	281.77	280.7	775.4	814.7	794.6
6	514.53	572.84	572.7	270.0	303.02	302.0	974.19	1020.1	996.7
5	524.88	581.15	585.5	279.5	310.70	310.1	1183.5	1235.7	1209.5
4	548.55	611.26	630.55	296.3	334.09	334.0	1399.5	1457.5	1430.3
3	535.65	618.02	631.10	296.6	330.82	333.1	1618.3	1680.5	1656.4
2	**588.77**	**726.30**	681.79	**307.2**	**346.19**	**358.7**	1837.5	1898.9	1889.4
1	527.8	707.38	**697.14**	253.7	257.73	261.2	**2053.2**	**2099.3**	**2135.3**

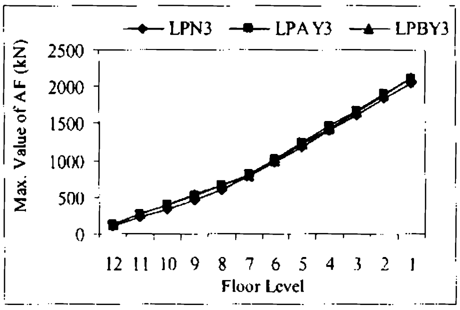
Table 4.34b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 4.34a and % variation with respect to LPN3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LPN3	588.77	
	LPAY3	726.30	+23.3
	LPBY3	697.14	+18.4
Shear force (kN)	LPN3	307.20	
	LPAY3	346.19	+12.6
	LPBY3	358.70	+16.7
Axial force (kN)	LPN3	2053.2	
	LPAY3	2099.3	+2.2
	LPBY3	2135.3	+3.9

There is an increase of 23% for column bending moment when discrete elements are used and 18% using continuum elements showing that there is 5% variation in the maximum bending moment in the frame when two models for soil are considered. The corresponding variations in shear force show an increase of 13% and 17% giving a variation of 4%. As for axial force it is 2% and 4% giving a variation of 2%. This shows that even though both elements are equally good in modeling the properties of soil, discrete model gives a higher value for column bending moment and has to be considered in the design.



a. Bending moment b. Shear force



c. Axial force

Fig. 4.36 Variation of maximum values of (a) bending moment,(b) shear force and (c)axial force in **columns** for different models for **alluvial** soil when fixed at characteristic depth.

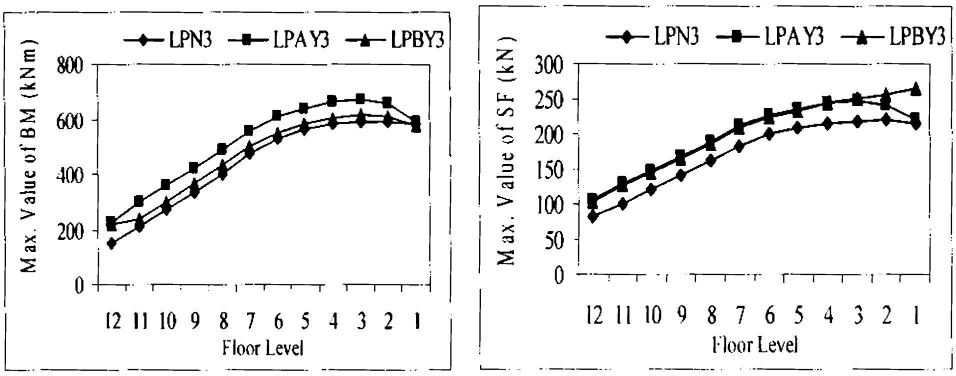
Maximum values of bending moments and shear forces in beams are reported in Table 4.35a and the percentage variations of maximum responses with respect to LPN3 are reported in Table 4.35b. The variations along the floor level are shown in Fig. 4.37.

Table 4.35a. Maximum values of bending moments and shear forces in **beams** for different models for **alluvial** soil when fixed at characteristic depth

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	LPN3	LPAY3	LPBY3	LPN3	LPAY3	LPBY3
12	150.50	223.14	216.84	83.60	105.85	103.70
11	208.70	295.06	239.20	101.30	128.41	125.80
10	271.10	356.80	301.30	120.80	147.50	144.90
9	334.00	419.98	364.30	140.47	167.34	164.70
8	402.70	488.93	433.20	161.90	188.87	186.30
7	477.20	559.20	503.20	183.76	210.83	208.30
6	526.29	607.00	550.30	198.70	225.78	223.40
5	560.80	638.10	581.00	209.30	235.49	233.60
4	580.80	663.60	605.20	216.00	243.45	243.30
3	588.81	**671.97**	**614.60**	218.80	**246.07**	249.90
2	**589.79**	658.40	607.80	**219.20**	241.85	257.20
1	581.72	591.16	576.10	215.60	220.81	**265.20**

Table 4.35b. Maximum values of bending moments and shear forces in **beams** given in Table 4.35a. and % variation with respect to LPN3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LPN3	589.79	
	LPAY3	671.97	+13.9
	LPBY3	614.60	+4.2
Shear force (kN)	LPN3	219.20	
	LPAY3	246.07	+12.2
	LPBY3	265.20	+20.9



a. Bending moment b. Shear force

Fig. 4.37 Variation of maximum values of (a)bending moment and (b)shear force in **beams** for different models for **alluvial** soil when fixed at characteristic depth.

The percentage variation of bending moment in beam is 14% using discrete model and 4% using continuum model when pile length is taken as characteristic depth showing that there is 10% variation in the maximum bending moment when two models for soil are considered. The corresponding variations in shear force are 12% and 21% showing a variation of 9%. The maximum variation in beam response is 10%. This shows that soil structure interaction increases the responses in beams in both models when piles are fixed at characteristic depth.

4.8.3.5 Influence of SSI of alluvial soil considering full depth of piles

The analytical results of LFN3, LFAY3 and LFBY3 are used to study the influence of SSI using discrete and continuum model for alluvial soil when piles are fixed at full depth. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 4.36a. and the percentage variations of maximum responses with respect to LFN1 are reported in Table 4.36b. The variations along the floor level is shown in Fig. 4.38.

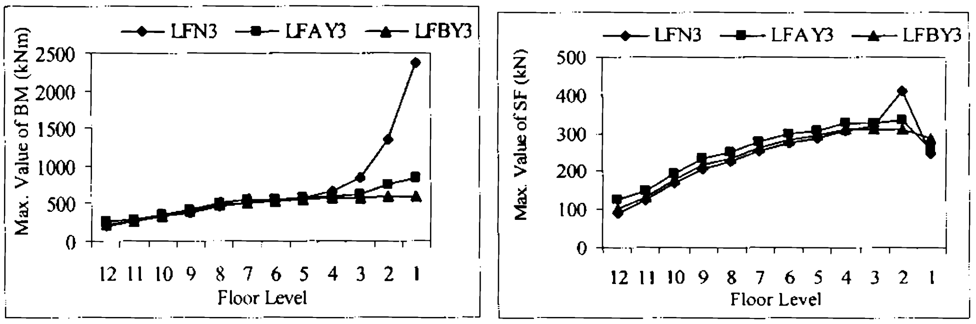
Table 4.36a Maximum values of bending moments, shear forces and axial forces in **columns** for different models for **alluvial** soil when fixed at full depth

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)			Max values of axial force (kN)		
	LFN3	LFAY3	LFBY3	LFN3	LFAY3	LFBY3	LFN3	LFAY3	LFBY3
12	198.4	265.5	224.5	86.8	124.2	101.3	116.0	128.37	122.0
11	254.8	290.0	268.5	124.2	148.98	133.8	232.3	258.02	244.9
10	322.2	361.9	337.5	167.9	194.33	178.1	347.7	386.29	366.6
9	385.1	424.9	400.4	205.59	232.6	216.0	462.5	514.36	488.1
8	472.9	510.9	487.2	226.3	248.15	234.7	586.7	641.4	608.4
7	504.1	542.1	517.3	254.7	277.2	263.3	769.6	804.9	769.3
6	532.0	563.8	539.1	275.3	298.3	283.9	968.3	1008.5	966.9
5	564.5	570.5	548.6	286.3	306.12	292.6	1180.4	1222.2	1174.8
4	664.0	593.4	575.3	307.5	328.25	312.2	1408.5	1441.2	1389.1
3	836.0	626.2	574.6	317.6	324.6	**312.5**	1659.5	1660.1	1605.3
2	1349.3	750.7	602.1	**412.6**	**333.7**	308.5	1966.7	1870.1	1820.1
1	**2369.9**	**833.5**	**607.8**	245.0	257.8	286.8	**2426.6**	**2051.3**	**2025.6**

Table 4.36b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 4.36a. and % variation with respect to LFN3

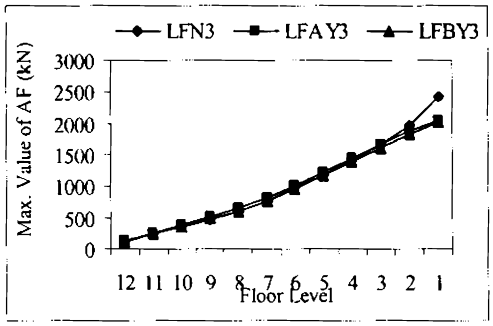
Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LFN3	2369.9	
	LFAY3	833.5	-64.8
	LFBY3	607.8	-74.3
Shear force (kN)	LFN3	412.6	
	LFAY3	333.7	-19.1
	LFBY3	312.5	-24.2
Axial force (kN)	LFN3	2426.6	
	LFAY3	2051.3	-15.4
	LFBY3	2025.6	-16.5

There is a decrease of 65% for column bending moment using discrete model and 74% using continuum model when the full depth of pile is considered giving a variation of 9% in the maximum bending moment. The corresponding variations in shear force shows a decrease of 19% and 24%, giving a variation of 5%. As for axial force it is 15% and 17% giving a variation of 2%. The minimum decrease in column bending moment is 65%. This may be due to the effect of soil structure interaction which reduced the responses in the frame.



a. Bending moment

b. Shear force



c. Axial Force

Fig. 4.38 Variation of maximum values of (a)bending moment, (b)shear force and (c)axial force in **columns** for different models for **alluvial** soil when fixed at full depth.

Maximum values of bending moments and shear forces in beams are reported in Table 4.37a and the percentage variations of maximum responses with respect to LFN3 are reported in Table 4.37b. The variations along the floor level are shown in Fig. 4.39.

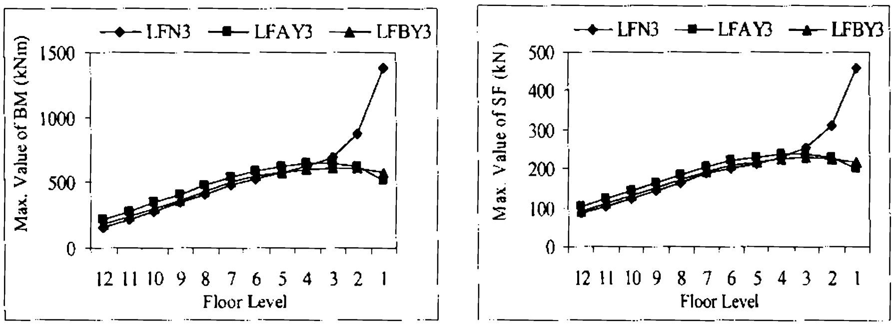
Table 4.37a. Maximum values of bending moments and shear forces in **beams** for different models for **alluvial** soil when fixed at full depth

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	LFN3	LFAY3	LFBY3	LFN3	LFAY3	LFBY3
12	158.4	210.9	176.8	85.7	101.99	91.1
11	217.8	280.5	239.2	104.19	123.85	110.8
10	280.1	342.3	301.3	123.5	143.03	130.1
9	343.1	405.4	364.3	143.2	162.79	149.9
8	412.1	474.38	433.2	164.8	184.31	171.4
7	482.6	544.5	503.2	186.8	206.21	193.2
6	531.9	591.8	550.3	202.2	221.02	207.9
5	571.0	622.1	581.0	214.5	230.47	217.5
4	624.5	644.7	605.2	231.2	237.5	225.1
3	698.1	**647.8**	**614.6**	254.3	**238.52**	**228.1**
2	880.2	620.7	607.8	311.0	230.07	225.9
1	**1384.2**	521.6	576.1	**459.9**	199.05	216.2

Table 4.37b.Maximum values of bending moments and shear forces in **beams** given in Table 4.37a.and % variation with respect to LFN3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LFN3	1384.2	
	LFAY3	647.80	-53.2
	LFBY3	614.60	-55.5
Shear force (kN)	LFN3	459.90	
	LFAY3	238.52	-48.1
	LFBY3	228.10	-50.4

There is a decrease of 53% for beam bending moment using discrete model and 56% using continuum model when full depth of pile is considered giving a variation of 3% in the maximum bending moment. The corresponding variations in shear force are 48% and 50% decrease showing a variation of 2%. The responses in the beams are reduced in both cases. As in the case of columns this may be due to the effect of soil structure interaction which reduced the responses in the frame.

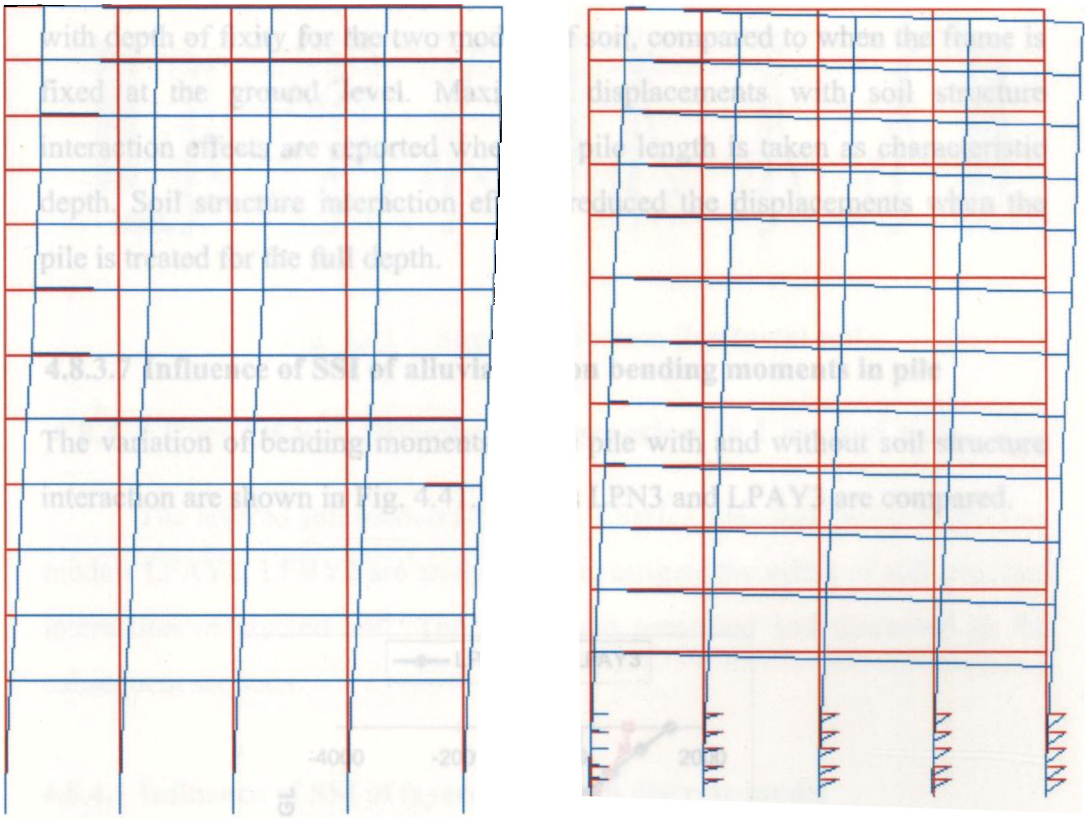


a. Bending moment b. Shear force

Fig. 4.39Variation of maximum values of(a) bending moment and (b)shear force in **beams** for different models for **alluvial** soil when fixed at full depth.

4.8.3.6 Influence of SSI and founding depth on displacements in alluvial soil

The models LG3, LPN3, LPAY3, LPBY3, LFN3, LFAY3 and LFBY3 are analysed to investigate the effect of soil structure interaction and founding depth on displacements in alluvial soil. The maximum values of horizontal and vertical displacements are reported in Table 4.38. Fig. 4.40 shows the deflected shapes when the pile is taken for characteristic length, with and without soil structure interaction.



a.Without SSI (m)
Max.horizontal displacement:0.355
Max.vertical displacement:0.007

a.With SSI (m)
Max.horizontal displacement:0.978
Max.vertical displacement:0.37

Fig. 4.40 Deflected shapes (a)without and (b) with soil structure interaction

Table 4.38 Effect of fixity with and without SSI effect of **alluvial** soil on displacements

Depth of fixity			Max values of displacement (m)	
			Horizontal direction	Vertical direction
Ground Level			0.302	0.00676
Characteristic depth	Without SSI		0.355	0.0074
	With SSI	Discrete model	0.978	0.374
		Continuum model	0.693	0.1595
Full depth	Without SSI		1.32	0.011
	With SSI	Discrete model	0.567	0.144
		Continuum model	0.485	0.048

When displacements are considered, it is observed that the maximum values of displacement both in the horizontal and vertical direction increases with depth of fixity for the two models of soil, compared to when the frame is fixed at the ground level. Maximum displacements with soil structure interaction effects are reported when the pile length is taken as characteristic depth. Soil structure interaction effects reduced the displacements when the pile is treated for the full depth.

4.8.3.7 Influence of SSI of alluvial soil on bending moments in pile

The variation of bending moments in the pile with and without soil structure interaction are shown in Fig. 4.41. Models LPN3 and LPAY3 are compared.

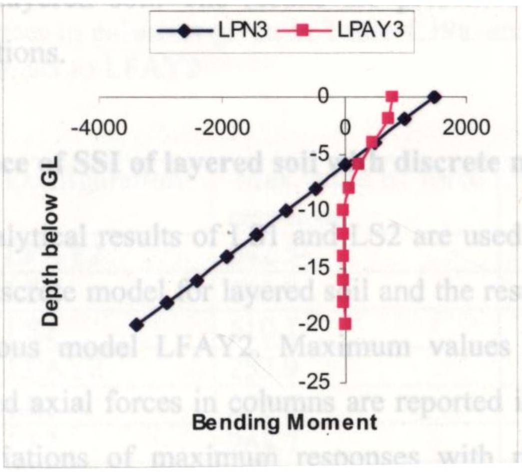


Fig. 4.41 Variation of bending moments in the **pile** with and without SSI

The bending moments in the pile are reduced when soil structure interaction effects are considered.

4.8.3.8 Stress distribution in soil using continuum model.

The distribution of horizontal, vertical and von Mises stress in the soil when modeled using continuum elements is shown in Fig. 4.42. The stress distribution between the middle, intermediate and outer pile are shown.

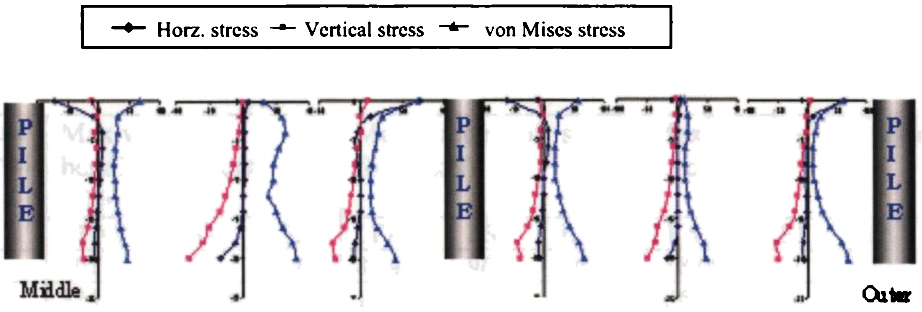


Fig. 4.42 Stress distribution in **alluvial** soil

4.8.4 Effect Of Soil Structure Interaction In Layered Soil

The layered soil models LS1, LS2, LSB1, LSB2 and the homogeneous models LFAY2, LFBY2 are analysed to investigate the effect of soil structure interaction in layered soil. The results are presented and discussed in the subsequent sections.

4.8.4.1 Influence of SSI of layered soil with discrete model

The analytical results of LS1 and LS2 are used to study the influence of SSI using discrete model for layered soil and the results are compared with the homogeneous model LFAY2. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 4.39a. and the percentage variations of maximum responses with respect to LFAY2 are reported in Table 4.39b. The variations along the floor level is shown in Fig. 4.43.

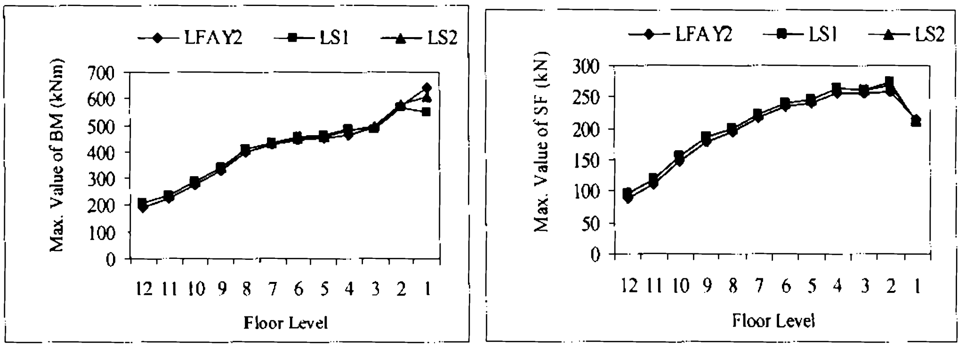
Table 4.39a Maximum values of bending moments, shear forces and axial forces in **columns** for **layered** soil with discrete model

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)			Max values of axial force (kN)		
	LFAY2	LS1	LS2	LFAY2	LS1	LS2	LFAY2	LS1	LS2
12	191.6	208	207	87.49	96.6	96	118.09	121	120.7
11	224.9	236.6	236.6	112.2	119.8	119.8	236.4	242.4	241.7
10	280.14	289.8	289.2	148.52	155	154.6	353.7	362.8	361.7
9	331.3	341.1	340.5	179.5	186.1	185.7	470.8	483.0	481.6
8	401.8	411.3	411.0	194.0	199.4	199.2	587.1	602.5	600.6
7	426.5	436.7	436.0	217.4	223	222.7	715.8	728	729.1
6	443.8	454.7	453.7	234.3	240	239.7	891.54	905.9	907.1
5	449.5	461.8	459.9	241.0	246.7	246.3	1075.4	1092.2	1093.4
4	465.5	484.7	479.7	257.3	264.4	263.7	1263.7	1283.5	1284.4
3	491.7	487.1	496.1	255.2	262.3	261.4	1451.9	1476.1	1475.9
2	573.8	**565.0**	580.9	**257.9**	**273.5**	**268.7**	1633.5	1665.5	1662
1	**642.54**	546.7	**610.1**	213.8	208.7	211.5	**1793.3**	**1842.6**	**1829.8**

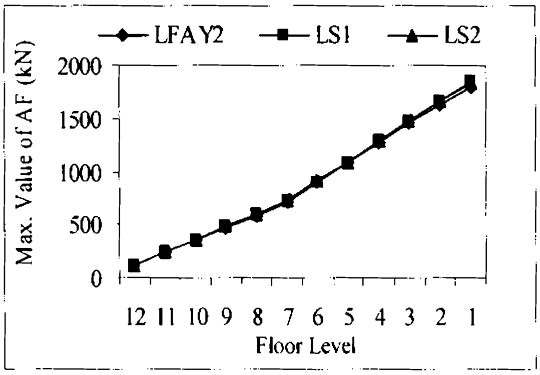
Table 4.39b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 4.39a. and % variation with respect to LFAY2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LFAY2	642.54	
	LS1	565.0	-12.0
	LS2	610.1	-5.0
Shear force (kN)	LFAY2	257.9	
	LS1	273.5	+6.0
	LS2	268.7	+4.1
Axial force (kN)	LFAY2	1793.3	
	LS1	1842.6	+2.7
	LS2	1829.8	+2.0

There is a decrease of 12% and 5% in column bending moment when modeled using discrete elements showing that there is 7% variation in the maximum bending moment in the frame when two types of layering for soil are considered. The corresponding variations in shear force show an increase of 6% and 4% giving a variation of 2%. As for axial force it is 3% and 2% giving a variation of 1%. This shows that even though bending moments in the columns are reduced when soil layering changes from hard to medium to soft, a slight increase is shown in the variations of shear force and axial force.



a. Bending moment b. Shear force



c. Axial force

Fig. 4.43 Variation of maximum values of (a)bending moment,(b) shear force and (c) axial force in **columns** for **layered** soil with discrete model.

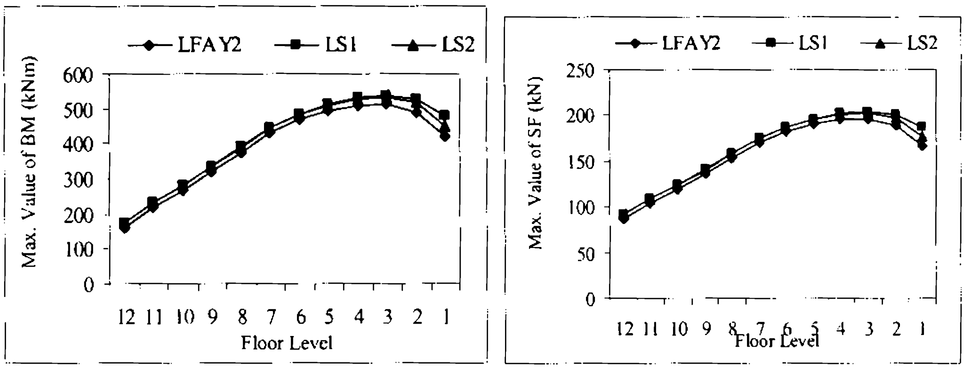
Maximum values of bending moments and shear forces in beams are reported in Table 4.40a and the percentage variations of maximum responses with respect to LFAY2 are reported in Table 4.40b. The variations along the floor level are shown in Fig. 4.44.

Table 4.40a. Maximum values of bending moments and shear forces in **beams** for **layered** soil with discrete model

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	LFAY2	LS1	LS2	LFAY2	LS1	LS2
12	162.0	176	175.4	86.7	91.1	91.02
11	215.5	232.3	231.6	103.5	108.8	108.6
10	266.1	282.8	282.1	119.2	124.4	124.2
9	317.3	334.1	333.4	135.27	140.5	140.3
8	373.3	390.1	389.4	152.7	158	157.8
7	430.2	447.2	446.5	170.5	175.8	175.6
6	468.3	485.7	484.9	182.4	187.9	187.6
5	492.6	510.8	509.6	190.0	195.7	195.4
4	510.1	531.0	528.6	195.5	202.0	201.3
3	**512.28**	**537.8**	**533.0**	**196.1**	**204**	**202.6**
2	491.0	528.6	516.55	189.5	201.3	197.5
1	418.83	480.6	452.0	166.6	186.3	177.3

Table 4.40b.Maximum values of bending moments and shear forces in **beams** given in Table 4.40a.and % variation with respect to LFAY2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LFAY2	512.28	
	LS1	537.8	+4.9
	LS2	533.0	+4.0
Shear force (kN)	LFAY2	196.1	
	LS1	204.0	+4.0
	LS2	202.6	+3.3



a. Bending moment b. Shear force

Fig. 4.44 Variation of maximum values of (a)bending moment and (b)shear force in **beams** for **layered** soil with discrete model.

The percentage variation of bending moment in beam is 5% and 4% when modeled using discrete elements showing that there is 1% variation in the maximum bending moment when two models for soil are considered. The corresponding variations in shear force are 4% and 3% showing a variation of 1%. This shows that the responses in beams show slight increase when soil layering changes from hard to medium to soft when modeled using discrete elements.

4.8.4.2 Influence of SSI of layered soil with continuum model

The analytical results of LSB1 and LSB2 are used to study the influence of SSI using continuum model for layered soil and the results are compared with the homogeneous model LFBY2. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 4.41a. and the percentage variations of maximum responses with respect to LFAY2 are reported in Table 4.41b. The variations along the floor level is shown in Fig. 4.45.

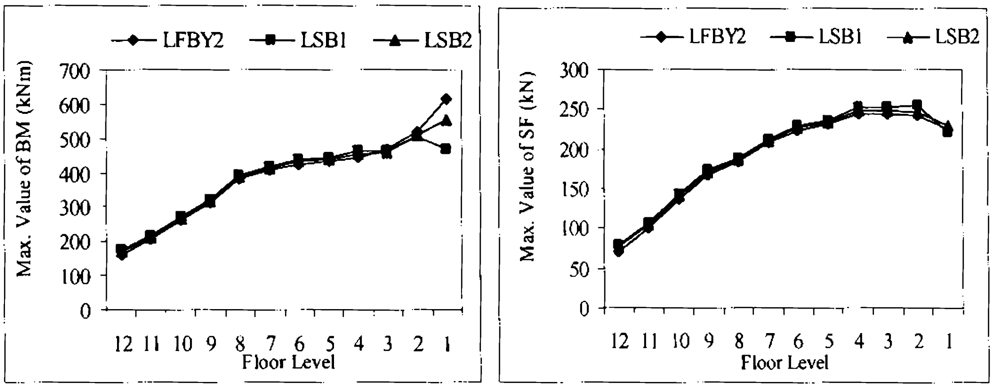
Table 4.41a. Maximum values of bending moments, shear forces and axial forces in **columns** for **layered** soil with continuum model

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)			Max values of axial force (kN)		
	LFBY2	LSB1	LSB2	LFBY2	LSB1	LSB2	LFBY2	LSB1	LSB2
12	161.48	177.5	171.3	70.68	79.6	76.1	113.46	116.4	115.5
11	207.43	215.8	212.6	101.13	107	104.7	226.75	233	231.0
10	262.26	271.7	268.1	136.69	143	140.5	339.24	348.7	345.7
9	313.30	322.9	319.2	167.35	173.8	171.3	451.39	464.1	460.17
8	384.35	393.7	390	184.23	189.4	187.4	562.71	578.7	573.7
7	408.08	418.1	414.2	207.24	212.7	210.5	697.8	700.4	698
6	425.06	435.7	431.5	223.69	229.3	227.1	870.5	873.6	870.7
5	431.43	443.5	438.5	231.04	236.5	234.4	1051.3	1055.1	1051.7
4	445.45	464.7	450.8	**245.21**	252.1	**249.4**	1236.8	1241.9	1237.5
3	466.59	461.4	458.9	244.73	251.8	249.2	1422.57	1430.3	1424.3
2	517.36	**501.5**	507.2	241.37	**254.6**	246.6	1603.49	1617.5	1608
1	**616.38**	468.2	**556.3**	225.52	220.4	228.9	**1767.3**	**1797.2**	**1778.8**

Table 4.41b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 4.41a. and % variation with respect to LFBY2

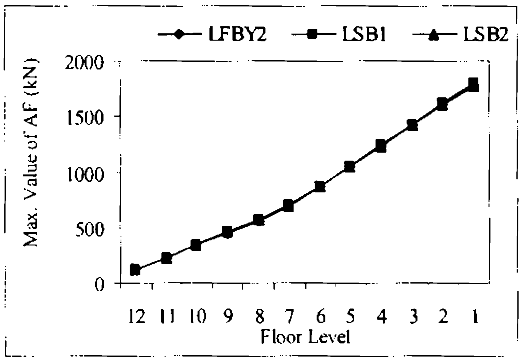
Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LFBY2	616.38	
	LSB1	501.5	-18.6
	LSB2	556.3	-9.7
Shear force (kN)	LFBY2	245.21	
	LSB1	254.6	+3.8
	LSB2	249.4	+1.7
Axial force (kN)	LFBY2	1767.3	
	LSB1	1797.2	+1.6
	LSB2	1778.8	+0.65

There is a decrease of 19% and 10% for column bending moment when modeled using continuum elements showing that there is 9% variation in the maximum bending moment in the frame when two types of layering for soil are considered. The corresponding variations in shear force show an increase of 4% and 2% giving a variation of 2%. As for axial force it is 2% and 1% giving a variation of 1%. This shows that even though bending moments in the columns are reduced when soil layering changes from hard to medium to soft, a slight increase is shown in the variations of shear force and axial force as in the case of discrete modeling.



a. Bending moment

b. Shear force



c. Axial force

Fig. 4.45 Variation of maximum values of bending moments, shear forces and axial forces in **columns** for **layered** soil with continuum model

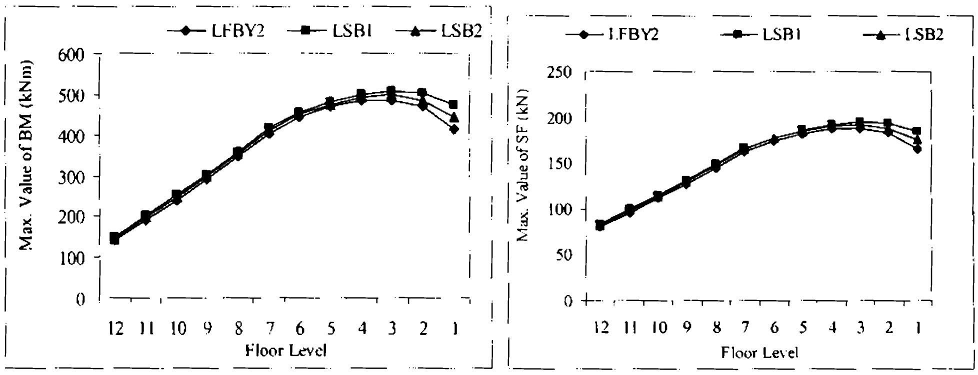
Maximum values of bending moments and shear forces in beams are reported in Table 4.42a and the percentage variations of maximum responses with respect to LFAY2 are reported in Table 4.42b. The variations along the floor level are shown in Fig. 4.46.

Table 4.42a. Maximum values of bending moments and shear forces in **beams** for **layered** soil with continuum model.

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)		
	LFBY2	LSB1	LSB2	LFBY2	LSB1	LSB2
12	140.41	150.6	146.7	79.97	83.1	81.9
11	189.4	201.5	196.8	95.34	99.1	97.6
10	240.2	252.2	247.6	111.16	114.8	113.4
9	291.3	303.4	298.8	127.16	130.9	129.4
8	347.3	359.4	354.8	144.65	148.4	146.9
7	404.1	416.4	411.7	162.40	166.2	164.7
6	441.9	454.5	449.7	174.23	178.2	176.6
5	468.5	479.4	474.2	181.78	185.9	184.3
4	483.2	499	492.6	187.11	192	190
3	**486.1**	**506.6**	**497.8**	**188.0**	**194.4**	**191.6**
2	468.9	501.8	486.2	182.65	192.9	188
1	413.62	473.2	444.6	165.43	184.0	175.1

Table 4.42b.Maximum values of bending moments and shear forces in **beams** given in Table 4.42a.and % variation with respect to LFBY2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	LFBY2	486.1	
	LSB1	506.6	+4.2
	LSB2	497.8	+2.4
Shear force (kN)	LFBY2	188.0	
	LSB1	194.4	+3.4
	LSB2	191.6	+1.9



a. Bending moment

b. Shear force

Fig. 4.46Variation of maximum values of (a)bending moments and (b)shear forces in **beams** for **layered** soil with continuum model

The percentage variation of bending moment in beam is 4% and 2% when modeled using continuum elements showing that there is 2% variation in the maximum bending moment when two types of layering for soil are considered. The corresponding variations in shear force are 3% and 2% showing a variation of 1%. This shows that the responses in beams show slight increase when soil layering changes from hard to medium to soft when modeled using continuum elements as in the case of discrete elements.

4.8.4.3 Influence of layering on displacements.

The layered soil models LS1, LS2, LSB1, LSB2 and the homogeneous models LFAY2, LFBY2 are analysed to investigate the effect of layering on displacements. The maximum values of horizontal and vertical displacements are reported in Table 4.43

Table 4.43 Effect of SSI on displacements in **layered** soil

Type of soil		Max values of displacement (m)	
		Horizontal direction	Vertical direction
Homogeneous	Discrete model	0.311	0.035
	Continuum model	0.296	0.015
Layered 1	Discrete model	0.39	0.070
	Continuum model	0.337	0.021
Layered 2	Discrete model	0.375	0.070
	Continuum model	0.32	0.020

It is observed that displacements are highest in the case of soil with medium layering compared to the other two models. No change in displacement is observed in the vertical direction even though the values are upper bound than that for the homogeneous medium.

4.9 SUMMARY

Linear static analysis has been conducted on the finite element model for the frame – pile – soil system for different depths of fixity, with and without soil structure interaction effects. The study has been conducted on three major soil types of Kerala viz., laterite, sand and alluvium. The study has been extended to two types of layered soils and to two soil models viz., discrete and continuum. It has been observed that the responses in the frame viz., bending moment, shear force and axial force in columns; and bending moment and shear force in beams; shows appreciable increase when the depth of fixity is taken from ground level to the characteristic depth. Beyond this depth, when depth of fixity is taken to the full depth of the pile, the increase is minimal. The inclusion of soil structure interaction effects through discrete and continuum models of soil shows that even though the responses in the frame increases upto the characteristic depth, it decreases when the full depth of pile is considered. This validates the concept of characteristic depth and explains the reason for not making soil structure interaction studies mandatory in the analysis of structures

CHAPTER 5

FREE VIBRATION ANALYSIS OF MULTI STOREY FRAMES

5.1 INTRODUCTION

Linear dynamic analysis is concerned with the responses of a linear system to time dependent loads. Depending upon the assumptions made for the characteristics of mass, stiffness, damping matrices and loads, different analysis types are obtained and those performed in the present study are

a. Eigenvalue analysis or free vibration analysis
b. Shock spectrum analysis

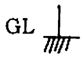
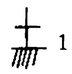
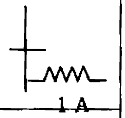
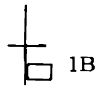
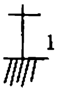
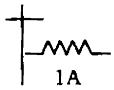
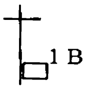
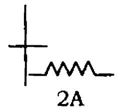
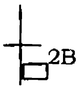
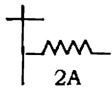
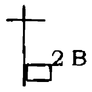
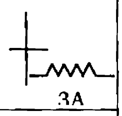
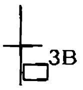
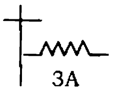
Eigenvalue analysis deals with the analysis of undamped free vibration of a structure. It does not represent the response due to any loading, but yields the natural frequencies or eigenvalues and the corresponding mode shapes or eigenvectors in the undamped condition. These parameters are then used for computation of response in the presence of dynamic loads in modal dynamic analysis.

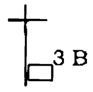
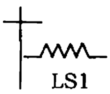
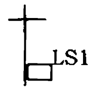
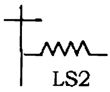
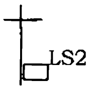
Free vibration analysis has been performed on the frame which has been chosen for linear static analysis for all the configurations and soil conditions. The details of the frame selected for numerical investigations have been given in section 4.2. The details of the analyses are described subsequently.

5.2 FINITE ELEMENT MODEL

The finite element model prepared for eigenvalue analysis is same as that for linear static analysis. The various frames analysed and the nomenclature are given in Table 5.1

Table 5.1 Description of the frames for eigenvalue analysis

Sl No	Nomenclature	Description	Notation
1	EG	Frame fixed at GL	
2	EPN	EG with pile fixed at characteristic depth with out SSI	
3	EPAY1	EG with pile fixed at characteristic depth on laterite soil using discrete model for soil	
4	EPBY1	EG with pile fixed at characteristic depth on laterite soil using continuum model for soil	
5	EFN	EG with full length of pile with out SSI	
6	EFAY1	EG with full length of pile on laterite soil using discrete model for soil.	
7	EFBY1	EG with full length of pile on laterite soil using continuum model for soil.	
8	EPAY2	EG with pile fixed at characteristic depth on sandy soil using discrete model for soil	
9	EPBY2	EG with pile fixed at characteristic depth on sandy soil using continuum model for soil	
10	EFAY2	EG with full length of pile on sandy soil using discrete model for soil.	
11	EFBY2	EG with full length of pile on sandy soil using continuum model for soil.	
12	EPAY3	EG with pile fixed at characteristic depth on alluvial soil using discrete model for soil	
13	EPBY3	EG with pile fixed at characteristic depth on alluvial soil using continuum model for soil	
14	EFAY3	EG with full length of pile on alluvial soil using discrete model for soil.	

15	EFBY3	EG with full length of pile on alluvial soil using continuum model for soil.	
16	ELS1	Frame with type1 layered soil represented by discrete model	
17	ELSB1	Frame with type1 layered soil represented by continuum model	
18	ELS2	Frame with type2 layered soil represented by discrete model	
19	ELSB2	Frame with type2 layered soil represented by continuum model	

5.3 INPUT PARAMETERS

The input parameters for the eigenvalue analysis include material properties, boundary conditions and geometric properties.

For beams, columns and piles the material properties given are the modulus of elasticity of concrete, density of concrete and Poisson's ratio. The elastic property of the soil medium is incorporated in finite element model through the spring stiffness K in discrete modeling and through Young's modulus E_s in continuum modeling.

Geometrical properties of the model include shape and cross-sectional dimensions for the beam, column and foundation. For modeling the soil no geometric properties are required.

Different eigen extraction methods are used in eigenvalue analysis. In the present work, conventional subspace iteration and accelerated subspace Iteration methods have been used. Both the algorithms use simultaneous inverse iterations with a set of vectors until the eigenvalues have converged to a specified tolerance. The conventional subspace method is an iterative transformation technique. The accelerated subspace iteration employs shifting to accelerate the convergence of roots far away from the lower end of eigenvalue spectrum, and hence can be termed as tracking and transformation method.

5.4 OUTPUT FEATURES

The output from eigenvalue analysis consists of natural frequencies or eigenvalues and eigenvectors. Modal participation factors, modal masses, modal stresses and reactions are also obtained.

5.5 NUMERICAL INVESTIGATIONS

Numerical Investigations are carried out on the frame shown in Fig. 4.2 for all the cases mentioned in Table 5.1. Conventional and accelerated subspace iteration methods are used for eigen extraction. Lumped mass formulation has been used. Eigenvalue analysis has been performed using NISA and the results are reported.

5.6 RESULTS AND DISCUSSIONS

Results obtained from finite element eigenvalue analysis for the frame with depth of fixity at ground level, full depth and at characteristic depth with and without soil structure interaction for different types of soil viz., laterite, sand, alluvium and layered are given in subsequent sections.

5.6.1 Natural Frequencies For Different Depths Of Fixity With out SSI.

Natural frequencies when the frame is fixed at ground level, characteristic depth and full depth of pile without soil structure interaction effects are given in Table 5.2. Models EG, EPN and EFN have been analysed.

Table 5.2 Natural frequencies for different depths of fixity without SSI

Mode Number	Natural frequency (Hz)		
	EG	EPN	EFN
1	0.023	0.22	0.019
2	0.074	0.073	0.063
3	0.137	0.133	0.095
4	0.242	0.239	0.113
5	0.245	0.240	0.183
6	0.318	0.283	0.229
7	0.380	0.367	0.329
8	0.442	0.433	0.349
9	0.497	0.480	0.452
10	0.574	0.572	0.508
11	0.714	0.692	0.526
12	0.740	0.730	0.547
13	0.862	0.827	0.551
14	1.00	0.893	0.593
15	1.02	0.980	0.675

The number of eigenvalues depend on the degrees of freedom of the structure. The first 15 natural frequencies are reported in the table.

5.6.2 Natural Frequencies For Frame Fixed At Characteristic Depth With Discrete Model For Soil

Natural frequencies for the case when the frame is fixed at characteristic depth with discrete model for soil is given in Table 5.3. Models EPAY1, EPAY2 and EPAY3 have been analysed.

Table 5.3 Natural frequencies for frame fixed at characteristic depth with discrete model for soil

Node Number	Natural Frequency (Hz)
1	0.099
2	0.114
3	0.167
4	0.217
5	0.249
6	0.320
7	0.319
8	0.320
9	0.383
10	0.396
11	0.423
12	0.549
13	0.617
14	0.628
15	0.666

When piles are fixed at characteristic depth, discrete modeling showed very small variation (in the order of 10^{-5}) in the natural frequencies for the three soil types, viz., laterite, sand and alluvium. Hence only a representative value is reported in the table.

5.6.3 Natural Frequencies For Frame Fixed At Full Depth With Discrete Model For Soil

Natural frequencies for the case when the frame is fixed at full depth with discrete model for soil is given in Table 5.4. Models EFAY1, EFAY2 and EFAY3 have been analysed.

Table 5.4 Natural frequencies for frame fixed at full depth with discrete model for soil.

Mode Number	Natural frequency (Hz)
1	0.044
2	0.053
3	0.063
4	0.067
5	0.068
6	0.139
7	0.186
8	0.207
9	0.293
10	0.301
11	0.306
12	0.442
13	0.495
14	0.546
15	0.588

When piles are fixed at full depth, discrete modeling showed very small variation (in the order of 10^{-5}) in the natural frequencies for the three soil types, namely, laterite, sand and alluvium. Hence only a representative value is reported in the table.

5.6.4 Natural Frequencies For Frame Fixed At Different Depth Of Fixity With Continuum Model For Soil

Natural frequencies for the frame fixed at characteristic depth and full depth of pile with continuum model for soil are given in Table 5. 5. Models EPBY1, EFBY1, EPBY2, EFBY2, EPBY3 and EFBY3 have been analysed.

Table 5.5 Natural frequencies for frame fixed at characteristic and full depth with continuum model for soil.

Mode Number	Natural frequency (Hz)					
	EPBY1	EFBY1	EPBY2	EFBY2	EPBY3	EFBY3
1	0.022	0.022	0.022	0.022	0.021	0.021
2	0.074	0.072	0.071	0.072	0.068	0.056
3	0.136	0.134	0.133	0.104	0.126	0.068
4	0.243	0.198	0.235	0.141	0.202	0.096
5	0.252	0.238	0.264	0.183	0.224	0.135
6	0.294	0.239	0.366	0.237	0.232	0.143
7	0.375	0.299	0.419	0.241	0.336	0.207
8	0.450	0.341	0.476	0.257	0.398	0.234
9	0.495	0.378	0.563	0.347	0.423	0.238
10	0.613	0.429	0.678	0.371	0.440	0.277
11	0.724	0.492	0.699	0.409	0.490	0.323
12	0.740	0.564	0.707	0.433	0.526	0.377
13	0.781	0.568	0.804	0.483	0.558	0.381
14	0.862	0.694	0.868	0.543	0.584	0.411
15	0.952	0.719	0.920	0.565	0.645	0.420

It has been observed that discrete model does not show much difference in the natural frequencies for different types of soils compared to continuum models. This may be due to the fact that since the number of degrees of freedom of discrete model is less, the number of eigenvalues extracted is also less giving widely spaced values compared to that of continuum models.

5.6.5 Natural Frequencies For Frames In Layered Soil

Natural frequencies for discrete and continuum models of the two types of layered soil are given in Table 5.6. Models ELS1, ELSB1, ELS2 and ELSB2 have been compared.

Table 5.6 Natural frequencies for frames in layered soil.

Mode Number	Natural frequency (Hz)			
	ELS1	ELSB1	ELS2	ELSB2
1	0.044	0.022	0.044	0.022
2	0.053	0.070	0.053	0.071
3	0.064	0.095	0.063	0.094
4	0.067	0.139	0.067	0.139
5	0.068	0.147	0.068	0.151
6	0.140	0.223	0.140	0.229
7	0.186	0.234	0.186	0.236
8	0.208	0.238	0.208	0.239
9	0.248	0.284	0.256	0.311
10	0.294	0.314	0.294	0.323
11	0.307	0.363	0.307	0.367
12	0.442	0.420	0.442	0.423
13	0.444	0.438	0.444	0.454
14	0.495	0.396	0.495	0.462
15	0.546	0.492	0.546	0.515

5.7 SUMMARY

Free vibration analysis has been conducted on the finite element model for the frame – pile – soil system for different depths of fixity, with and without soil structure interaction effects. The study has been conducted on three major soil types of Kerala viz., laterite, sand and alluvium; and two types of layered soils. The study has been extended to two soil models viz., discrete and continuum. It has been observed that the natural frequencies are very closely spaced, especially in the higher frequency ranges. Further it has been observed that inclusion of soil properties through discrete model is not effective when free vibration analysis has been conducted in different types of soil.

CHAPTER 6

SHOCK SPECTRUM ANALYSIS OF MULTI STOREY FRAMES

6.1 INTRODUCTION

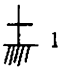
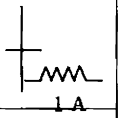
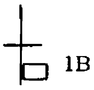
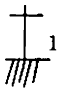
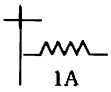
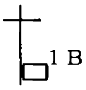
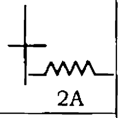
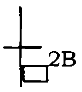
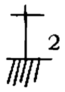
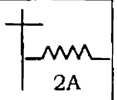
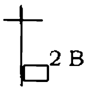
Modal dynamic analysis (normal mode analysis) is a method of forced vibration analysis. In this method the equations of motion are decoupled by expressing the responses in terms of modal responses. Modal Dynamic Analysis(MDA) involves forming the modal loads, solving for the modal responses in each mode of vibration and computing the physical responses such as displacements, velocities and stresses through modal superposition.

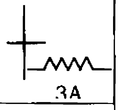
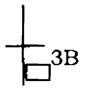
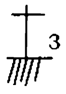
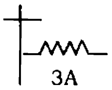
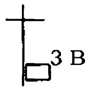
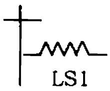
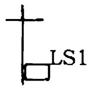
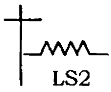
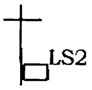
The shock spectrum analysis is a type of modal dynamic analysis in which, the maximum response of a multi-degree of freedom structure, subjected to an arbitrarily oriented foundation shock spectra input is estimated. The maximum response that a specified ground motion will produce on a single degree of freedom system having various natural frequencies and damping ratios, is given as the input. The excitation is assumed to be the same at all support points.

6.2 FINITE ELEMENT MODEL FOR SHOCK SPECTRUM ANALYSIS

The finite element model prepared for linear static analysis is used in shock spectrum analysis also. Configurations of the frames used in the analysis and the nomenclature are given in Table 6.1.

Table 6.1 Description of the frames for Shock Spectrum Analysis

Sl No	Nomenclature	Description	Notation
1	SG1	Frame fixed at ground level with spectrum corresponding to laterite	
2	SPN1	SG1 with pile fixed at characteristic depth with out SSI	
3	SPAY1	SG1 with pile fixed at characteristic depth and discrete model for soil	
4	SPBY1	SG1 with pile fixed at characteristic depth and continuum model for soil	
5	SFN1	SG1 with full length of pile with out SSI	
6	SFAY1	SG1 with full length of pile and discrete model for soil.	
7	SFBY1	SG1 with full length of pile and continuum model for soil.	
8	SG2	Frame fixed at ground level with spectrum corresponding to sand	
9	SPN2	SG2 with pile fixed at characteristic depth with out SSI	
10	SPAY2	SG2with pile fixed at characteristic depth and discrete model for soil	
11	SPBY2	SG2with pile fixed at characteristic depth and continuum model for soil	
12	SFN2	SG2with full length of pile with out SSI	
13	SFAY2	SG2with full length of pile and discrete model for soil.	
14	SFBY2	SG2 with full length of pile and continuum model for soil.	

15	SG3	Frame fixed at ground level with spectrum corresponding to alluvial soil	
16	SPN3	SG3with pile fixed at characteristic depth with out SSI	
17	SPAY3	SG3with pile fixed at characteristic depth and discrete model for soil	
18	SPBY3	SG3with pile fixed at characteristic depth and continuum model for soil	
19	SFN3	SG3with full length of pile with out SSI	
20	SFAY3	SG3 with full length of pile and discrete model for soil.	
21	SFBY3	SG3with full length of pile and continuum model for soil.	
22	SLS1	Frame with type1 layered soil represented by discrete model	
23	SLSB1	Frame with type1 layered soil represented by continuum model	
24	SLS2	Frame with type2 layered soil represented by discrete model	
25	SLSB2	Frame with type2 layered soil represented by continuum model	

6.3 SHOCK LOAD

The loads for the shock spectrum analysis includes the dead load, imposed load and seismic load.

Dead load and imposed load are calculated based on the unit weight of materials given in IS 875 (part1)[20] and the relevant clauses of IS 875 (part 2) [21] as already described in section 3.4.1.

The seismic load is given as an arbitrarily oriented foundation shock spectra. Instead of directly specifying the ground motion, the maximum response that the ground motion will produce on a single degree of freedom system having various natural frequencies and damping ratio is given as the input.

The response spectrum for 5% damping given in IS 1893 (part 1) [22] shown in Fig. 3.8 has been given as the input. The spectrum values for different types of soil are given in Table 6.2.

Table 6.2 Spectrum values for the design spectra for 5% damping

Period (seconds)	Spectral Acceleration Coefficient (Sa / g)		
	Laterite	Sand	Alluvium
0	1	1	1
0.107	2.5	2.5	2.5
0.5	2.0833	2.5	2.5
0.5357		2.5	2.5
0.6428			2.5
1.0	1.0416	1.333	1.666
1.5	0.625	0.9166	1.125
2.0	0.500	0.666	0.8333
2.5	0.4166	0.5416	0.666
3.0	0.333	0.4583	0.5833
3.5	0.2916	0.375	0.4583
4.0	0.25	0.333	0.4166

6.4 INPUT PARAMETERS

The input parameters for shock spectrum analysis in NISA are described in the following data groups.

a. **Damping** :- *to input the damping value.* 5% structural damping has been used in the present study.

b. **Ground** :- *to specify the type of spectrum, whether acceleration, velocity or displacement and to specify the centre* *of excitation.* Acceleration spectrum corresponding to 5% damping has been given as input in the present study.

c. **Mode Selection** :- *to specify the modes from the free vibration analysis which are to be considered in the shock spectrum analysis.* Maximum number of available modes are selected in this study giving importance to modes of smaller periods. The eigenvalues given in section 5.6 have been used. Modal combination methods have been used to combine the effects due to different modes.

d. **Spectrum** :- *to specify the spectral values.* The values can be accelerations, velocity or displacements given as a function of frequency in cycles per second or radians per second or as a function of period or as a constant value. The spectral input can be a single spectrum curve or a family of multiple damping spectrum. The spectral values given in Table 6.2 has been given as the input in the present study.

6.5 OUTPUT FEATURES

The output relevant for the present study are selected from the **Response** data group of the NISA shock spectrum analysis. The different responses available are the nodal response quantities like displacements, velocities, accelerations and stresses. These values are evaluated from different modal combination procedures like absolute sum, square root of sum of squares, complete quadratic method etc. The output includes nodal reactions and beam element end forces as well.

6.6 NUMERICAL INVESTIGATIONS

Numerical Investigations are carried out on the frame shown in Fig 4.2. for all the cases mentioned in Table 6.1. Spectral values shown in Table 6.2 are given as the input. Linear interpolation method is adopted for in between values. Participating modes are selected from the eigenvalue analysis and given as input. Complete Quadratic Combination (CQC) method is employed for combining peak response quantities like member forces, displacements, storey forces, storey shears etc. Shock spectrum analysis has been performed using NISA and the results are reported.

6.7 RESULTS AND DISCUSSIONS

Results obtained from finite element shock spectrum analysis for the frame with depth of fixity at ground level, full depth and at characteristic depth with and without soil structure interaction for different types of soil viz., lateritic, sandy, alluvial and layered are given in subsequent sections.

6.7.1 Effect Of Soil Structure Interaction And Founding Depth In Laterite

The models SG1, SPN1, SPAY1, SPBY1, SFN1, SFAY1 and SFBY1 are analysed to investigate the effect of soil structure interaction and founding depth in laterite. The results are presented and discussed in the subsequent sections. Bending moments, shear forces and axial forces in columns of the frame and the corresponding values in the beams for different models are compared. Displacements and storey drifts in the frame and bending moments in the pile are also reported.

6.7.1.1 Influence of founding depth without SSI

The analytical results of SG1, SPN1 and SFN1 are used to study the influence of founding depth without SSI. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 6.3a. and the percentage variations of maximum responses with respect to SG1 are reported in Table 6.3b The variations along the floor level is shown in Fig. 6.1.

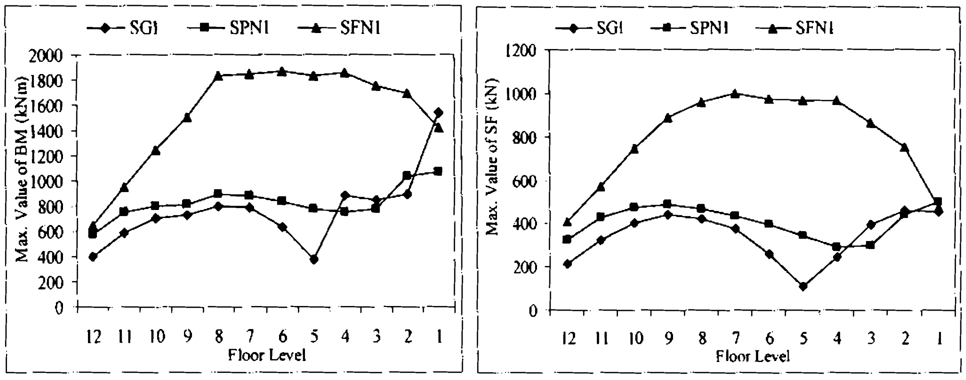
Table 6.3a. Maximum values of bending moments, shear force and axial force in **columns** for different depths of fixity without SSI with spectral values corresponding to **laterite**

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)			Max values of axial force(kN)		
	SG1	SPN1	SFN1	SG1	SPN1	SFN1	SG1	SPN1	SFN1
12	401.5	575.1	649.4	212.8	324.5	410.7	63.8	99.7	82.3
11	591.1	753.4	950.4	321.2	430.7	570.9	166.7	245.7	221.9
10	702.5	800.0	1249.7	404	476.5	745.2	316.6	431.7	446.9
9	733.9	817.4	1511.2	439.3	485.7	887.5	501.1	630.3	758.2
8	794.9	892.3	1838.9	423.3	465.6	958.1	706.5	828.4	920.0
7	790.1	883.3	1851.5	376.2	437.1	**996.0**	900.6	1005.1	1162.1
6	631.4	832.5	**1871.9**	262.2	394.8	972.7	1037.2	1137.0	1452.0
5	378.3	779.4	1836.8	112.2	341.0	968.2	**1085.8**	1211.6	1646.2
4	884.0	757.7	1863.1	249.5	293.8	964.6	1026.3	**1212.5**	1686.0
3	846.4	777.5	1752.8	396.3	296.8	861.7	896.3	1151.0	**2665.5**
2	894.7	1030.1	1689.3	**459.2**	442.0	751.8	721.9	1022.3	2021.0
1	**1540.6**	**1073.8**	1423.7	455.0	**500.2**	474.6	570.0	845.5	1750.0

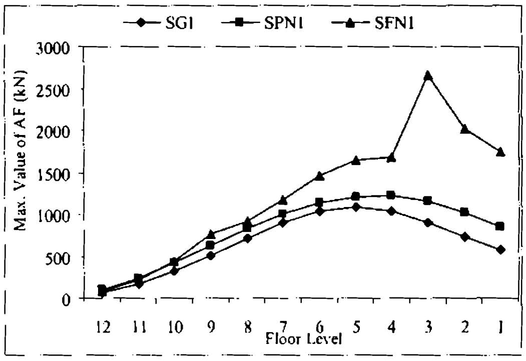
Table 6.3b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 6.3a. and % variation with respect to SG1

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG1	1540.6	
	SPN1	1073.8	-30.2
	SFN1	1871.9	+21.5
Shear force (kN)	SG1	459.2	
	SPN1	500.2	+8.9
	SFN1	996.0	+116.8
Axial force (kN)	SG1	1085.8	
	SPN1	1212.5	+11.6
	SFN1	2665.5	+145.4

There is a decrease of 30% for column bending moment when the pile length is taken as characteristic depth and an increase of 22% when pile is treated for full length showing that there is 52% increase in the maximum bending moment in the frame when no soil medium is considered. The corresponding variations in shear force is 9% and 117% showing an increase of 108%. As for axial force it is 12% and 145% giving an increase of 133%. This drastic increase in the responses may be due to the lowering of the support of the frame and the subsequent increase in the cantilever action.



a. Bending moment b. Shear force



c. Axial force

Fig. 6.1 Variation of maximum values of(a) bending moment,(b) shear force and (c)axial force in **columns** for different depths of fixity without SSI with spectral values corresponding to **laterite**

Maximum values of bending moments and shear forces in beams are reported in Table 6.4a and the percentage variations of maximum responses with respect to SG1 are reported in Table 6.4b. The variations along the floor level is shown in Fig. 6.2.

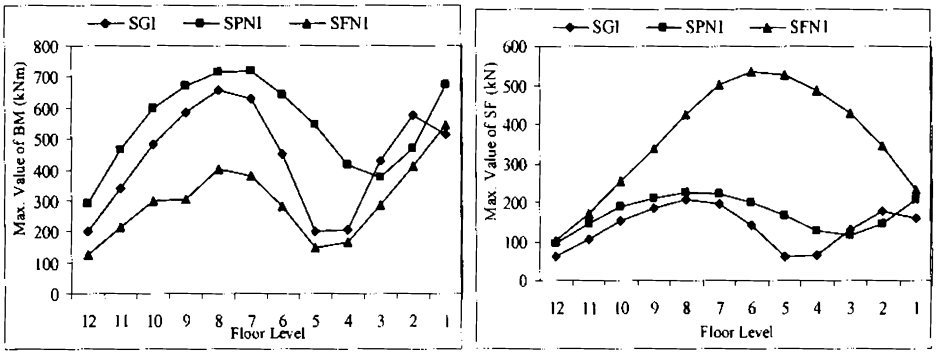
Table 6.4a. Maximum values of bending moments and shear forces in **beams** for different depths of fixity without SSI with spectral values corresponding to **laterite.**

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)		
	SG1	SPN1	SFN1	SG1	SPN1	SFN1
12	202.4	289.2	126.6	63.01	93.9	103.3
11	340.4	463.5	212.4	106.2	145.1	171.9
10	484.3	599.2	300.5	151.4	187.3	253.6
9	586.4	672.2	304.9	185.4	210.2	337.2
8	**658.7**	714.6	400.1	**205.7**	**223.9**	425.5
7	632.2	**719.1**	381.9	195.0	223.1	503.0
6	453.3	645.8	280.6	141.8	198.8	**534.6**
5	199.0	543.6	148.6	62.1	168.0	527.1
4	205.0	416.8	163.3	63.8	128.7	487.7
3	427.0	376.8	286.8	132.3	116.7	430.1
2	576.4	468.3	410.6	178.4	145.2	344.0
1	512.0	673.3	**545.6**	158.3	207.0	231.0

Table 6.4b. Maximum values of bending moments and shear forces in **beams** given in Table 6.4a. and % variation with respect to SG1

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG1	658.7	
	SPN1	719.1	+9.1
	SFN1	545.6	-17.1
Shear force (kN)	SG1	205.7	
	SPN1	223.9	+8.8
	SFN1	534.6	+159.8

There is an increase of 9% for beam bending moment when the pile length is taken as characteristic depth and 17% decrease when pile is treated for full length showing that there is 26% decrease in the maximum bending moment when no soil medium is considered. The corresponding variations in shear force is 9% and 160% showing an increase of 151%. This shows that the bending moments in beams are less influenced than shear forces by change in length. The large variation in shear force may be due to the harmonic movement caused by the ground motion.



a. Bending moment b. Shear force

Fig. 6.2 Variation of maximum values of(a) bending moment and (b)shear force in **beams** for different depths of fixity without SSI with spectral values corresponding to **laterite**

6.7.1.2 Influence of founding depth with SSI using discrete model for laterite

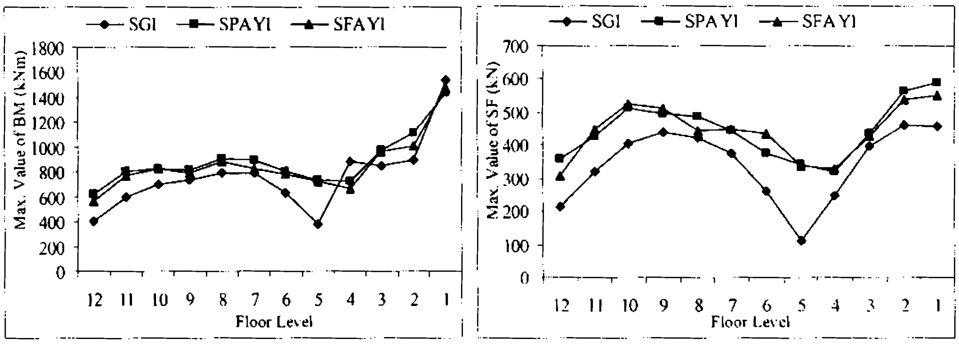
The analytical results of SG1, SPAY1and SFAY1 are used to study the influence of founding depth with SSI using discrete model for laterite. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 6.5a. and the percentage variations of maximum responses with respect to SG1 are reported in Table 6.5b. The variations along the floor level is shown in Fig. 6.3.

Table 6.5a. Maximum values of bending moments, shear forces and axial forces in **columns** for different depths of fixity with SSI using discrete model for **laterite**

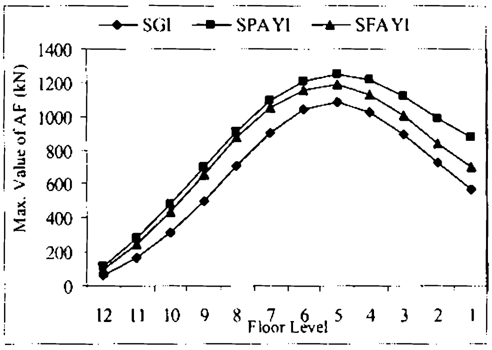
Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)			Max values of axial force(kN)		
	SG1	SPAY1	SFAY1	SG1	SPAY1	SFAY1	SG1	SPAY1	SFAY1
12	401.5	620.2	556.4	212.8	357.7	309.3	63.8	117.8	95.2
11	591.1	796.9	767.4	321.2	425.4	449.2	166.7	280.5	241.2
10	702.5	827.6	827.4	404	511.3	525.5	316.6	485.5	437.6
9	733.9	810.3	786.6	439.3	496.0	510.6	501.1	702.2	655.7
8	794.9	901.3	886.3	423.3	485.1	442.4	706.5	913.9	871.1
7	790.1	894.1	829.5	376.2	443.3	448.0	900.6	1090.4	1046.9
6	631.4	806.8	784.19	262.2	373.7	434.5	1037.2	1207.2	1155.3
5	378.3	734.1	725.9	112.2	341.1	336.0	**1085.8**	**1251.9**	**1186.8**
4	884.0	723.3	662.9	249.5	321.3	330.5	1026.3	1217.4	1130.3
3	846.4	972.3	968.5	396.3	433.9	425.8	896.3	1123.4	1006.2
2	894.7	1110.2	1005.6	**459.2**	563.7	538.9	721.9	988.4	838.9
1	**1540.6**	**1436.2**	**1470.8**	455.0	**588.5**	**549.8**	570.0	872.3	696.5

Table 6.5b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 6.5a. and % variation with respect to SG1

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG1	1540.6	
	SPAY1	1436.2	-6.7
	SFAY1	1470.8	-4.5
Shear force (kN)	SG1	459.2	
	SPAY1	588.5	+28.1
	SFAY1	549.8	+19.7
Axial force (kN)	SG1	1085.8	
	SPAY1	1251.9	+15.2
	SFAY1	1186.8	+9.3



a. Bending moment b. Shear force



c. Axial force

Fig. 6.3 Variation of maximum values of (a)bending moment, (b)shear force and (c)axial force in **columns** for different depths of fixity with SSI using discrete model for **laterite.**

There is a decrease of 7% for column bending moment when the pile length is taken as characteristic depth and 5% when pile is treated for full length showing that there is 2% increase in the maximum bending moment in the frame when discrete model for soil is considered. The corresponding variations in shear force are an increase of 28% and 20% showing a decrease of 8%. As for axial force it is 15% and 9% giving a decrease of 6%. The maximum increase in response is only 2% for bending moments. This validates the concept of characteristic depth in the design regarding force output.

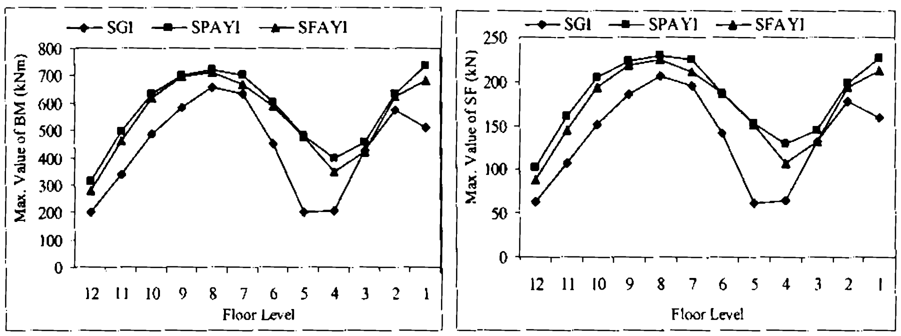
Maximum values of bending moments and shear forces in beams are reported in Table 6.6a and the percentage variations of maximum responses with respect to SG1 are reported in Table 6.6b. The variations along the floor level are shown in Fig. 6.4.

Table 6.6a. Maximum values of bending moments and shear forces in **beams** for different depths of fixity with SSI using discrete model for **laterite**

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)		
	SG1	SPAY1	SFAY1	SG1	SPAY1	SFAY1
12	202.4	314.2	280.6	63.01	102.6	88.4
11	340.4	496.8	459.5	106.2	160.2	144.5
10	484.3	632.6	616.6	151.4	204.2	193.7
9	586.4	699.7	696.8	185.4	223.3	218.8
8	**658.7**	722.3	**713.6**	**205.7**	**229.4**	**224.7**
7	632.2	700.3	669.3	195.0	224.1	210.4
6	453.3	602.3	587.5	141.8	186.6	187.8
5	199.0	480.3	477.5	62.1	152.0	150.3
4	205.0	399.5	346.9	63.8	128.7	107.7
3	427.0	455.3	422.5	132.3	144.4	132.0
2	576.4	634.8	622.4	178.4	197.7	193.8
1	512.0	**735.2**	684.5	158.3	226.7	212.12

Table 6.6b. Maximum values of bending moments and shear forces in **beams** given in Table 6.6a and % variation with respect to SG1

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG1	658.7	
	SPAY1	735.2	+11.6
	SFAY1	713.6	+8.3
Shear force (kN)	SG1	205.7	
	SPAY1	229.4	+11.5
	SFAY1	224.7	+9.2



a. Bending moment b. Shear force

Fig. 6.4 Variation of maximum values of(a) bending moment and (b)shear force in **beams** for different depths of fixity with SSI using discrete model for **laterite**

There is an increase of 12% for beam bending moment when the pile length is taken as characteristic depth and 8% when pile is treated for full length showing that there is 4% decrease in the maximum bending moment when discrete model for soil is considered. The corresponding variations in shear force are 12% and 9% showing a decrease of 3%. The responses in the beams have reduced when pile is taken from characteristic to full depth. As in the case of responses in columns this validates the concept of characteristic depth in the design regarding force output.

6.7.1.3 Influence of founding depth with SSI using continuum model for laterite

The analytical results of SG1, SPBY1 and SFBY1 are used to study the influence of founding depth with SSI using continuum model for laterite. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 6.7a. and the percentage variations of maximum responses with respect to SG1 are reported in Table 6.7b. The variations along the floor level are shown in Fig. 6.5.

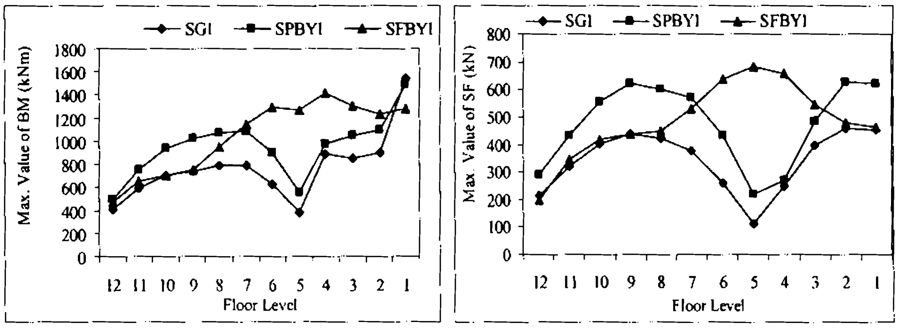
Table 6.7a. Maximum values of bending moments, shear forces and axial forces in **columns** for different depths of fixity with SSI using continuum model for **laterite**

Floor Level	Max values of bending moment (kNm)			Max values of shear force(kN)			Max values of axial force (kN)		
	SG1	SPBY1	SFBY1	SG1	SPBY1	SFBY1	SG1	SPBY1	SFBY1
12	401.5	491.9	467.2	212.8	292.0	196.8	63.8	78.2	205.8
11	591.1	749.3	659.0	321.2	435.6	344.4	166.7	208.2	504.3
10	702.5	935.4	708.9	404.0	557.8	419.6	316.6	404.4	823.5
9	733.9	1024.3	755.0	439.3	620.8	440.1	501.1	654.6	1126.6
8	794.9	1075.9	952.8	423.3	603.3	447.8	706.5	944.8	1388.1
7	790.1	1088.9	1152.2	376.2	568.4	531.7	900.6	1233.9	1563.3
6	631.4	896.1	1298.2	262.2	433.2	639.4	1037.2	1458.2	**1624.5**
5	378.3	558.6	1275.1	112.2	219.7	**681.7**	**1085.8**	**1571.1**	1584.9
4	884.0	974.5	**1416.5**	249.5	268.4	658.2	1026.3	1540.9	1484.7
3	846.4	1050.4	1306.0	396.3	484.2	545.0	896.3	1398.9	1378.1
2	894.7	1098.1	1236.9	**459.2**	**626.4**	480.6	721.9	1167.2	1315.6
1	**1540.6**	**1496.6**	1286.7	455.0	622.9	461.3	570.0	907.1	1372.6

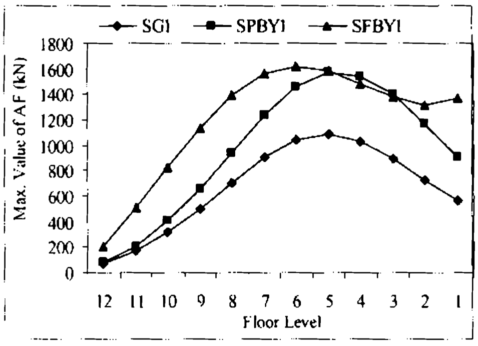
Table 6.7b Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 6.7a. and % variation with respect to SG1

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG1	1540.6	
	SPBY1	1496.6	-2.8
	SFBY1	1416.5	-8.0
Shear force (kN)	SG1	459.2	
	SPBY1	626.4	+36.4
	SFBY1	681.7	+48.4
Axial force (kN)	SG1	1085.8	
	SPBY1	1571.1	+44.6
	SFBY1	1624.5	+49.6

There is a decrease of 3% for column bending moment when the pile length is taken as characteristic depth and 8% when pile is treated for full length showing that there is 5% decrease in the maximum bending moment in the frame when continuum model for soil is considered. The corresponding variations in shear force are an increase of 36% and 48% showing a increase of 12%. As for axial force it is 45% and 50% giving an increase of 5%. It is observed that even when the bending moment shows considerable decrease, the shear force and axial force shows an increase when the pile depth is taken from characteristic depth to full depth using continuum model.



a. Bending moment b. Shear force



c. Axial force

Fig. 6.5 Variation of maximum values of(a) bending moment, (b)shear force and (c)axial force in **columns** for different depths of fixity with SSI using continuum model for **laterite**

Maximum values of bending moments and shear forces in beams are reported in Table 6.8a and the percentage variations of maximum responses with respect to SG1 are reported in Table 6.8b. The variations along the floor level are shown in Fig. 6.6.

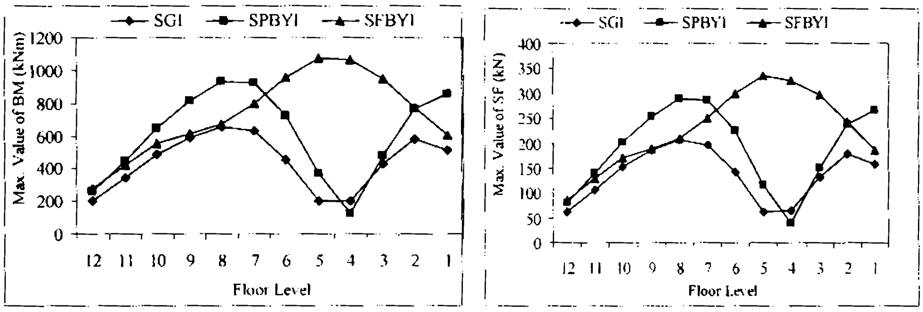
Table 6.8a. Maximum values of bending moments and shear forces in **beams** for different depths of fixity with SSI using continuum model for **laterite**

Floor Level	Max values of bending moment (kNm)			Max values of shear force(kN)		
	SG1	SPBY1	SFBY1	SG1	SPBY1	SFBY1
12	202.4	260.3	276.4	63.01	80.6	84.3
11	340.4	447.4	419.2	106.2	139	129.7
10	484.3	649.5	549.8	151.4	201.7	169.7
9	586.4	816.2	608.4	185.4	253.4	187.8
8	**658.7**	**930.3**	669.3	**205.7**	**288.7**	209
7	632.2	922	797.9	195.0	286.2	249.1
6	453.3	719.9	959.1	141.8	223.5	299.5
5	199.0	373.1	**1073.5**	62.1	115.9	**335.3**
4	205.0	122.2	1063.8	63.8	39.5	324.9
3	427.0	476.2	948	132.3	149.4	296.1
2	576.4	764.9	772.5	178.4	238	241.3
1	512.0	859.6	601	158.3	265.8	184.8

Table 6.8b. Maximum values of bending moments and shear forces in **beams** given in Table 6.8a. and % variation with respect to SG1

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG1	658.7	
	SPBY1	930.3	+41.2
	SFBY1	1073.5	+62.9
Shear force (kN)	SG1	205.7	
	SPBY1	288.7	+40.3
	SFBY1	335.3	+63.0

There is 41% increase for beam bending moment when the pile length is taken as characteristic depth and 63% when pile is treated for full length showing that there is 22% increase in the maximum bending moment when continuum model for soil is considered. The corresponding variations in shear force are 40% and 63% showing an increase of 13%.



a. Bending moment b. Shear force

Fig. 6.6 Variation of maximum values of (a)bending moment and (b)shear force in **beams** for different depths of fixity with SSI using continuum model for **laterite**.

6.7.1.4 Influence of SSI of laterite when piles are fixed at characteristic depth

The analytical results of SPN1, SPAY1 and SPBY1 are used to study the influence of SSI using discrete and continuum model for laterite when piles are fixed at characteristic depth. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 6.9a. and the percentage variations of maximum responses with respect to SPN1 are reported in Table 6.9b. The variations along the floor level is shown in Fig. 6.7.

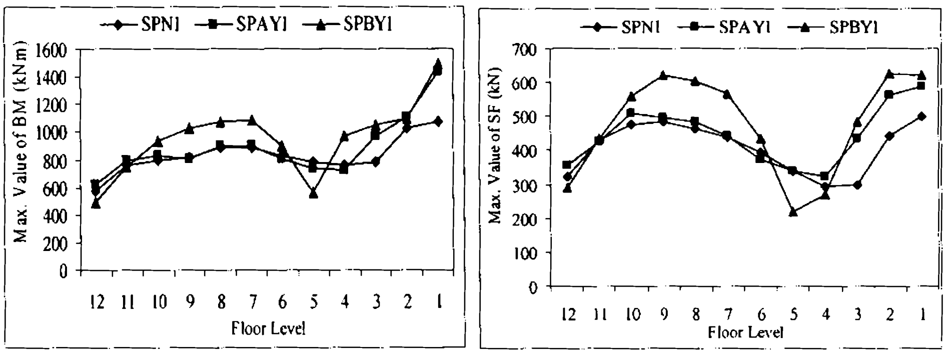
Table 6.9a. Maximum values of bending moments, shear forces and axial forces in **columns** for different models for **laterite** when fixed at characteristic depth

Floor Level	Max values of bending moment (kNm)			Max values of shear force(kN)			Max values of axial force (kN)		
	SPN1	SPAY1	SPBY1	SPN1	SPAY1	SPBY1	SPN1	SPAY1	SPBY1
12	575.1	620.2	491.9	324.5	357.7	292.0	99.7	117.8	78.2
11	753.4	796.9	749.3	430.7	425.4	435.6	245.7	280.5	208.2
10	800.0	827.6	935.4	476.5	511.3	557.8	431.7	485.5	404.4
9	817.4	810.3	1024.3	485.7	496.0	620.8	630.3	702.2	654.6
8	892.3	901.3	1075.9	465.6	485.1	603.3	828.4	913.9	944.8
7	883.3	894.1	1088.9	437.1	443.3	568.4	1005.1	1090.4	1233.9
6	832.5	806.8	896.1	394.8	373.7	433.2	1137.0	1207.2	1458.2
5	779.4	734.1	558.6	341.0	341.1	219.7	1211.6	**1251.9**	**1571.1**
4	757.7	723.3	974.5	293.8	321.3	268.4	**1212.5**	1217.4	1540.9
3	777.5	972.3	1050.4	296.8	433.9	484.2	1151.0	1123.4	1398.9
2	1030.1	1110.2	1098.1	442.0	563.7	**626.4**	1022.3	988.4	1167.2
1	**1073.8**	**1436.2**	**1496.6**	**500.2**	**588.5**	622.9	845.5	872.3	907.1

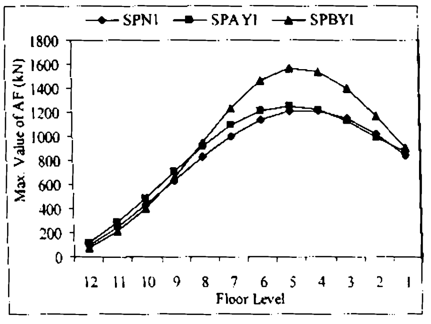
Table 6.9b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 6.9a. and % variation with respect to SPN1

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SPN1	1073.8	
	SPAY1	1436.2	+33.7
	SPBY1	1496.6	+39.3
Shear force (kN)	SPN1	500.2	
	SPAY1	588.5	+17.6
	SPBY1	626.4	+25.2
Axial force (kN)	SPN1	1212.5	
	SPAY1	1251.9	+3.2
	SPBY1	1571.1	+29.5

There is an increase of 34% for column bending moment when modeled using discrete elements and 39% using continuum elements showing that there is 5% variation in the maximum bending moment in the frame when two models for soil are considered. The corresponding variations in shear force are an increase of 18% and 25% showing a variation of 7%. As for axial force it is 3% and 30% giving a variation of 27%. This shows that continuum model is giving higher values when the pile length is taken for characteristic depth.



a. Bending moment b. Shear force



c. Axial force

Fig. 6.7 Variation of maximum values of (a)bending moment,(b) shear force and (c)axial force in **columns** for different models for **laterite** when fixed at characteristic depth

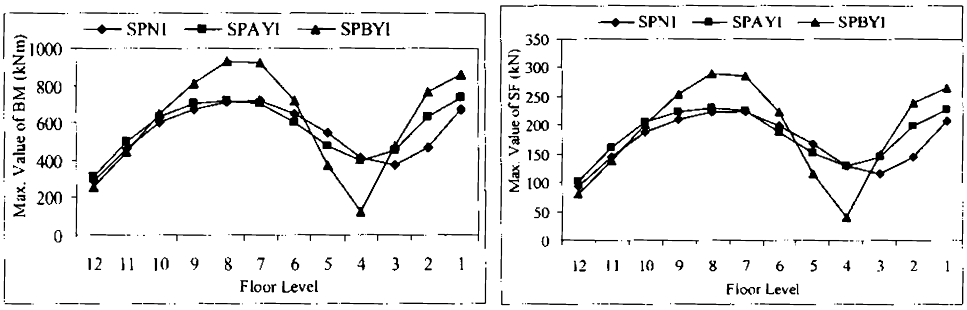
Maximum values of bending moments and shear forces in beams are reported in Table 6.10a and the percentage variations of maximum responses with respect to SPN1 are reported in Table 6.10b. The variations along the floor level are shown in Fig. 6.8.

Table 6.10a. Maximum values of bending moments and shear forces in **beams** for different models for **laterite** when fixed at characteristic depth

Floor Level	Max values of bending moment (kNm)			Max values of shear force(kN)		
	SPN1	SPAY1	SPBY1	SPN1	SPAY1	SPBY1
12	289.2	314.2	260.3	93.9	102.6	80.6
11	463.5	496.8	447.4	145.1	160.2	139
10	599.2	632.6	649.5	187.3	204.2	201.7
9	672.2	699.7	816.2	210.2	223.3	253.4
8	714.6	722.3	**930.3**	**223.9**	**229.4**	**288.7**
7	**719.1**	700.3	922	223.1	224.1	286.2
6	645.8	602.3	719.9	198.8	186.6	223.5
5	543.6	480.3	373.1	168.0	152.0	115.9
4	416.8	399.5	122.2	128.7	128.7	39.5
3	376.8	455.3	476.2	116.7	144.4	149.4
2	468.3	634.8	764.9	145.2	197.7	238
1	673.3	**735.2**	859.6	207.0	226.7	265.8

Table 6.10b. Maximum values of bending moments and shear forces in **beams** given in Table 6.10a. and % variation with respect to SPN1

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SPN1	719.1	
	SPAY1	735.2	+2.2
	SPBY1	930.3	+29.3
Shear force (kN)	SPN1	223.9	
	SPAY1	229.4	+2.4
	SPBY1	288.7	+28.9



a. Bending moment b. Shear force

Fig. 6.8 Variation of maximum values of (a)bending moment and (b)shear force in **beams** for different models for **laterite** when fixed at characteristic depth

There is 2% increase for beam bending moment when modeled using discrete elements and 29% using continuum elements showing that there is 27% variation in the maximum bending moment when two models for soil are considered. The corresponding variations in shear force are 2% and 29% showing a variation of 27%. The variation in beam response is 27% for the two models with continuum model giving upper bound values.

6.7.1.5 Influence of SSI of laterite considering full depth of piles

The analytical results of SFN1, SFAY1 and SFBY1 are used to study the influence of SSI using discrete and continuum model for laterite when piles are fixed at full depth. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 6.11a. and the percentage variations of maximum responses with respect to SFN1 are reported in Table 6.11b. The variations along the floor level is shown in Fig. 6.9.

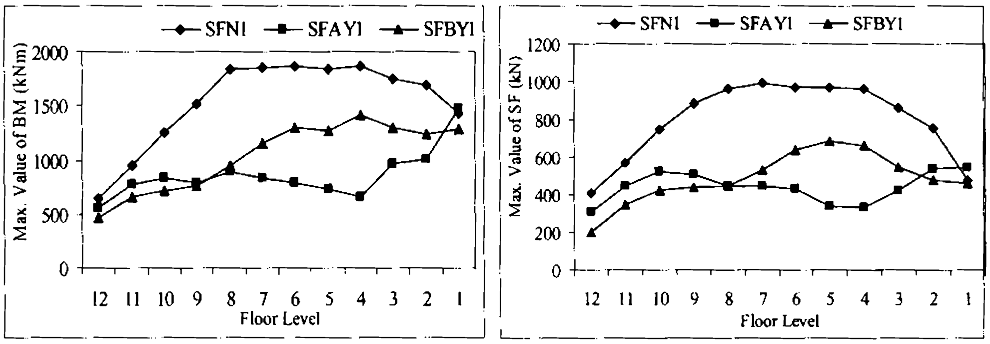
Table 6.11a. Maximum values of bending moments, shear forces and axial forces in **columns** for different models for **laterite** when fixed at full depth.

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)			Max values of axial force(kN)		
	SFN1	SFAY1	SFBY1	SFN1	SFAY1	SFBY1	SFN1	SFAY1	SFBY1
12	649.4	556.4	467.2	410.7	309.3	196.8	82.3	95.2	205.8
11	950.4	767.4	659.0	570.9	449.2	344.4	221.9	241.2	504.3
10	1249.7	827.4	708.9	745.2	525.5	419.6	446.9	437.6	823.5
9	1511.2	786.6	755.0	887.5	510.6	440.1	758.2	655.7	1126.6
8	1838.9	886.3	952.8	958.1	442.4	447.8	920.0	871.1	1388.1
7	1851.5	829.5	1152.2	**996.0**	448.0	531.7	1162.1	1046.9	1563.3
6	**1871.9**	784.1	1298.2	972.7	434.5	639.4	1452.0	1155.3	**1624.5**
5	1836.8	725.9	1275.1	968.2	336.0	**681.7**	1646.2	**1186.8**	1584.9
4	1863.1	662.9	**1416.5**	964.6	330.5	658.2	1686.0	1130.3	1484.7
3	1752.8	968.5	1306.0	861.7	425.8	545.0	**2665.5**	1006.2	1378.1
2	1689.3	1005.6	1236.9	751.8	538.9	480.6	2021.0	838.9	1315.6
1	1423.7	**1470.8**	1286.7	474.6	**549.8**	461.3	1750.0	696.5	1372.6

Table 6.11b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 6.10a. and % variation with respect to SFN1

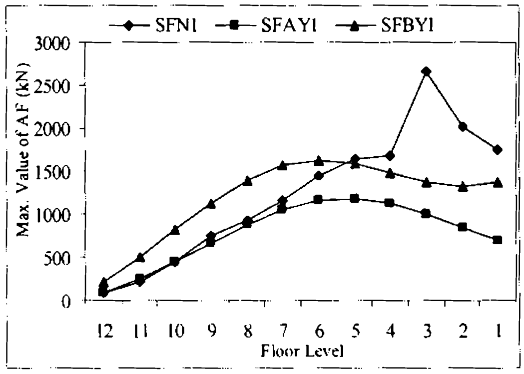
Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SFN1	1871.9	
	SFAY1	1470.8	-21.4
	SFBY1	1416.5	-24.3
Shear force (kN)	SFN1	996.0	
	SFAY1	549.8	-44.7
	SFBY1	681.7	-31.5
Axial force (kN)	SFN1	2665.5	
	SFAY1	1186.8	-55.4
	SFBY1	1624.5	-39.0

There is a decrease of 21% for column bending moment when the full depth of pile is considered using discrete model and 24% using continuum model of soil giving a variation of 3% for the two models. The corresponding variations in shear force are a decrease of 45% and 32% showing a variation of 13%. As for axial force it is 55% and 39% giving a variation of 16%. The minimum decrease in response is 21%. This reduction in responses in the frame may be due to the effect of soil structure interaction.



a. Bending moment

b. Shear force



c. Axial force

Fig. 6.9 Variation of maximum values of (a)bending moment, (b)shear force and (c)axial force in **columns** for different models for **laterite** when fixed at full depth.

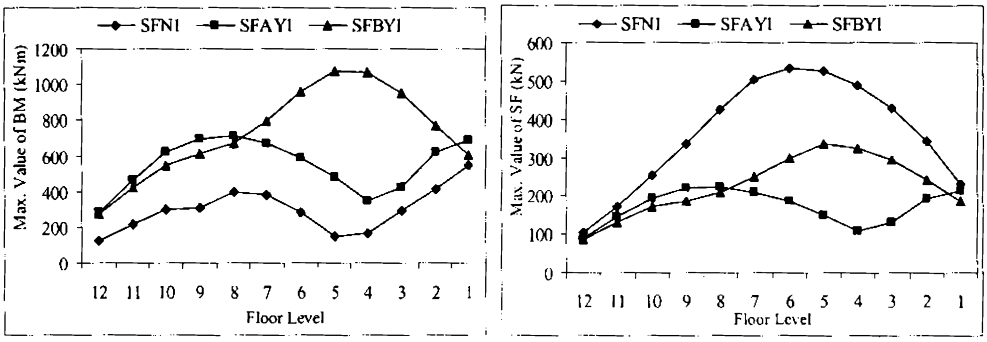
Maximum values of bending moments and shear forces in beams are reported in Table 6.12a. and the percentage variations of maximum responses with respect to SFN1 are reported in Table 6.12b. The variations along the floor level are shown in Fig. 6.10.

Table 6.12a. Maximum values of bending moments and shear forces in **beams** for different models for **laterite** when fixed at full depth.

Floor Level	Max values of bending moment (kNm)			Max values of shear force(kN)		
	SFN1	SFAY1	SFBY1	SFN1	SFAY1	SFBY1
12	126.6	280.6	276.4	103.3	88.4	84.3
11	212.4	459.5	419.2	171.9	144.5	129.7
10	300.5	616.6	549.8	253.6	193.7	169.7
9	304.9	696.8	608.4	337.2	218.8	187.8
8	400.1	**713.6**	669.3	425.5	**224.7**	209.0
7	381.9	669.3	797.9	503.0	210.4	249.1
6	280.6	587.5	959.1	**534.6**	187.8	299.5
5	148.6	477.5	**1073.5**	527.1	150.3	**335.3**
4	163.3	346.9	1063.8	487.7	107.7	324.9
3	286.8	422.5	948.0	430.1	132.0	296.1
2	410.6	622.4	772.5	344.0	193.8	241.3
1	**545.6**	684.5	601.0	231.0	212.1	184.8

Table 6.12b. Maximum values of bending moments and shear forces in **beams** given in Table 6.12a and % variation with respect to SFN1

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SFN1	545.6	
	SFAY1	713.6	+30.8
	SFBY1	1073.5	+96.7
Shear force (kN)	SFN1	534.6	
	SFAY1	224.7	-57.9
	SFBY1	335.3	-37.2



a. Bending moment b. Shear force

Fig. 6.10 Variation of maximum values of(a) bending moment and (b)shear force in **beams** for different models for **laterite** when fixed at full depth.

There is an increase of 31% for beam bending moment when modeled using discrete elements and 97% using continuum elements giving a variation of 66%. The corresponding variations in shear force are 58% and 37% decrease showing a variation of 21%. It has been observed that contradictory to column bending moments, soil structure interaction effects increases the bending moments in the beams.

6.7.1.6 Influence of SSI and founding depth on displacements and storey drifts in laterite

The models SG1, SPN1, SPAY1, SPBY1, SFN1, SFAY1 and SFBY1 are analysed to investigate the effect of soil structure interaction and founding depth on displacement in laterite. The maximum values of horizontal and vertical displacements are reported in Table 6.13. Fig. 6.11 shows the deflected shapes when the pile is taken for characteristic length, with discrete and continuum model for soil.

Table 6.13. Effect of fixity with and without SSI effect of **laterite** on displacements

Depth of fixity			Max values of displacement (m)	
			Horizontal direction	Vertical direction
Ground Level			0.115	0.0048
Characteristic depth	Without SSI		0.136	0.0170
	With SSI	Discrete model	0.135	0.0161
		Continuum model	0.179	0.0118
Full depth	Without SSI		0.501	0.0191
	With SSI	Discrete model	0.131	0.0098
		Continuum model	0.136	0.0155

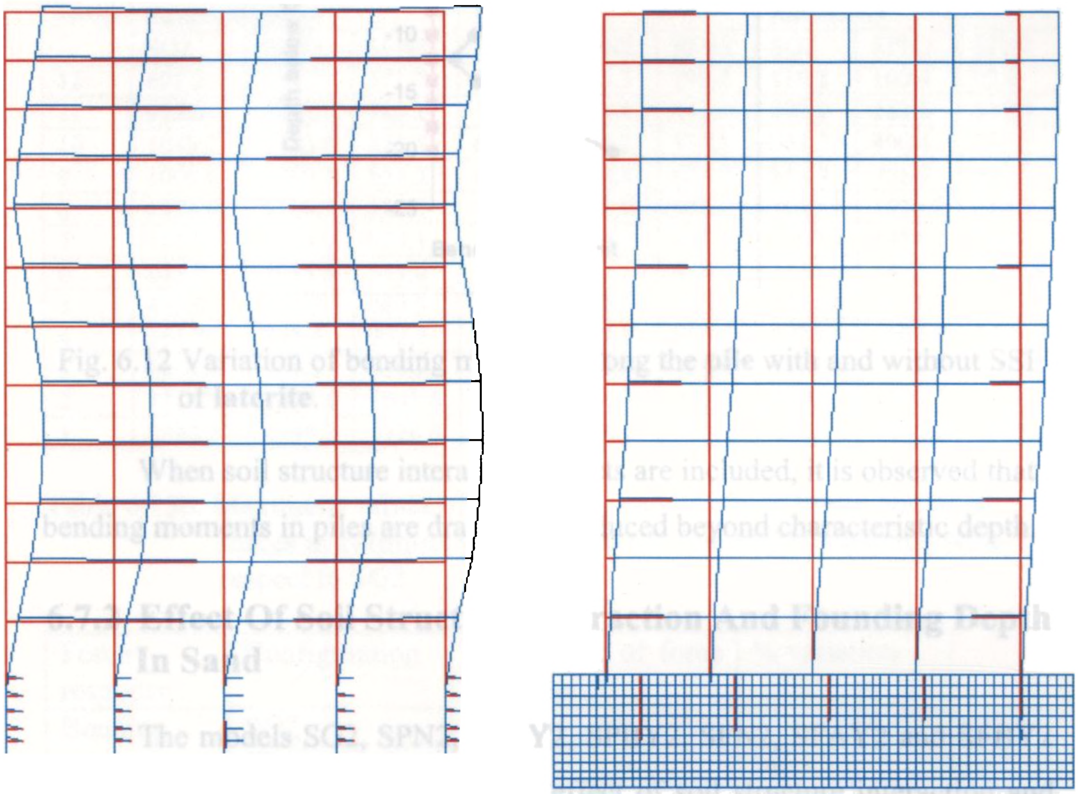
From the above table it has been observed that the maximum value of displacement both in the horizontal and vertical direction increases with depth of fixity for both models for SSI effects compared to when the frame is assumed to be fixed at ground level. When SSI effects are considered the maximum values of displacements are reported when piles are fixed at characteristic depth. This may be due to the increased soil structure interaction effect exerted by the soil medium when the full depth of pile is considered.

The storey drift for different models is given in Table 6.14.

Table 6.14. Storey drift for different models in **laterite**

Floor Level	SG1	SPN1	SPAY1	SPBY1	SFN1	SFAY1	SFBY1
12	0.0159	0.019	0.1229	0.022	0.027	0.021	0.031
11	0.0249	0.0256	-0.0709	0.034	0.04	-0.689	0.028
10	0.0324	0.0289	0.0308	0.047	0.056	0.7485	0.012
9	0.02896	0.0215	0.0143	-0.064	0.072	0.0129	-0.0119
8	-0.0405	-0.0129	-0.0272	-0.462	0.108	-0.0283	-0.0217
7	-0.041	-0.0344	-0.0369	0.47	0.1073	-0.0344	-0.0344
6	-0.0236	-0.0287	-0.025	0.007	0.0007	-0.0247	0.013
5	-0.0006	-0.017	-0.009	-0.063	-0.103	-0.008	-0.004
4	0.0202	0.001	0.012	0.018	-0.098	0.013	0.002
3	0.0349	0.017	0.0298	0.041	-0.082	0.032	0.011
2	-0.0109	0.0358	0.0454	0.055	-0.057	0.0451	0.0242
1	0.0714	0.0508	0.04108	0.05	-0.023	0.037	0.0288
GL	0	0.0294	0.00672	0.015	0.453	0.0039	0.058

From the storey drift values it has been observed that the frame is not moving linearly in one direction. The positive and negative values indicate that certain floors are moving outward and others are moving inward with respect to the adjacent storeys. The storey drift values are representative of the deflected shape of the frame.



a.Discrete model
Max. horz. displacement:0.135m
Max. vert. displacement:0.016m

b.Continuum model
Max. horz. displacement:0.179m
Max. vert. displacement:0.011m

Fig. 6.11 Deflected shape with (a)discrete and (b)continuum model

6.7.1.7 Influence of SSI on bending moments in piles

The variation of bending moments in piles with and without SSI effect of laterite are shown in Fig. 6.12. Models SFN1 and SFAY1 are compared.

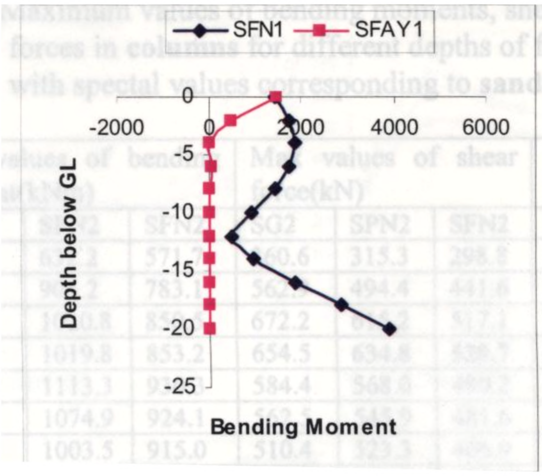


Fig. 6.12 Variation of bending moments along the **pile** with and without SSI of **laterite**.

When soil structure interaction effects are included, it is observed that bending moments in piles are drastically reduced beyond characteristic depth.

6.7.2 Effect Of Soil Structure Interaction And Founding Depth In Sand

The models SG2, SPN2, SPAY2, SPBY2, SFN2, SFAY2 and SFBY2 have been analysed to investigate the effect of soil structure interaction and founding depth in sand. The results are presented and discussed in the subsequent sections. Bending moments, shear forces and axial forces in columns of the frame and the corresponding values in the beams for different models are compared. Displacements and storey drifts in the frame and bending moments in the pile are also reported.

6.7.2.1 Influence of founding depth without SSI

The analytical results of SG2, SPN2 and SFN2 are used to study the influence of founding depth without SSI. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 6.15a. and the percentage variations of maximum responses with respect to SG2 are reported in Table 6.15b The variations along the floor level is shown in Fig. 6.13.

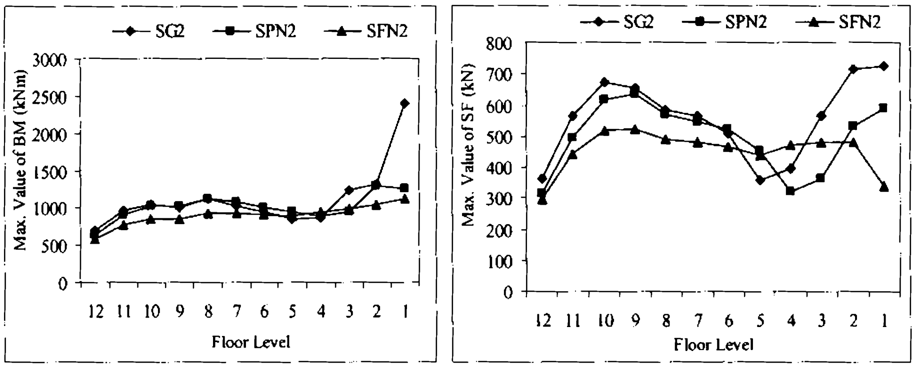
Table 6.15a. Maximum values of bending moments, shear forces and axial forces in **columns** for different depths of fixity without SSI with spectal values corresponding to **sand**.

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)			Max values of axial force(kN)		
	SG2	SPN2	SFN2	SG2	SPN2	SFN2	SG2	SPN2	SFN2
12	691.2	632.2	571.7	360.6	315.3	298.8	110.2	100.4	92.8
11	975.8	904.2	783.1	562.9	494.4	441.6	292.2	262.6	237.9
10	1049.2	1020.8	850.5	672.2	615.2	517.1	541.2	490.4	432.7
9	1009.0	1019.8	853.2	654.5	**634.8**	**520.7**	818.3	756.7	649.5
8	1123.0	1113.3	930.3	584.4	568.0	490.2	1089.9	1036.2	868.9
7	1017.3	1074.9	924.1	562.5	545.9	481.6	1309.7	1288.3	1067.1
6	943.4	1003.5	915.0	510.4	523.3	466.9	1442.0	1472.1	1225.9
5	853.0	954.3	889.5	357.5	449.8	438.5	**1472.4**	**1571.8**	1345.5
4	861.7	897.4	952.7	397.3	319.8	472.6	1383.4	1568.8	1429.4
3	1245.5	955.9	986.2	563.0	361.9	479.8	1208.3	1478.9	1497.3
2	1314.0	**1304.4**	1041.6	715.3	530.8	478.9	990.6	1299.7	1544.2
1	**2393.2**	1249.2	**1126.8**	**724.5**	586.1	340.1	830.3	1065.6	**1558.4**

Table 6.15b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 6.15a. and % variation with respect to SG2

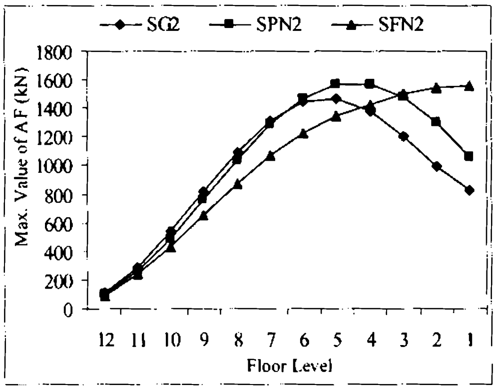
Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG2	2393.2	
	SPN2	1304.4	-45.4
	SFN2	1126.8	-52.9
Shear force (kN)	SG2	724.5	
	SPN2	634.8	-12.3
	SFN2	520.7	-28.1
Axial force (kN)	SG2	1472.4	
	SPN2	1571.8	+6.7
	SFN2	1558.4	+5.8

There is a decrease of 45% for column bending moment when the pile length is taken as characteristic depth and an decrease of 53% when pile is treated for full length showing that there is 8% decrease in the maximum bending moment in the frame when no soil medium is considered. The corresponding variations in shear force is 12% and 28% showing a decrease of 16%. As for axial force it is 7% and 6% giving a decrease of 1%.



a. Bending moment

b. Shear force



c. Axial force

Fig. 6.13 Variation of maximum values of (a)bending moment,(b) shear force and (c)axial force in **columns** for different depths of fixity without SSI with spectral values corresponding to **sand**

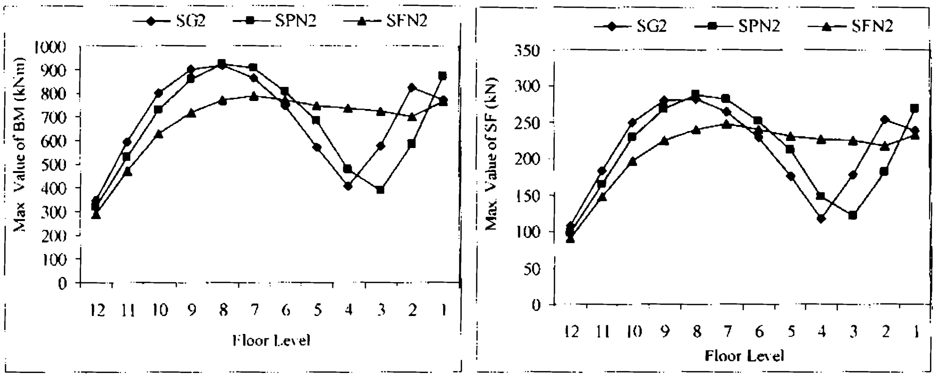
Maximum values of bending moments and shear forces in beams are reported in Table 6.16a and the percentage variations of maximum responses with respect to SG2 are reported in Table 6.16b. The variations along the floor level is shown in Fig. 6.14.

Table6.16a. Maximum values of bending moments and shear forces in **beams** for different depths of fixity without SSI with spectral values corresponding to **sand**.

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)		
	SG2	SPN2	SFN2	SG2	SPN2	SFN2
12	347.7	318.5	288.3	107.7	99.1	90.0
11	592.1	529.8	470.5	184.0	165.5	147.1
10	800.9	732.1	629.5	248.8	228.8	196.6
9	900.7	860.7	719.2	279.4	269.0	224.6
8	**918.9**	**920.6**	769.4	**282.6**	**287.7**	240.2
7	862.8	903.5	**789.9**	264.7	281.7	**246.9**
6	745.3	808.6	770.6	229.2	251.9	240.8
5	570.7	681.7	749.9	175.8	211.6	231.6
4	408.8	477.2	734.9	117.6	147.7	227.8
3	573.7	389.9	724.8	177.0	120.8	224.8
2	821.1	585.0	700.3	252.8	181.5	217.0
1	772.9	872.2	764.7	237.7	268.2	232.8

Table 6.16b.Maximum values of bending moments and shear forces in **beams** given in Table 6.16a. and % variation with respect toSG2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG2	918.9	
	SPN2	920.6	+0.18
	SFN2	789.9	-14.0
Shear force (kN)	SG2	282.6	
	SPN2	287.7	+1.8
	SFN2	246.9	-12.6



a. Bending moment b. Shear force

Fig. 6.14 Variation of maximum values of(a)bending moment and (b)shear force in **beams** for different depths of fixity without SSI with spectral values corresponding to **sand**.

The percentage variation of bending moment in beam is nil when the pile length is taken as characteristic depth and 14% decrease when pile is treated for full length showing that there is 14% decrease in the maximum bending moment when no soil medium is considered. The corresponding variations in shear force is 2% increase and 13% decrease showing an variation of 15%. This shows that the bending moment and shear force in beams are reduced by change in length.

6.7.2.2 Influence of founding depth with SSI using discrete model for soil

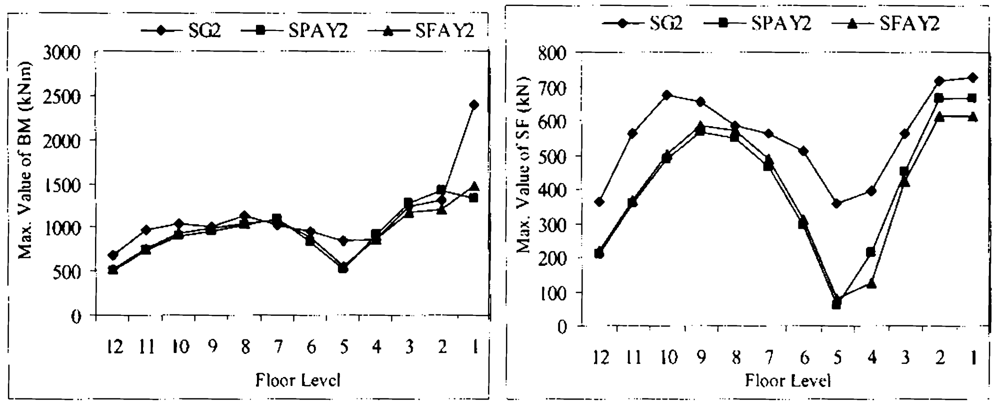
The analytical results of SG2, SPAY2 and SFAY2 are used to study the influence of founding depth with SSI using discrete model for soil. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 6.17a. and the percentage variations of maximum responses with respect to SG2 are reported in Table 6.17b. The variations along the floor level are shown in Fig. 6.15.

Table 6.17a Maximum values of bending moments, shear forces and axial forces in **columns** for different depths of fixity with SSI using discrete model for **sand.**

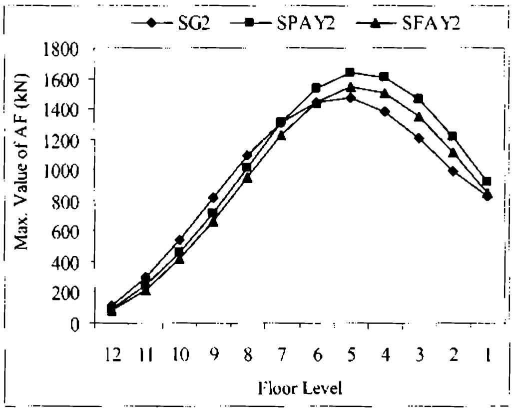
Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)			Max values of axial force(kN)		
	SG2	SPAY2	SFAY2	SG2	SPAY2	SFAY2	SG2	SPAY2	SFAY2
12	691.2	511.4	527.2	360.6	209.4	216.4	110.2	92.0	79.8
11	975.8	743.8	762.9	562.9	358.7	367.2	292.2	244.9	216.2
10	1049.2	897.6	926.4	672.2	489.5	503.5	541.2	458.6	415.4
9	1009.0	952.5	988.9	654.5	565.7	584.7	818.3	720.6	664.7
8	1123.0	1016.6	1050.1	584.4	550.8	571.9	1089.9	1015.4	949.1
7	1017.3	1094.8	1072.9	562.5	465.7	487.1	1309.7	1306.3	1229.6
6	943.4	834.8	887.8	510.4	293.7	312.8	1442.0	1529.5	1442.5
5	853.0	521.5	555.4	357.5	61.8	78.6	**1472.4**	**1640.4**	**1543.0**
4	861.7	918.6	861.4	397.3	212.4	125.5	1383.4	1607.4	1500.6
3	1245.5	1281.2	1173.8	563.0	451.0	425.5	1208.3	1461.8	1350.1
2	1314.0	1417.2	1208.3	715.3	665.1	611.7	990.6	1215.6	1112.1
1	**2393.2**	**1330.9**	**1482.0**	**724.5**	**665.6**	**614.7**	830.3	915.4	846.7

Table 6.17b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 6.17a. and % variation with respect to SG2.

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG2	2393.2	
	SPAY2	1330.9	-44.3
	SFAY2	1482.0	-38.0
Shear force (kN)	SG2	724.5	
	SPAY2	665.6	-8.1
	SFAY2	614.7	-15.15
Axial force (kN)	SG2	1472.4	
	SPAY2	1640.4	+11.4
	SFAY2	1543.0	+4.7



a. Bending moment b. Shear force



c. Axial Force

Fig. 6.15 Variation of maximum values of bending moments, shear force and axial force in **columns** for different depths of fixity with SSI using discrete model for **sand**

There is a decrease of 44% for column bending moment when the pile length is taken as characteristic depth and 38% when pile is treated for full length showing that there is 6% increase in the maximum bending moment in the frame when discrete model for soil is considered. The corresponding variations in shear force is a decrease of 8% and 15% showing a decrease of 7%. As for axial force it is 11% and 5% giving a decrease of 6%. The maximum increase in response is 6% for bending moments.

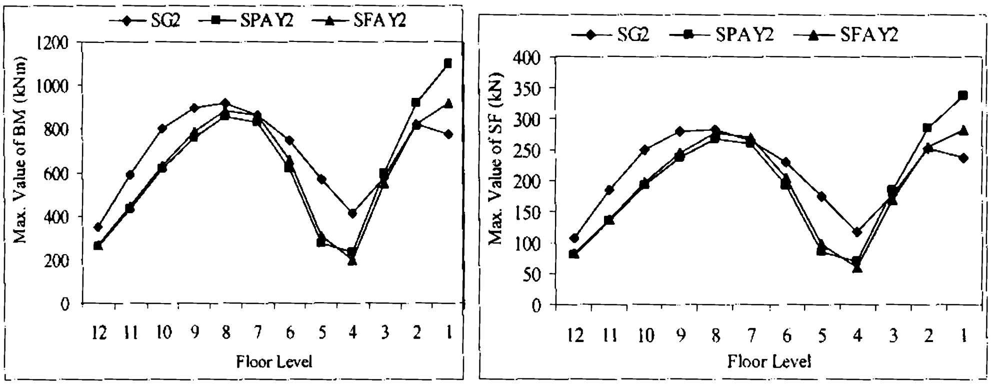
Maximum values of bending moments and shear forces in beams are reported in Table 6.18a and the percentage variations of maximum responses with respect to SG2 are reported in Table 6.18b. The variations along the floor level are shown in Fig. 6.16.

Table 6.18a. Maximum values of bending moments and shear forces in **beams** for different depths of fixity with SSI using discrete model for **sand**

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	SG2	SPAY2	SFAY2	SG2	SPAY2	SFAY2
12	347.7	259.1	267.8	107.7	80.4	83.0
11	592.1	431.6	444.0	184.0	134.7	138.5
10	800.9	616.0	634.1	248.8	192.3	197.9
9	900.7	763.1	788.1	279.4	238.2	246.0
8	**918.9**	856.6	887.1	**282.6**	267.5	277.4
7	862.8	830.2	866.7	264.7	259.3	270.6
6	745.3	620.5	657.1	229.2	193.7	205.1
5	570.7	273.0	309.2	175.8	85.1	96.3
4	408.8	229.9	197.2	117.6	71.1	61.0
3	573.7	597.1	546.2	177.0	185.0	169.2
2	821.1	918.6	826.1	252.8	284.7	256.0
1	772.9	**1098.2**	**917.2**	237.7	**338.2**	**283.7**

Table 6.18b. Maximum values of bending moments and shear forces in **beams** given in Table 6.18a. and % variation with respect to SG2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG2	918.9	
	SPAY2	1098.2	+19.5
	SFAY2	917.2	-0.18
Shear force (kN)	SG2	282.6	
	SPAY2	338.2	+19.6
	SFAY2	283.7	+0.38



a. Bending moment b. Shear force

Fig. 6.16 Variation of maximum values of (a)bending moment and (b)shear force in **beams** for different depths of fixity with SSI using discrete model for **sand.**

The percentage variation of bending moment in beam is 20% when the pile length is taken as characteristic depth and nil when pile is treated for full length showing that there is 19% decrease in the maximum bending moment when discrete model for soil is considered. The corresponding variations in shear force are 20% and 0% showing a decrease of 20%. The responses in the beams have reduced when pile is taken from characteristic to full depth. As in the case of responses in columns this validates the concept of characteristic depth in the design regarding force output.

6.7.2.3 Influence of founding depth with SSI using continuum model for soil

The analytical results of SG2, SPBY2 and SFBY2 are used to study the influence of founding depth with SSI using continuum model for soil. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 6.19a. and the percentage variations of maximum responses with respect to SG2 are reported in Table 6.19b. The variations along the floor level are shown in Fig. 6.17.

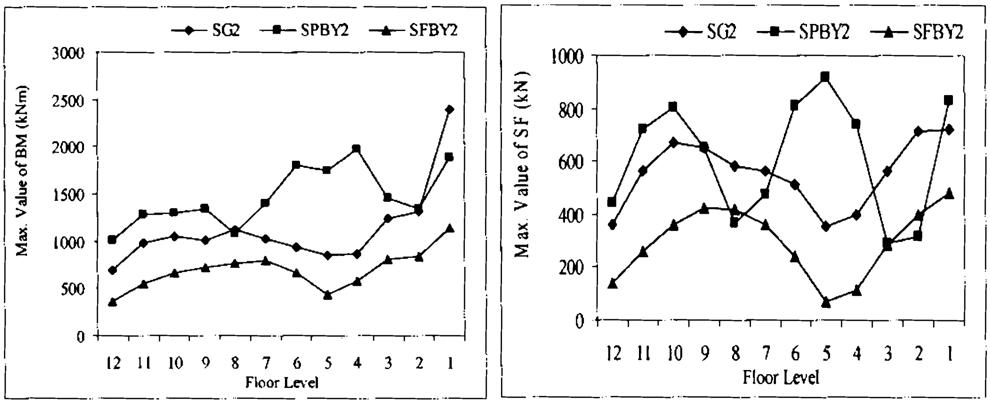
Table 6.19a. Maximum values of bending moments, shear forces and axial forces in **columns** for different depths of fixity with SSI using continuum model for **sand**

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)			Max values of axial force(kN)		
	SG2	SPBY2	SFBY2	SG2	SPBY2	SFBY2	SG2	SPBY2	SFBY2
12	691.2	1010.6	356.2	360.6	445.4	141.5	110.2	307.4	58.9
11	975.8	1289.2	544.6	562.9	723.8	257.5	292.2	749.2	158.1
10	1049.2	1303.0	668.1	672.2	804.6	358.6	541.2	1236.9	303.8
9	1009.0	1335.7	722.0	654.5	654.5	421.5	818.3	1686.2	487.7
8	1123.0	1082.8	760.3	584.4	366.2	419.0	1089.9	2021.8	699.2
7	1017.3	1395.8	786.9	562.5	476.7	362.1	1309.7	2157.0	910.7
6	943.4	1808.9	661.1	510.4	812.9	239.3	1442.0	2094.3	1075.7
5	853.0	1748.4	428.1	357.5	**917.3**	72.1	**1472.4**	1958.6	**1161.2**
4	861.7	**1982.7**	576.6	397.3	739.3	114.7	1383.4	1930.2	1143.6
3	1245.5	1461.2	813.2	563.0	293.1	287.5	1208.3	2052.1	1047.3
2	1314.0	1346.6	836.8	715.3	314.5	399.6	990.6	2289.3	886.6
1	**2393.2**	1894.7	**1137.3**	**724.5**	832.0	**477.8**	830.3	**2601.3**	706.2

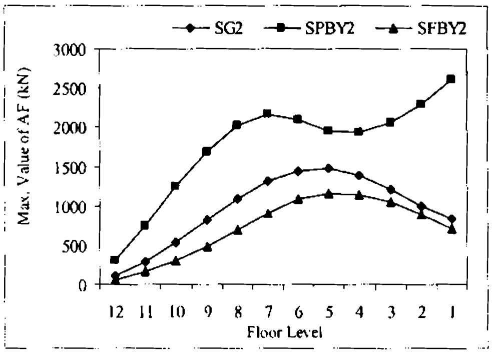
Table 6.19b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 6.19a. and % variation with respect to SG2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG2	2393.2	
	SPBY2	1982.7	-17.1
	SFBY2	1137.3	-52.4
Shear force (kN)	SG2	724.5	
	SPBY2	917.3	+26.6
	SFBY2	477.8	-34.0
Axial force (kN)	SG2	1472.4	
	SPBY2	2601.3	+76.6
	SFBY2	1161.2	-21.1

There is a decrease of 17% for column bending moment when the pile length is taken as characteristic depth and 52% when pile is treated for full length showing that there is 35% decrease in the maximum bending moment in the frame when continuum model for soil is considered. The corresponding variations in shear force are an increase of 27% and decrease of 34% showing a decrease of 61%. As for axial force it is 77% and 21% giving a decrease of 98%. The responses are observed to be decreasing when the depth of pile is taken from characteristic depth to full depth. This validates the concept of characteristic depth in the design regarding force output.



a. Bending moment b. Shear force



c. Axial force

Fig. 6.17 Variation of maximum values of (a)bending moment, (b)shear force and(c) axial force in **columns** for different depths of fixity with SSI using continuum model for **sand.**

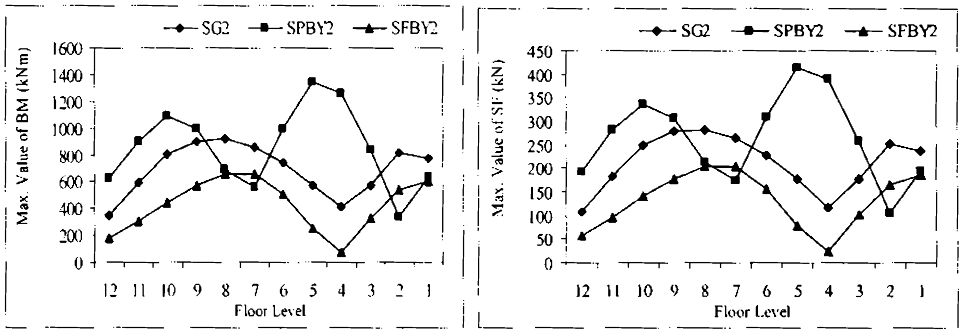
Maximum values of bending moments and shear forces in beams are reported in Table 6.20a and the percentage variations of maximum responses with respect to SG2 are reported in Table 6.20b. The variations along the floor level are shown in Fig. 6.18.

Table 6.20a. Maximum values of bending moments and shear forces in **beams** for different depths of fixity with SSI using continuum model for **sand**

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	SG2	SPBY2	SFBY2	SG2	SPBY2	SFBY2
12	347.7	627.5	179.1	107.7	193.3	55.8
11	592.1	904.4	307.0	184.0	280.6	95.8
10	800.9	1090.1	448.1	248.8	337.0	140.0
9	900.7	993.3	569.4	279.4	307.3	176.6
8	**918.9**	685.5	659.2	**282.6**	213.17	**203.2**
7	862.8	558.5	**659.7**	264.7	172.6	203.1
6	745.3	996.0	510.6	229.2	310.2	157.2
5	570.7	**1341.9**	254.7	175.8	**413.9**	78.4
4	408.8	1259.1	78.79	117.6	389.1	24.3
3	573.7	835.2	331.7	177.0	259.0	102.7
2	821.1	341.9	537.9	252.8	105.6	166.4
1	772.9	633.7	599.5	237.7	196.4	185.7

Table 6.20b. Maximum values of bending moments and shear forces in **beams** given in Table 6.20a. and % variation with respect to SG2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG2	918.9	
	SPBY2	1341.9	+46.0
	SFBY2	659.7	-28.2
Shear force (kN)	SG2	282.6	
	SPBY2	413.9	+46.4
	SFBY2	203.2	-28.0



a. Bending moment b. Shear force

Fig. 6.18 Variation of maximum values of bending moments and shear forces in **beams** for different depths of fixity with SSI using continuum model for **sand.**

There is 46% increase for beam bending moment when the pile length is taken as characteristic depth and 28% decrease when pile is treated for full length showing that there is 74% decrease in the maximum bending moment when continuum model for soil is considered. The corresponding variations in shear force are 46% and 28% showing a decrease of 74%. The maximum responses in beams are reported when pile length is taken as characteristic depth.

6.7.2.4 Influence of SSI of sand when piles are fixed at characteristic depth

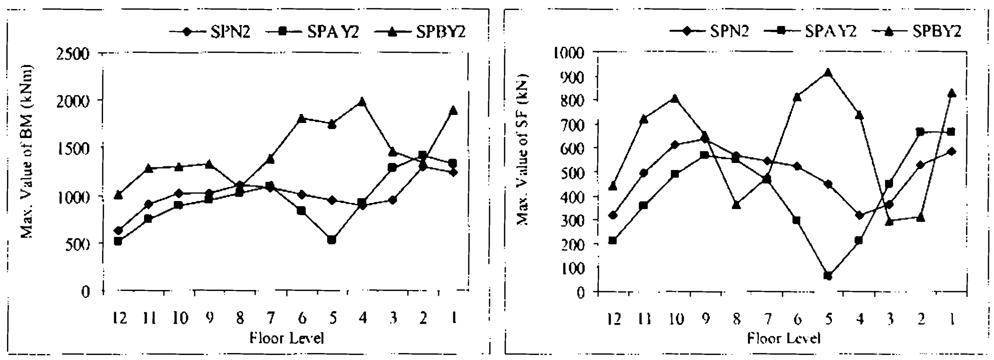
The analytical results of SPN2, SPAY2 and SPBY2 are used to study the influence of SSI using discrete and continuum model for sand when piles are fixed at characteristic depth. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 6.21a. and the percentage variations of maximum responses with respect to SPN2 are reported in Table 6.21b. The variations along the floor level is shown in Fig. 6.19.

Table 6.21a. Maximum values of bending moments, shear forces and axial forces in **columns** for different models for **sand** when fixed at characteristic depth

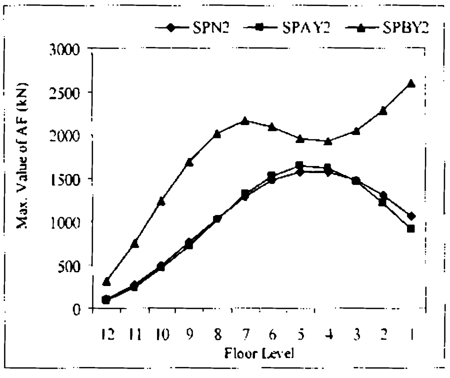
Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)			Max values of axial force (kN)		
	SPN2	SPAY2	SPBY2	SPN2	SPAY2	SPBY2	SPN2	SPAY2	SPBY2
12	632.2	511.4	1010.6	315.37	209.4	445.4	100.4	92	307.4
11	904.2	743.8	1289.2	494.4	358.7	723.8	262.6	244.9	749.2
10	1020.8	897.6	1303	615.2	489.5	804.6	490.4	458.6	1236.9
9	1019.8	952.5	1335.7	**634.8**	565.7	654.5	756.7	720.6	1686.2
8	1113.3	1016.6	1082.8	568	550.8	366.2	1036.2	1015.4	2021.8
7	1074.9	1094.8	1395.8	545.9	465.7	476.7	1288.3	1306.3	2157
6	1003.5	834.8	1808.9	523.3	293.7	812.9	1472.1	1529.5	2094.3
5	954.3	521.5	1748.4	449.8	61.8	**917.3**	**1571.8**	**1640.4**	1958.6
4	897.4	918.6	**1982.7**	319.8	212.4	739.3	1568.8	1607.4	1930.2
3	955.9	1281.2	1461.2	361.9	451.0	293.1	1478.9	1461.8	2052.1
2	**1304.4**	**1417.2**	1346.6	530.8	665.1	314.5	1299.7	1215.6	2289.3
1	1249.2	1330.9	1894.7	586.1	**665.6**	832.0	1065.6	915.4	**2601.3**

Table 6.21b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 6.21a. and % variation with respect to SPN2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SPN2	1304.4	
	SPAY2	1417.2	+8.6
	SPBY2	1982.7	+52
Shear force (kN)	SPN2	634.8	
	SPAY2	665.6	+4.8
	SPBY2	917.3	+44.5
Axial force (kN)	SPN2	1571.8	
	SPAY2	1640.4	+4.3
	SPBY2	2601.3	+65.4



a. Bending moment b. Shear force



c. Axial Force

Fig. 6.19 Variation of maximum values of (a)bending moment, (b)shear force and (c)axial force in **columns** for different models for **sand** when fixed at characteristic depth.

There is an increase of 9% for column bending moment when modeled using discrete elements and 52% using continuum elements showing that there is 43% variation in the maximum bending moment in the frame when two models for soil are considered. The corresponding variations in shear force are an increase of 5% and 45% showing a variation of 40%. As for axial force it is 4% and 65% giving a variation of 61%. This shows that continuum model is giving higher values when the pile length is taken for characteristic depth.

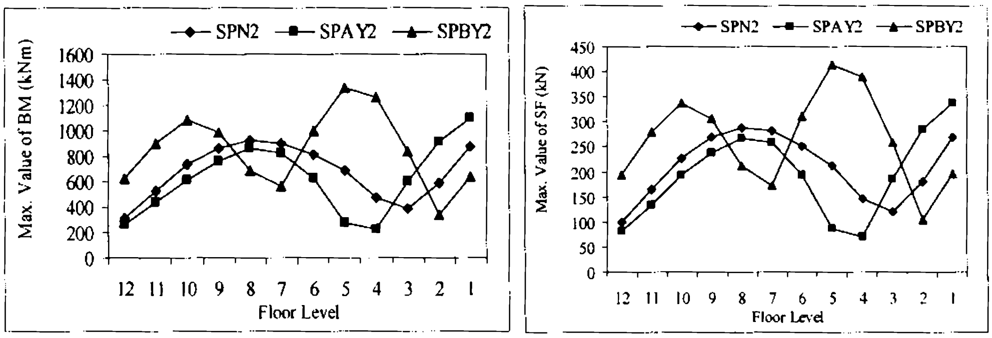
Maximum values of bending moments and shear forces in beams are reported in Table 6.22a and the percentage variations of maximum responses with respect to SPN2 are reported in Table 6.22b. The variations along the floor level are shown in Fig. 6.20.

Table 6.22a. Maximum values of bending moments and shear forces in **beams** for different models for **sand** when fixed at characteristic depth

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	SPN2	SPAY2	SPBY2	SPN2	SPAY2	SPBY2
12	318.5	259.1	627.5	99.1	80.4	193.3
11	529.8	431.6	904.4	165.5	134.7	280.6
10	732.1	616	1090.1	228.8	192.3	337
9	860.7	763.1	993.3	269	238.2	307.3
8	**920.6**	856.6	685.5	**287.7**	267.5	213.17
7	903.5	830.2	558.5	281.7	259.3	172.6
6	808.6	620.5	996	251.9	193.7	310.2
5	681.7	273.0	**1341.9**	211.6	85.1	**413.9**
4	477.2	229.9	1259.1	147.7	71.1	389.19
3	389.9	597.1	835.2	120.8	185	259
2	585	918.6	341.9	181.5	284.7	105.6
1	872.2	**1098.2**	633.7	268.2	**338.2**	196.4

Table 6.22b. Maximum values of bending moments and shear forces in **beams** given in Table 6.22a. and % variation with respect to SPN2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SPN2	920.6	
	SPAY2	1098.2	+19.2
	SPBY2	1341.9	+45.7
Shear force (kN)	SPN2	287.7	
	SPAY2	338.2	+17.5
	SPBY2	413.9	+43.8



a. Bending moment b. Shear force

Fig. 6.20 Variation of maximum values of (a)bending moment and (b)shear force in **beams** for different models for **sand** when fixed at characteristic depth

There is 19% increase for beam bending moment when modeled using discrete elements and 46% increase using continuum elements showing that there is 27% variation in the maximum bending moment when two models for soil are considered. The corresponding variations in shear force are 18% and 44% showing a variation of 26%. The variation in beam response is 27% and 26% for the two models with continuum model giving upper bound values.

6.7.2.5 Influence of SSI of sand considering full depth of piles

The analytical results of SFN2, SFAY2 and SFBY2 are used to study the influence of SSI using discrete and continuum model for soil when piles are fixed at full depth. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 6.23a. and the percentage variations of maximum responses with respect to SFN2 are reported in Table 6.23b. The variations along the floor level is shown in Fig. 6.21.

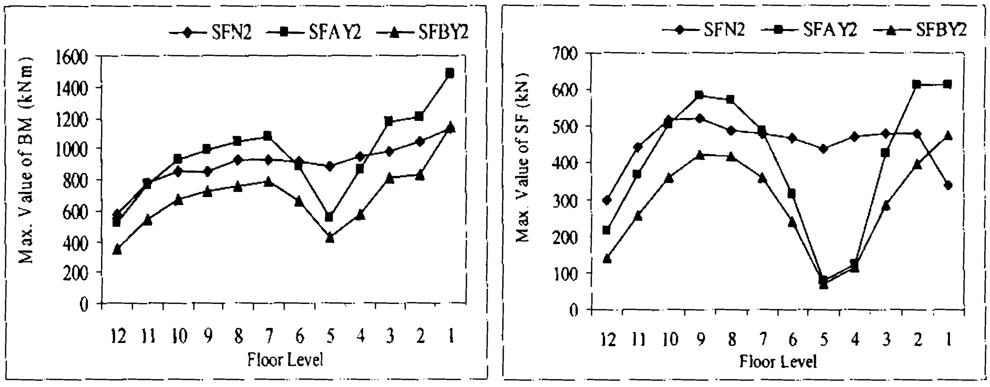
Table 6.23a. Maximum values of bending moments, shear forces and axial forces in **columns** for different models for **sand** when fixed at full depth

Floor Level	Max values of bending moment (kNm)			Max values of shear force(kN)			Max values of axial force(kN)		
	SFN2	SFAY2	SFBY2	SFN2	SFAY2	SFBY2	SFN2	SFAY2	SFBY2
12	571.7	527.2	356.2	298.8	216.4	141.5	92.81	79.8	58.9
11	783.1	762.9	544.6	441.6	367.2	257.5	237.9	216.2	158.1
10	850.5	926.4	668.1	517.1	503.5	358.6	432.7	415.4	303.8
9	853.2	988.9	722.0	**520.7**	584.7	421.5	649.5	664.7	487.7
8	930.3	1050.1	760.3	490.2	571.9	419.0	868.9	949.1	699.2
7	924.1	1072.9	786.9	481.6	487.1	362.1	1067.1	1229.6	910.7
6	915.0	887.8	661.1	466.9	312.8	239.3	1225.9	1442.5	1075.7
5	889.5	555.4	428.1	438.5	78.6	72.10	1345.5	**1543.0**	**1161.2**
4	952.7	861.4	576.6	472.6	125.5	114.7	1429.4	1500.6	1143.6
3	986.2	1173.8	813.2	479.8	425.5	287.5	1497.3	1350.1	1047.3
2	1041.6	1208.3	836.8	478.9	611.7	399.6	1544.2	1112.1	886.6
1	**1126.8**	**1482.0**	**1137.3**	340.1	**614.7**	**477.8**	**1558.4**	846.7	706.2

Table 6.23b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 6.23a. and % variation with respect to SFN2

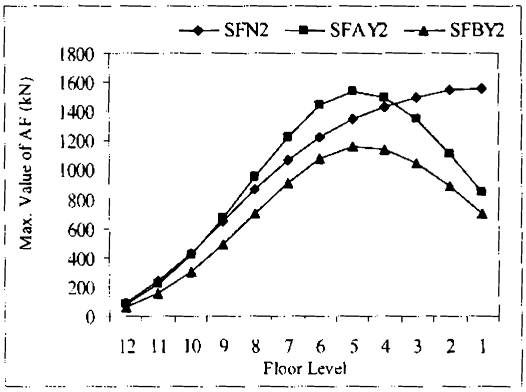
Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SFN2	1126.8	
	SFAY2	1482.0	+31.5
	SFBY2	1137.3	+0.93
Shear force (kN)	SFN2	520.7	
	SFAY2	614.7	+18
	SFBY2	477.8	-8.2
Axial force (kN)	SFN2	1558.4	
	SFAY2	1543.0	-0.98
	SFBY2	1161.2	-25.4

There is an increase of 32% for column bending moment when the full depth of pile is considered using discrete model and 1% using continuum model of soil giving a variation of 31% for the two models. The corresponding variations in shear force are an increase of 18% and a decrease of 8% showing a variation of 26%. As for axial force it is 1% and 25% decrease giving a variation of 24%. Hence it is observed that the continuum model is showing the effect of soil structure interaction more clearly in this case. Discrete model seems to be amplifying the response.



a. Bending moment

b. Shear force



c. Axial Force

Fig. 6.21 Variation of maximum values of(a) bending moment, (b) shear force and (c)axial force in **columns** for different models for **sand** when fixed at full depth.

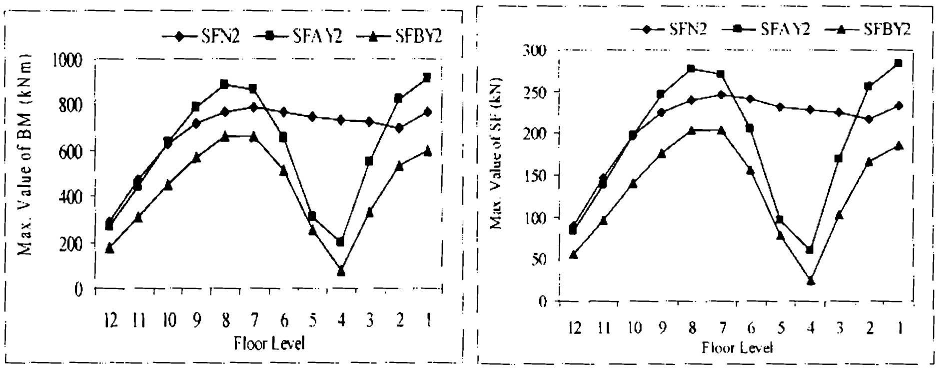
Maximum values of bending moments and shear forces in beams are reported in Table 6.24a. and the percentage variations of maximum responses with respect to SFN2 are reported in Table 6.24b. The variations along the floor level are shown in Fig. 6.22.

Table 6.24a. Maximum values of bending moments and shear force in **beams** for different models for **sand** when fixed at full depth

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	SFN2	SFAY2	SFBY2	SFN2	SFAY2	SFBY2
12	288.3	267.8	179.1	90.01	83.0	55.8
11	470.5	444	307.0	147.19	138.5	95.8
10	629.5	634.1	448.1	196.6	197.9	140.0
9	719.2	788.1	569.4	224.6	246.0	176.6
8	769.4	887.1	659.2	240.2	277.4	**203.2**
7	**789.9**	866.7	**659.7**	**246.9**	270.6	203.1
6	770.6	657.1	510.67	240.8	205.1	157.2
5	749.9	309.2	254.7	231.6	96.3	78.4
4	734.9	197.2	78.79	227.8	61.0	24.3
3	724.8	546.2	331.7	224.8	169.2	102.7
2	700.3	826.1	537.9	217.0	256.0	166.4
1	764.73	**917.2**	599.5	232.8	**283.7**	185.7

Table 6.24b. Maximum values of bending moments and shear force in **beams** given in Table 6.24a. and % variation with respect to SFN2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SFN2	789.9	
	SFAY2	917.2	+16.1
	SFBY2	659.7	-16.4
Shear force (kN)	SFN2	246.9	
	SFAY2	283.7	+14.9
	SFBY2	203.2	-17.6



a. Bending moment b. Shear force

Fig. 6.22 Variation of maximum values of (a)bending moment and(b) shear force in **beams** for different models for **sand** when fixed at full depth.

There is an increase of 16% for beam bending moment when modeled using discrete elements and 16% decrease using continuum elements giving a variation of 32%. The corresponding variations in shear forces are 15% and

18% showing a variation of 33%. As in the case of column responses, continuum model shows the effect of soil structure interaction more clearly.

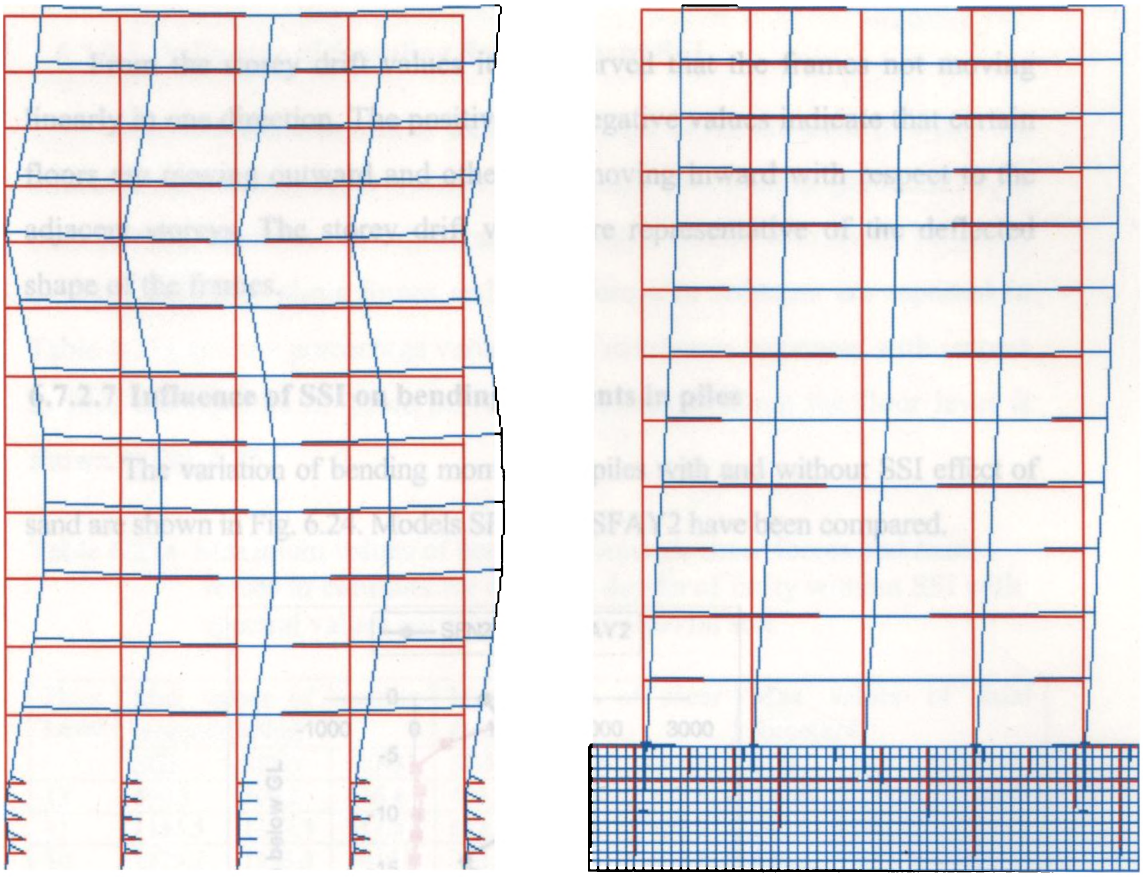
6.7.2.6 Influence of SSI and founding depth on displacements and storey drifts in sand

The models SG2, SPN2, SPAY2, SPBY2, SFN2, SFAY2 and SFBY2 have been analysed to investigate the effect of soil structure interaction and founding depth on displacement in sand. The maximum values of horizontal and vertical displacements are reported in Table 6.25. Fig. 6.23 shows the deflected shapes when the pile is taken for characteristic length, with discrete and continuum model for soil.

Table 6.25 Effect of fixity with and without SSI effect of **sand** on displacements

Depth of fixity			Max values of displacement (m)	
			Horizontal direction	Vertical direction
Ground Level			0.16	0.0069
Characteristic depth	Without SSI		0.1765	0.0077
	With SSI	Discrete model	0.1975	0.0464
		Continuum model	0.141	0.0682
Full depth	Without SSI		0.213	0.0092
	With SSI	Discrete model	0.178	0.02284
		Continuum model	0.128	0.0098

From the above table it is observed that the maximum value of displacement both in the horizontal and vertical direction increases with depth of fixity for discrete models for SSI effects compared to when the frame is assumed to be fixed at ground level while the continuum model shows a decrease. When SSI effects are considered the maximum values of displacements are reported when piles are fixed at characteristic depth.



a.Discrete model
Max. horizontal displacement:0.197m
Max.vertical displacement :0.046m

b.Continuum model
Max. horizontal displacement:0.141m
Max.vertical displacement :0.068m

Fig. 6.23 Deflected shapes with (a) discrete and (b) continuum model for **sand**

The storey drift for different models are given in Table 6.26.

Table 6.26. Storey drift for different models in **sand**

Floor Level	SG2	SPN2	SPAY2	SPBY2	SFN2	SFAY2	SFBY2
12	0.026	0.0233	0.0099	0.052	0.017	0.025	0.0169
11	0.0372	0.0339	0.0411	0.064	0.023	0.036	0.0242
10	-0.4772	0.03975	0.0516	-0.025	0.026	0.0461	0.033
9	0.5292	0.03055	0.058923	-0.055	0.026	0.05484	0.039
8	-0.0388	-0.0187	-0.06612	-0.029	0.024	-0.05734	-0.034
7	-0.043	-0.046	-0.0867	0.025	0.008	-0.0616	-0.0457
6	-0.0288	-0.0388	-0.0252	0.067	-0.009	-0.0416	-0.0305
5	-0.0051	-0.0222	-0.0146	-0.005	-0.016	-0.0104	-0.009
4	0.0229	1E-04	0.0154	-0.057	-0.019	0.021	0.013
3	0.047	0.0241	0.0403	-0.017	-0.02	0.04	0.0287
2	0.0577	0.0491	0.0585	0.028	-0.016	0.0549	0.0394
1	0.0329	0.0648	-0.1327	0.045	-0.013	0.0501	0.0348
GL	0	0.0366	0.216	0.048	0.182	0.012	0.0121

From the storey drift values it is observed that the frames not moving linearly in one direction. The positive and negative values indicate that certain floors are moving outward and others are moving inward with respect to the adjacent storeys. The storey drift values are representative of the deflected shape of the frames.

6.7.2.7 Influence of SSI on bending moments in piles

The variation of bending moments in piles with and without SSI effect of sand are shown in Fig. 6.24. Models SFN2and SFAY2 have been compared.

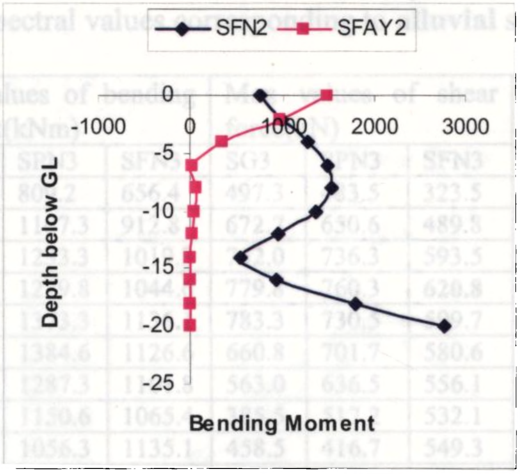


Fig. 6.24 Variation of bending moments along the **pile** with and without SSI of **sand**.

When soil structure interaction effects are included, it is observed that bending moments in piles are drastically reduced beyond characteristic depth.

6.7.3 Effect Of Soil Structure Interaction And Founding Depth In Alluvial Soil

The models SG3, SPN3, SPAY3, SPBY3, SFN3, SFAY3 and SFBY3 are analysed to investigate the effect of soil structure interaction and founding depth in alluvial soil. The results are presented and discussed in the subsequent sections. Bending moments, shear forces and axial forces in columns of the frame and the corresponding values in the beams for different models are compared. Displacements and storey drifts in the frame and bending moments in the pile are also reported.

6.7.3.1 Influence of founding depth without SSI

The analytical results of SG3, SPN3 and SFN3 are used to study the influence of founding depth without SSI. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 6.27a and the percentage variations of maximum responses with respect to SG3 are reported in Table 6.27b. The variations along the floor level is shown in Fig. 6.25.

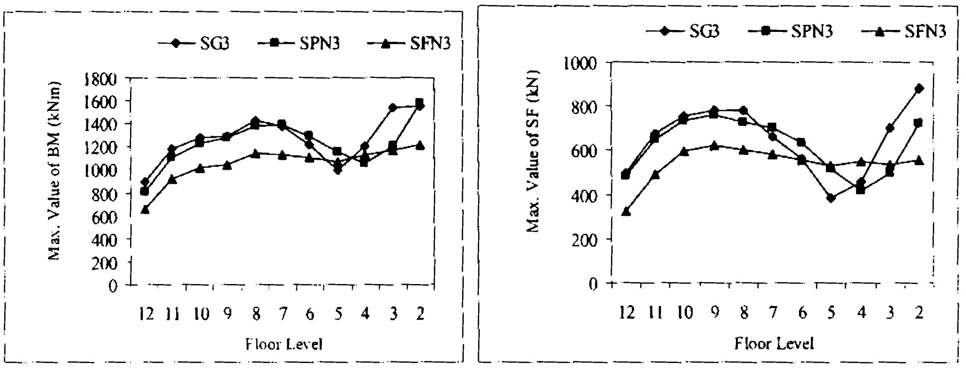
Table 6.27a Maximum values of bending moments, shear forces and axial forces in **columns** for different depths of fixity without SSI with spectral values corresponding to **alluvial** soil

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)			Max values of axial force(kN)		
	SG3	SPN3	SFN3	SG3	SPN3	SFN3	SG3	SPN3	SFN3
12	890.3	809.2	656.4	497.3	483.5	323.5	152.6	132.0	104.7
11	1185.5	1107.3	912.8	672.7	650.6	489.8	380.0	342.2	270.0
10	1279.2	1233.3	1019.3	752.0	736.3	593.5	624.4	617.7	496.8
9	1284.9	1279.8	1044.6	779.8	760.3	**620.8**	995.4	930.1	751.8
8	1426.8	1373.3	1136.1	783.3	730.5	599.7	1318.7	1260.3	1029.2
7	1380.6	1384.6	1126.6	660.8	701.7	580.6	1599.5	1569.6	1285.2
6	1220.0	1287.3	1101.8	563.0	636.5	556.1	1785.1	1809.8	1496.1
5	995.6	1150.6	1065.4	385.5	517.2	532.1	**1841.7**	1950.3	1656.5
4	1198.2	1056.3	1135.1	458.5	416.7	549.3	1742.5	**1952.5**	1766.9
3	1545.1	1207.8	1165.2	698.8	497.5	537.1	1531.8	1897.5	1851.5
2	1553.4	1575.5	1214.1	878.9	721.0	553.8	1255.2	1640.5	1905.5
1	**2948.3**	**1581.1**	**1331.2**	**904.2**	**765.8**	417.58	1033.6	1343.3	**1919.1**

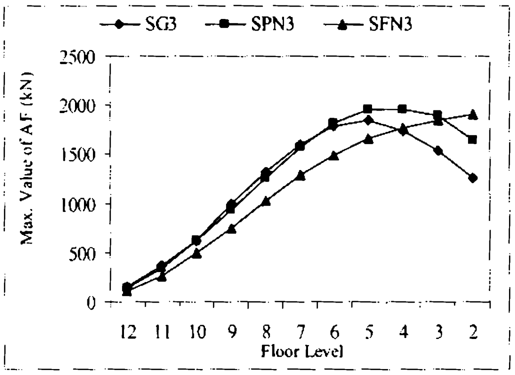
Table 6.27b Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 6.27a. and % variation with respect to SG3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG3	2948.3	
	SPN3	1581.1	-46.3
	SFN3	1331.2	-54.8
Shear force (kN)	SG3	904.2	
	SPN3	765.8	-15.3
	SFN3	620.8	-31.3
Axial force (kN)	SG3	1841.7	
	SPN3	1952.5	+6.0
	SFN3	1919.1	+4.2

There is a decrease of 46% for column bending moment when the pile length is taken as characteristic depth and 55% when pile is treated for full length showing that there is 9% variation in the maximum bending moment in the frame when no soil medium is considered. The corresponding variations in shear force is 15% and 31% showing an decrease of 16%. As for axial force it is 6% and 4% giving an variation of 2%.



a. Bending moment b. Shear force



c. Axial force

Fig. 6.25. Variation of maximum values of (a)bending moment, (b)shear force and (c)axial force in **columns** for different depths of fixity without SSI with spectral values corresponding to **alluvial** soil

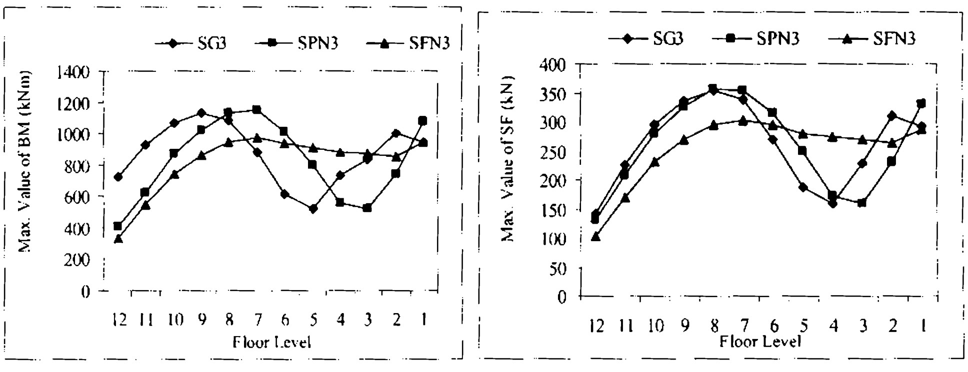
Maximum values of bending moments and shear forces in beams are reported in Table 6.28a and the percentage variations of maximum responses with respect to SG3 are reported in Table 6.28b. The variations along the floor level are shown in Fig. 6.26.

Table 6.28a. Maximum values of bending moments and shear forces in **beams** for different depths of fixity without SSI

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)		
	SG3	SPN3	SFN3	SG3	SPN3	SFN3
12	447.6	407.4	331.3	139.9	129.8	103.4
11	721.9	625.4	543.6	225.9	208.0	170.0
10	945.8	868.8	738.9	295.9	279.1	231.0
9	1071.6	1023.6	863.3	335.1	325.4	269.8
8	**1135.5**	1133.8	941.5	**354.9**	**356.8**	294.2
7	1087.4	**1148.0**	**971.8**	337.5	355.0	**303.6**
6	877.4	1012.5	940.5	270.1	315.2	293.7
5	608.6	801.7	904.9	187.2	248.6	280.5
4	516.4	553.1	882.3	159.5	171.2	274.3
3	736.8	516.6	870.2	228.2	160.1	270.3
2	1000.7	745.1	853.3	309.7	231.1	265.1
1	943.1	1075.1	945.9	291.3	330.6	287.8

Table 6.28b. Maximum values of bending moments and shear forces in **beams** given in Table 6.28a. and % variation with respect to SG3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG3	1135.5	
	SPN3	1148.0	+1.1
	SFN3	971.8	-14.4
Shear force (kN)	SG3	354.9	
	SPN3	356.8	+0.53
	SFN3	303.6	-14.4



a. Bending moment b. Shear force

Fig. 6.26 Variation of maximum values of(a) bending moment and (b)shear force in **beams** for different depths of fixity without SSI

The percentage variation of bending moment in beam is 1% when the pile length is taken as characteristic depth and 14% decrease when pile is treated for full length showing that there is 15% decrease in the maximum bending moment when no soil medium is considered. The corresponding variations in shear force is also 1% and 14% showing a decrease of 15%.

6.7.3.2 Influence of founding depth with SSI using discrete model for alluvial soil

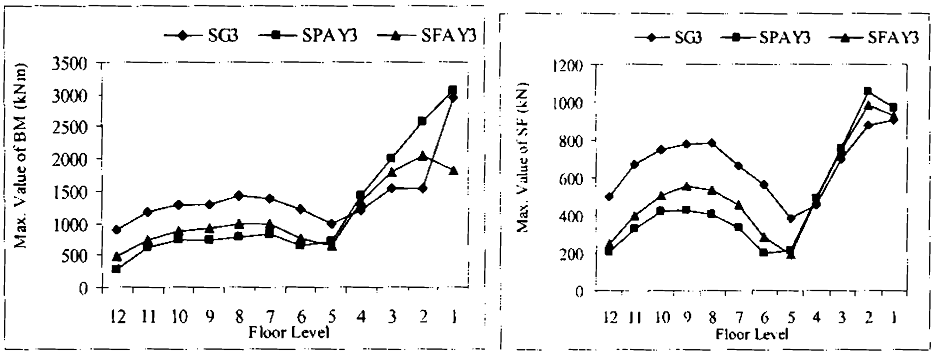
The analytical results of SG3, SPAY3 and SFAY3 are used to study the influence of founding depth with SSI using discrete model for alluvial soil. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 6.29a. and the percentage variations of maximum responses with respect to SG3 are reported in Table 6.29b. The variations along the floor level is shown in Fig. 6.27.

Table 6.29a. Maximum values of bending moments, shear forces and axial forces in **columns** for different depths of fixity with SSI using discrete model for **alluvial** soil

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)			Max values of axial force (kN)		
	SG3	SPAY3	SFAY3	SG3	SPAY3	SFAY3	SG3	SPAY3	SFAY3
12	890.3	269.6	483.5	497.3	203.9	251.9	152.6	179.7	174.7
11	1185.5	625.7	743.6	672.7	327.5	397.0	380.0	402.6	322.9
10	1279.2	734.9	878.2	752.0	420.2	508.6	624.4	672.8	598.2
9	1284.9	747.9	918.5	779.8	427.0	556.0	995.4	975.8	982.2
8	1426.8	790.3	998.9	783.3	410.1	533.8	1318.7	1305.7	1333.0
7	1380.6	820.3	985.8	660.8	336.2	458.0	1599.5	1613.5	1661.2
6	1220.0	633.6	768.8	563.0	197.7	287.6	1785.1	1845.6	1828.3
5	995.6	718.2	648.6	385.5	213.2	190.2	**1841.7**	**1958.7**	**2017.4**
4	1198.2	1418.1	1333.2	458.5	491.0	484.1	1742.5	1924	1972.1
3	1545.1	1995.2	1796.3	698.8	757.5	747.9	1531.8	1749.1	1788.5
2	1553.4	2579.7	**2041.9**	878.9	**1055.7**	**986.4**	1255.2	1415.2	1478.2
1	**2948.3**	**3060.3**	1813.2	**904.2**	968.5	931.3	1033.6	899.3	1080.3

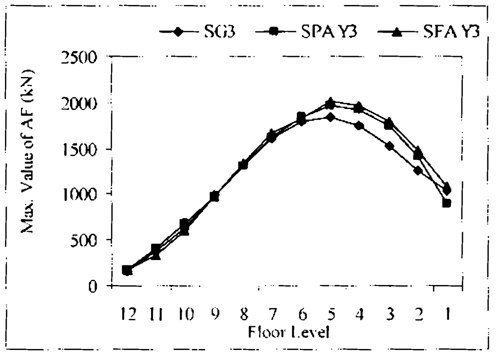
Table 6.29b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 6.29a. and % variation with respect to SG3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG3	2948.3	
	SPAY3	3060.3	+3.7
	SFAY3	2041.9	-30.7
Shear force (kN)	SG3	904.2	
	SPAY3	1055.7	+16.7
	SFAY3	986.4	+9.0
Axial force (kN)	SG3	1841.7	
	SPAY3	1958.7	+6.3
	SFAY3	2017.4	+9.5



a. Bending moment

b. Shear force



c. Axial force

Fig. 6.27 Variation of maximum values of (a)bending moment,(b) shear force and (c)axial force in **columns** for different depths of fixity with SSI using discrete model for **alluvial** soil

There is an increase of 4% for column bending moment when the pile length is taken as characteristic depth and 31% decrease when pile is treated for full length showing that there is 35% decrease in the maximum bending moment in the frame when discrete model for soil is considered. The corresponding variations in shear force are an increase of 17% and 9%

showing a decrease of 8%. As for axial force it is 6% and 10% giving a increase of 4%. The bending moment and shear force have been observed to decrease when the depth of pile is taken from characteristic depth to full depth. This validates the concept of characteristic depth in the design regarding force output.

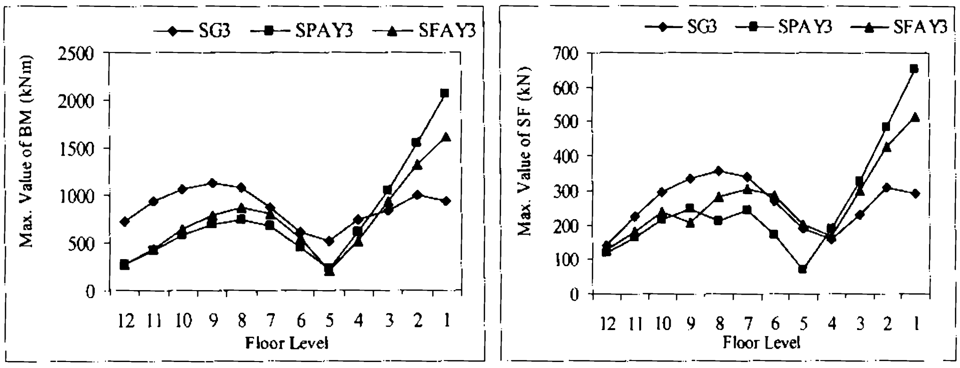
Maximum values of bending moments and shear forces in beams are reported in Table 6.30a and the percentage variations of maximum responses with respect to SG3 are reported in Table 6.30b. The variations along the floor level are shown in Fig. 6.28.

Table 6.30a Maximum values of bending moments and shear force in **beams** for different depths of fixity with SSI using discrete model for **alluvial** soil

Floor Level	Max values of bending moment (kNm)			Max values of shear force(kN)		
	SG3	SPAY3	SFAY3	SG3	SPAY3	SFAY3
12	447.6	269.6	276.7	139.9	120.5	126.8
11	721.9	412.8	443.1	225.9	165.0	178.8
10	945.8	573.5	640.2	295.9	213.6	238.5
9	1071.6	685.5	783.1	335.1	247.5	207.4
8	**1135.5**	743.3	864.5	**354.9**	213.0	281.8
7	1087.4	683.0	807.5	337.5	244.1	305.7
6	877.4	450.1	544.3	270.1	170.0	286.5
5	608.6	229.2	217.4	187.2	71.1	203.4
4	516.4	613.2	513.3	159.5	191.1	165.9
3	736.8	1044.3	927.5	228.2	326.6	298.3
2	1000.7	1547.0	1326.3	309.7	482.9	424.9
1	943.1	**2060.5**	**1609.0**	291.3	**652.3**	**514.8**

Table 6.30b. Maximum values of bending moments and shear force in **beams** given in Table 6.30a and % variation with respect to SG3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG3	1135.5	
	SPAY3	2060.5	+81.4
	SFAY3	1609.0	+41.6
Shear force (kN)	SG3	354.9	
	SPAY3	652.3	+83.7
	SFAY3	514.8	+45.0



a. Bending moment b. Shear force

Fig. 6.28 Variation of maximum values of(a) bending moment and (b)shear force in **beams** for different depths of fixity with SSI using discrete model for **alluvial** soil

There is 81% increase for beam bending moment when the pile length is taken as characteristic depth and 42% when pile is treated for full length showing that there is 39% decrease in the maximum bending moment when discrete model for soil is considered. The corresponding variations in shear force are 84% and 45% showing a decrease of 39%. The responses in the beams have reduced when pile is taken from characteristic to full depth. As in the case of responses in columns this validates the concept of characteristic depth in the design regarding force output.

6.7.3.3 Influence of founding depth with SSI using continuum model for alluvial soil

The analytical results of SG3, SPBY3 and SFBY3 are used to study the influence of founding depth with SSI using continuum model for alluvial soil. Models with fixity at ground level, at characteristic depth and at full depth are studied herein. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 6.31a. and the percentage variations of maximum responses with respect to SG3 are reported in Table 6.31b. The variations along the floor level are shown in Fig. 6.29.

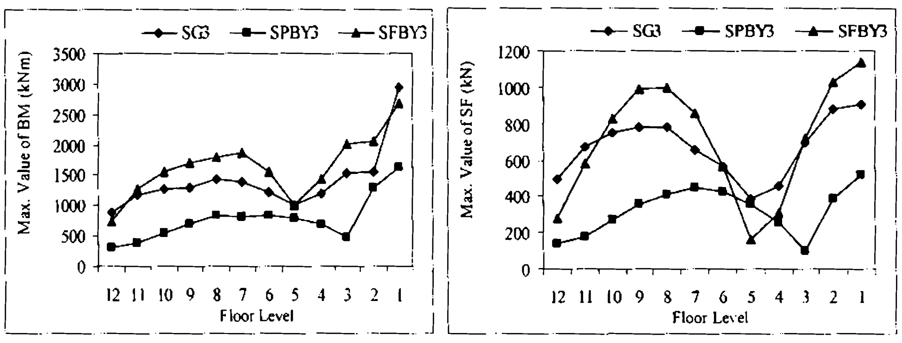
Table 6.31a. Maximum values of bending moments, shear forces and axial forces in **columns** for different depths of fixity with SSI using continuum model for **alluvial** soil

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)			Max values of axial force(kN)		
	SG3	SPBY3	SFBY3	SG3	SPBY3	SFBY3	SG3	SPBY3	SFBY3
12	890.3	306.5	748.4	497.3	137.2	281.2	152.6	69.8	156.1
11	1185.5	387.5	1267.4	672.7	178.4	584.5	380.0	155.1	406.9
10	1279.2	547.5	1569.1	752.0	268.7	831.0	624.4	217.9	772.4
9	1284.9	692.6	1709.4	779.8	357.7	987.8	995.4	261.7	1233.0
8	1426.8	848.2	1797.7	783.3	411.1	997.3	1318.7	304.0	1763.2
7	1380.6	824.4	1870.1	660.8	448.1	861.9	1599.5	364.8	2295.0
6	1220.0	844.6	1565.5	563.0	429.4	564.1	1785.1	447.7	2716.0
5	995.6	783.6	1006.9	385.5	353.3	164.6	**1841.7**	534.5	**2945.1**
4	1198.2	704.6	1444.6	458.5	258.7	310.3	1742.5	602.0	2925.3
3	1545.1	470.4	2002.5	698.8	99.6	718.2	1531.8	649.4	2715.7
2	1553.4	1300.1	2068.3	878.9	389.9	1032.1	1255.2	681.8	2353.5
1	**2948.3**	**1633.6**	**2675.2**	**904.2**	**516.2**	**1139.6**	1033.6	**705.5**	1939.0

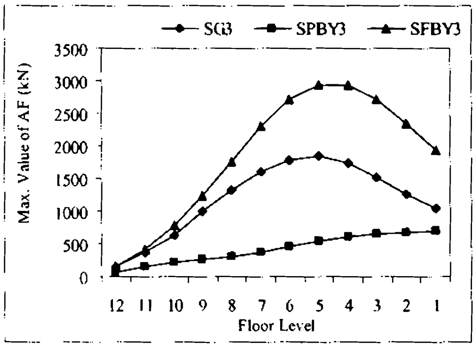
Table 6.31b Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 6.31a and % variation with respect to SG3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG3	2948.3	
	SPBY3	1633.6	-44.5
	SFBY3	2675.2	-9.2
Shear force (kN)	SG3	904.2	
	SPBY3	516.2	-42.9
	SFBY3	1139.6	+26.0
Axial force (kN)	SG3	1841.7	
	SPBY3	705.5	-61.6
	SFBY3	2945.1	+59.9

There is a decrease of 45% for column bending moment when the pile length is taken as characteristic depth and 9% when pile is treated for full length showing that there is 36% variation in the maximum bending moment in the frame when continuum model for soil is considered. The corresponding variations in shear force are a decrease of 43% and an increase of 26% showing a variation of 69%. As for axial force it is 62% and 60% giving an increase of 112%. It is observed that even when the bending moment shows considerable decrease, the shear force and axial force shows an increase when the pile length is taken from characteristic depth to full depth using continuum model.



a. Bending moment b. Shear force



c. Axial force

Fig. 6.29 Variation of maximum values of (a)bending moment,(b) shear force and axial force in **columns** for different depths of fixity with SSI using continuum model for **alluvial** soil.

Maximum values of bending moments and shear forces in beams are reported in Table 6.32a and the percentage variations of maximum responses with respect to SG3 are reported in Table 6.32b. The variations along the floor level are shown in Fig. 6.30.

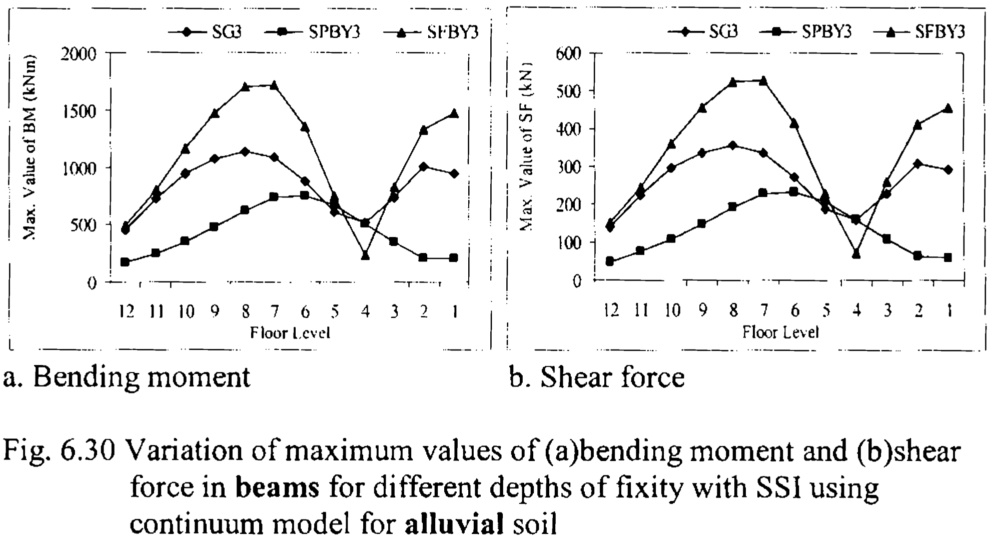
Table 6.32a. Maximum values of bending moments and shear forces in **beams** for different depths of fixity with SSI using continuum model for **alluvial** soil

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	SG3	SPBY3	SFBY3	SG3	SPBY3	SFBY3
12	447.6	164	496.3	139.9	49.5	150.7
11	721.9	242.1	794.0	225.9	75.1	244.7
10	945.8	349.3	1167.2	295.9	108.5	359.5
9	1071.6	477.5	1475.8	335.1	148.6	454.9
8	**1135.5**	616.4	1703.5	**354.9**	192.1	524.6
7	1087.4	730.8	**1714.7**	337.5	227.8	**527.3**
6	877.4	**748.1**	1359.1	270.1	**233.3**	417.9
5	608.6	669.3	742.6	187.2	208.6	227.9
4	516.4	507.8	237.4	159.5	158.2	73.4
3	736.8	344.4	832.1	228.2	107.2	259.6
2	1000.7	211.5	1323.4	309.7	65.0	412.6
1	943.1	210.2	1466.1	291.3	61.5	457.9

Table 6.32b Maximum values of bending moments and shear forces in **beams** given in Table 6.32a. and % variation with respect to SG3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SG3	1135.5	
	SPBY3	748.1	-34.1
	SFBY3	1714.7	+51
Shear force (kN)	SG3	354.9	
	SPBY3	233.3	-34.2
	SFBY3	527.3	+48.5

There is 34% decrease for beam bending moment when the pile length is taken as characteristic depth and 51% increase when pile is treated for full length showing that there is 85% increase in the maximum bending moment when continuum model for soil is considered. The corresponding variations in shear force are 34% and 49% showing a variation of 83%.



a. Bending moment b. Shear force

Fig. 6.30 Variation of maximum values of (a)bending moment and (b)shear force in **beams** for different depths of fixity with SSI using continuum model for **alluvial** soil

6.7.3.4 Influence of SSI of alluvial soil when piles are fixed at characteristic depth

The analytical results of SPN3, SPAY3 and SPBY3 are used to study the influence of SSI using discrete and continuum model for alluvial soil when piles are fixed at characteristic depth. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 6.33a and the percentage variations of maximum responses with respect to SPN3 are reported in Table 6.33b. The variations along the floor level are shown in Fig. 6.31.

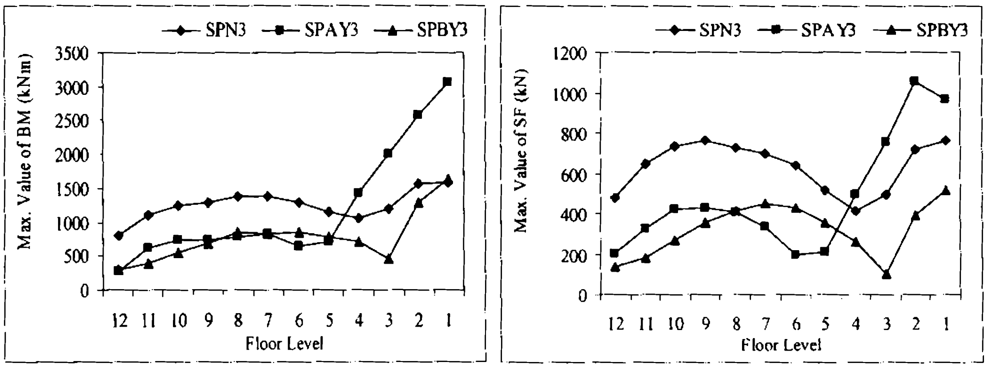
Table 6.33a Maximum values of bending moment, shear forces and axial forces in **columns** for different models for **alluvial** soil when fixed at characteristic depth

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)			Max values of axial force(kN)		
	SPN3	SPAY3	SPBY3	SPN3	SPAY3	SPBY3	SPN3	SPAY3	SPBY3
12	809.2	269.6	306.5	483.5	203.9	137.2	132.0	179.7	69.8
11	1107.3	625.7	387.5	650.6	327.5	178.4	342.2	402.6	155.1
10	1233.3	734.9	547.5	736.3	420.2	268.7	617.7	672.8	217.9
9	1279.8	747.9	692.6	760.3	427.0	357.7	930.1	975.8	261.7
8	1373.3	790.3	848.2	730.5	410.1	411.1	1260.3	1305.7	304.0
7	1384.6	820.3	824.4	701.7	336.2	448.1	1569.6	1613.5	364.8
6	1287.3	633.6	844.6	636.5	197.7	429.4	1809.8	1845.6	447.7
5	1150.6	718.2	783.6	517.2	213.2	353.3	1950.3	**1958.7**	534.5
4	1056.3	1418.1	704.6	416.7	491.0	258.7	**1952.5**	1924.0	602.0
3	1207.8	1995.2	470.4	497.5	757.5	99.6	1897.5	1749.1	649.4
2	1575.5	2579.7	1300.1	721.0	**1055.7**	389.9	1640.5	1415.2	681.8
1	**1581.1**	**3060.3**	**1633.6**	**765.8**	968.5	**516.2**	1343.3	899.3	**705.5**

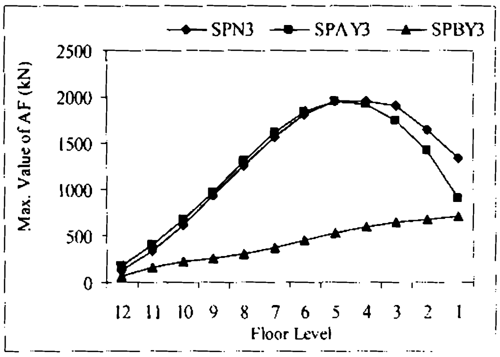
Table 6.33b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 6.33a and % variation with respect to SG3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SPN3	1581.1	
	SPAY3	3060.3	+93.5
	SPBY3	1633.6	+3.3
Shear force (kN)	SPN3	765.8	
	SPAY3	1055.7	+37.8
	SPBY3	516.2	-32.5
Axial force (kN)	SPN3	1952.5	
	SPAY3	1958.7	+0.3
	SPBY3	705.5	-63.8

There is an increase of 94% for column bending moment when modeled using discrete elements and 3% using continuum elements showing that there is 91% variation in the maximum bending moment in the frame when two models for soil are considered. The corresponding variations in shear force is an increase of 38% and decrease of 33% showing a variation of 71%. As for axial force it is 0% and 64% giving a variation of 64%. In this case the discrete model is giving higher values when the pile length is taken for characteristic depth.



a. Bending moment b. Shear force



c. Axial Force

Fig. 6.31 Variation of maximum values of (a)bending moment, (b)shear force and (c)axial force in **columns** for different models for **alluvial** soil when fixed at characteristic depth.

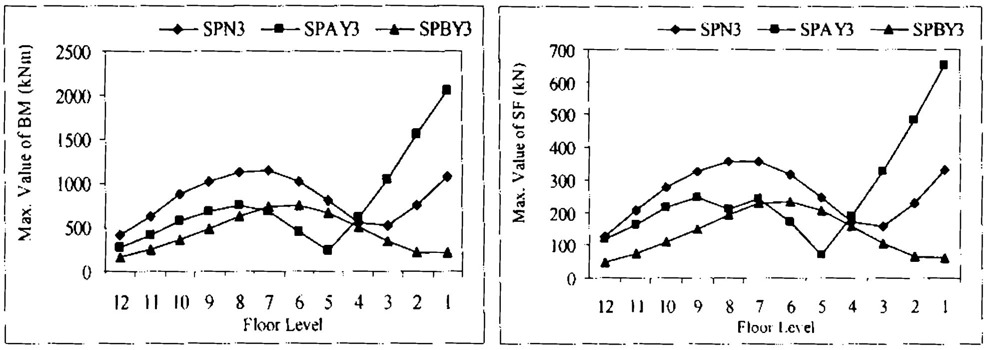
Maximum values of bending moments and shear forces in beams are reported in Table 6.34a and the percentage variations of maximum responses with respect to SPN3 are reported in Table 6.34b. The variations along the floor level are shown in Fig. 6.32.

Table 6.34a Maximum values of bending moments and shear forces in **beams** for different models for **alluvial** soil when fixed at characteristic depth

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)		
	SPN3	SPAY3	SPBY3	SPN3	SPAY3	SPBY3
12	407.4	269.6	164.0	129.8	120.5	49.5
11	625.4	412.8	242.1	208.0	165.0	75.1
10	868.8	573.5	349.3	279.1	213.6	108.5
9	1023.6	685.5	477.5	325.4	247.5	148.6
8	1133.8	743.3	616.4	**356.8**	213	192.1
7	**1148.0**	683.0	730.8	355.0	244.1	227.8
6	1012.5	450.1	**748.1**	315.2	170.0	**233.3**
5	801.7	229.2	669.3	248.6	71.1	208.6
4	553.1	613.2	507.8	171.2	191.1	158.2
3	516.6	1044.3	344.4	160.1	326.6	107.2
2	745.1	1547.0	211.5	231.1	482.9	65.0
1	1075.1	**2060.5**	210.2	330.6	**652.3**	61.5

Table 6.34b Maximum values of bending moments and shear forces in **beams** given in Table 6.34a and % variation with respect to SG3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SPN3	1148.0	
	SPAY3	2060.5	+79.4
	SPBY3	748.1	-34.8
Shear force (kN)	SPN3	356.8	
	SPAY3	652.3	+82.8
	SPBY3	233.3	-34.6



a. Bending moment b. Shear force

Fig. 6.32 Variation of maximum values of(a) bending moment and(b) shear force in **beams** for different models for **alluvial** soil when fixed at characteristic depth.

There is 79% increase for beam bending moment when modeled using discrete elements and 35%decrease using continuum elements showing that there is 114% variation in the maximum bending moment when two models for soil are considered. The corresponding variations in shear force are 83% and 35% showing a variation of 118%. The two models show wide variation with discrete model giving upper bound values.

6.7.3.5 Influence of SSI of alluvial soil considering full depth of piles

The analytical results of SFN3, SFAY3 and SFBY3 are used to study the influence of SSI using discrete and continuum model for alluvial soil when piles are fixed at full depth. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 6.35a and the percentage variations of maximum responses with respect to SFN3 are reported in Table 6.35b. The variations along the floor level are shown in Fig. 6.33.

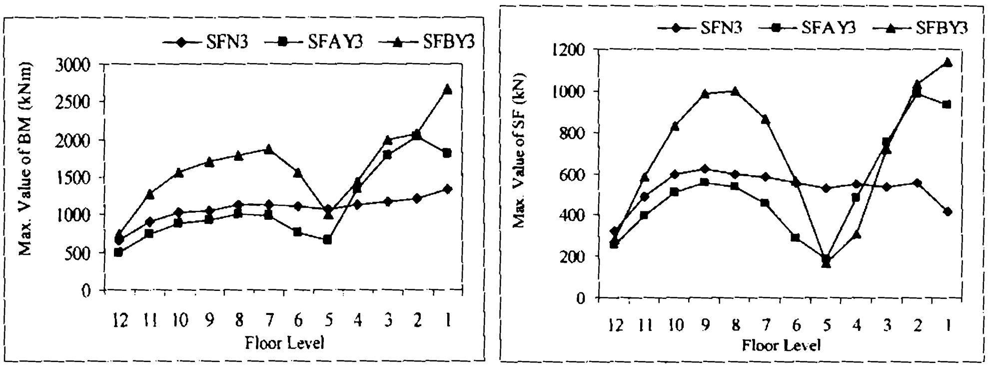
Table 6.35a Maximum values of bending moments, shear forces and axial forces in **columns** for different models for **alluvial** soil when fixed at full depth

Floor Level	Max values of bending moment(kNm)			Max values of shear force(kN)			Max values of axial force(kN)		
	SFN3	SFAY3	SFBY3	SFN3	SFAY3	SFBY3	SFN3	SFAY3	SFBY3
12	656.4	483.5	748.4	323.5	251.9	281.2	104.7	174.7	156.1
11	912.8	743.6	1267.4	489.8	397.0	584.5	270.0	322.9	406.9
10	1019.3	878.2	1569.1	593.5	508.6	831.0	496.8	598.2	772.4
9	1044.6	918.5	1709.4	**620.8**	556.0	987.8	751.8	982.2	1233.0
8	1136.1	998.9	1797.7	599.7	533.8	997.3	1029.2	1333.0	1763.2
7	1126.6	985.8	1870.1	580.6	458.0	861.9	1285.2	1661.2	2295.0
6	1101.8	768.8	1565.5	556.1	287.6	564.1	1496.1	1828.3	2716.0
5	1065.4	648.6	1006.9	532.1	190.2	164.6	1656.5	**2017.4**	**2945.1**
4	1135.1	1333.2	1444.6	549.3	484.1	310.3	1766.9	1972.1	2925.3
3	1165.2	1796.3	2002.5	537.1	747.9	718.2	1851.5	1788.5	2715.7
2	1214.1	**2041.9**	2068.3	553.8	**986.4**	1032.1	1905.5	1478.2	2353.5
1	**1331.2**	1813.2	**2675.2**	417.58	931.3	**1139.6**	**1919.1**	1080.3	1939.0

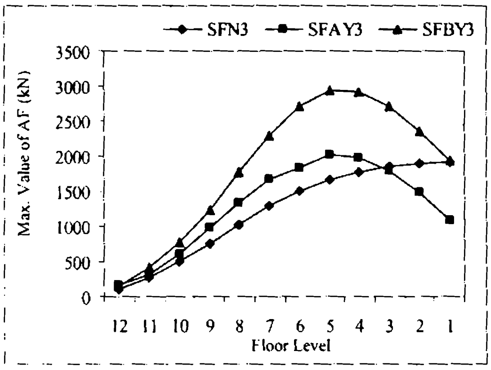
Table 6.35b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 6.35a. and % variation with respect to SFN3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SFN3	1331.2	
	SFAY3	2041.9	+53.3
	SFBY3	2675.2	+100
Shear force (kN)	SFN3	620.8	
	SFAY3	986.4	+58.8
	SFBY3	1139.6	+83.5
Axial force (kN)	SFN3	1919.1	
	SFAY3	2017.4	+5.1
	SFBY3	2945.1	+53.4

There is an increase of 53% for column bending moment when the full depth of pile is considered using discrete model and 100% using continuum model of soil giving a variation of 47% for the two models. The corresponding variations in shear force is 59% and 84% showing a variation of 25%. As for axial force it is 5% and 53% giving a variation of 48%.



a. Bending moment b. Shear force



c. Axial force

Fig. 6.33 Variation of maximum values of (a)bending moment,(b) shear force and (c)axial force in **columns** for different models for alluvial soil when fixed at full depth.

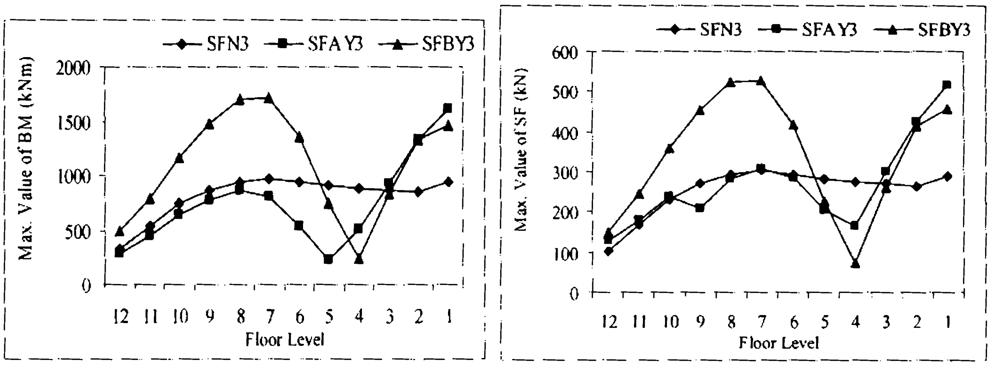
Maximum values of bending moments and shear forces in beams are reported in Table 6.36a. and the percentage variations of maximum responses with respect to SFN3 are reported in Table 6.36b. The variations along the floor level are shown in Fig. 6.34.

Table 6.36a. Maximum values of bending moments and shear forces in **beams** for different models for **alluvial** soil when fixed at full depth

Floor Level	Max values of bending moment (kNm)			Max values of shear force(kN)		
	SFN3	SFAY3	SFBY3	SFN3	SFAY3	SFBY3
12	331.3	276.7	496.3	103.4	126.8	150.7
11	543.6	443.1	794.0	170.0	178.8	244.7
10	738.9	640.2	1167.2	231.0	238.5	359.5
9	863.3	783.1	1475.8	269.8	207.4	454.9
8	941.5	864.5	1703.5	294.2	281.8	524.6
7	**971.8**	807.5	**1714.7**	**303.6**	305.7	**527.3**
6	940.5	544.3	1359.1	293.7	286.5	417.9
5	904.9	217.4	742.6	280.5	203.4	227.9
4	882.3	513.3	237.4	274.3	165.9	73.4
3	870.2	927.5	832.1	270.3	298.3	259.6
2	853.3	1326.3	1323.4	265.1	424.9	412.6
1	945.9	**1609.0**	1466.1	287.8	**514.8**	457.9

Table 6.36b Maximum values of bending moments and shear forces in **beams** given in Table 6.36a and % variation with respect to SFN3

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SFN3	971.8	
	SFAY3	1609.0	+65.5
	SFBY3	1714.7	+76.4
Shear force (kN)	SFN3	303.6	
	SFAY3	514.8	+69.5
	SFBY3	527.3	+73.6



a. Bending moment b. Shear force

Fig. 6.34 Variation of maximum values of(a) bending moment and (b)shear force in **beams** for different models for **alluvial** soil when fixed at full depth

There is an increase of 66% for beam bending moment when modeled using discrete elements and 76% using continuum elements giving a variation of 10%. The corresponding variations in shear force are 70% and 74% giving a variation of 4%. It has been observed that more congruence is shown by the two models regarding responses in the beam compared to the column.

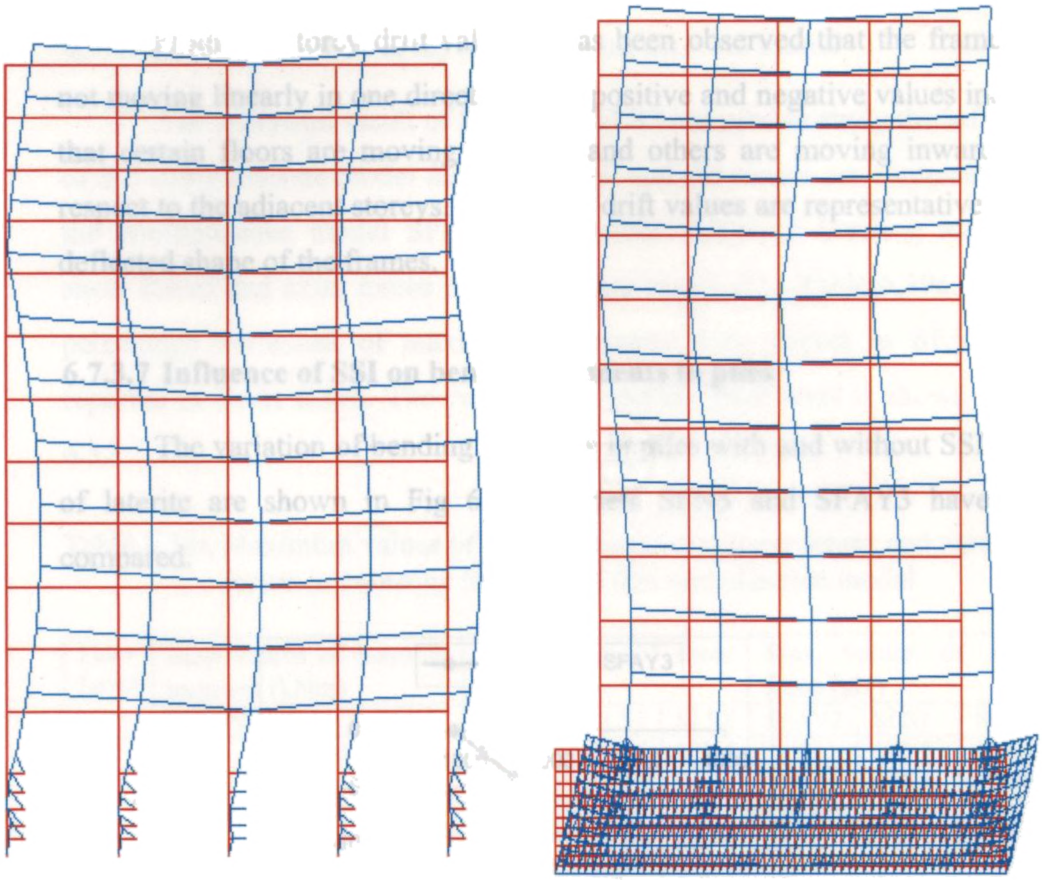
6.7.3.6 Influence of SSI and founding depth on displacements and storey drifts in alluvial soil

The models SG3, SPN3, SPAY3, SPBY3, SFN3, SFAY3 and SFBY3 are analysed to investigate the effect of soil structure interaction and founding depth on displacements in alluvial soil. The maximum values of horizontal and vertical displacements are reported in Table 6.37. Fig. 6.35 shows the deflected shapes when the pile is taken for characteristic length with discrete and continuum model for soil.

Table 6.37. Effect of fixity with and without SSI effect of **alluvial** soil on displacements.

Depth of fixity			Max values of displacement (m)	
			Horizontal direction	Vertical direction
Ground Level			0.196	0.0070
Characteristic depth	Without SSI		0.218	0.0091
	With SSI	Discrete model	0.317	0.1930
		Continuum model	0.153	0.0620
Full depth	Without SSI		0.263	0.0250
	With SSI	Discrete model	0.267	0.1270
		Continuum model	0.298	0.0100

From the above table it has been observed that the maximum value of displacement both in the horizontal and vertical direction increases with depth of fixity for both models for SSI effects compared to when the frame is assumed to be fixed at ground level. High values of vertical displacements are observed with discrete model for soil.



a.Discrete model
Max.horizontal displacement:0.317m
Max. vertical displacement: 0.193m

b.Continuum model
Max.horizontal displacement:0.153m
Max. vertical displacement: 0.062m

Fig. 6.35 Deflected shapes for (a) discrete and (b) continuum model for **alluvial** soil

The storey drift for different models is given in Table 6.38

Table 6.38. Storey drift for different models in **alluvial** soil

Floor Level	SG3	SPN3	SPAY3	SPBY3	SFN3	SFAY3	SFBY3
12	0.032	0.029	0.061	-0.0091	0.02	0.049	0.036
11	-0.7489	0.041	0.071	-0.0029	0.028	0.06	0.056
10	0.8415	0.0481	0.078	0.003	0.033	0.0688	0.076
9	0.0238	-0.4791	0.0279	0.012	0.033	0.0407	0.092
8	-0.0506	0.5015	-0.0989	0.024	0.032	-0.0905	-0.074
7	-0.0588	-0.0615	-0.089	0.006	0.009	-0.081	-0.108
6	-0.037	-0.051	-0.066	-0.027	-0.012	-0.055	-0.072
5	-0.003	-0.027	-0.033	-0.019	-0.022	-0.02	-0.02
4	0.029	0.001	0.001	-0.005	-0.023	0.015	0.033
3	0.057	0.031	0.034	0.008	-0.024	0.045	0.072
2	0.07	0.06	0.073	0.016	-0.019	0.072	0.0969
1	0.04	-0.325	0.1215	-0.001	-0.017	0.0834	0.0801
GL	0	0.45	0.0875	0.041	0.225	0.0516	0.016

From the storey drift values it has been observed that the frames are not moving linearly in one direction. The positive and negative values indicate that certain floors are moving outward and others are moving inward with respect to the adjacent storeys. The storey drift values are representative of the deflected shape of the frames.

6.7.3.7 Influence of SSI on bending moments in piles

The variation of bending moments in piles with and without SSI effect of laterite are shown in Fig 6.36. Models SFN3 and SFAY3 have been compared.

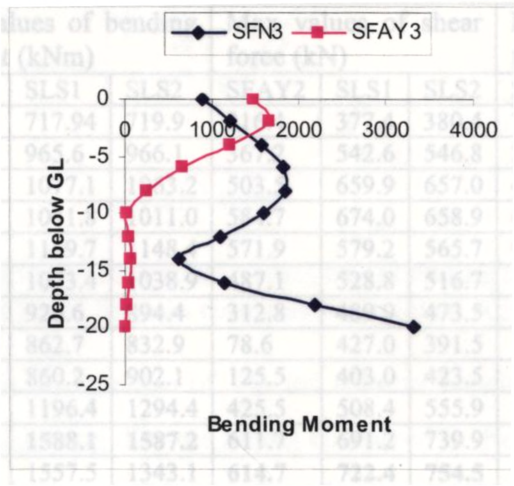


Fig. 6.36 Variation of bending moments along the **pile**

It has been observed that the pile is subjected to high values of bending moment up to considerable depth.

6.7.4 Effect Of Soil Structure Interaction In Layered Soil

The layered soil models SLS1, SLS2, SLSB1, SLSB2 and the homogeneous models SFAY2, SFBY2 are analysed to investigate the effect of soil structure interaction in layered soil. The results are presented and discussed in the subsequent sections.

6.7.4.1 Influence of SSI of layered soil with discrete model

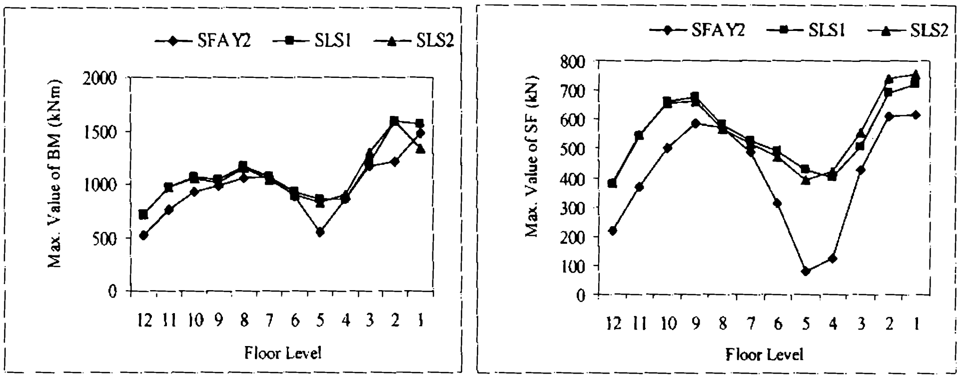
The analytical result of SLS1 and SLS2 are used to study the influence of SSI using discrete model for layered soil and the results are compared with the homogeneous model SFAY2. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 6.39a. and the percentage variations of maximum responses with respect to SFAY2 are reported in Table 6.39b. The variations along the floor level is shown in Fig. 6.37.

Table 6.39a Maximum values of bending moments, shear forces and axial forces in **columns** for **layered** soil with discrete model

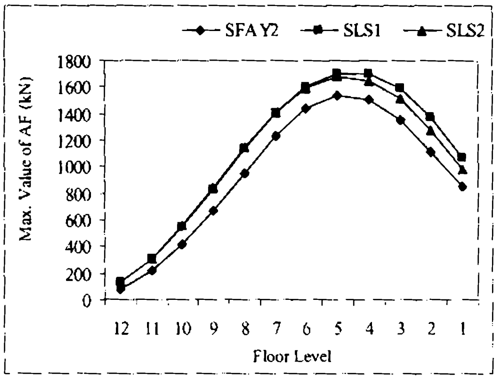
Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)			Max values of axial force (kN)		
	SFAY2	SLS1	SLS2	SFAY2	SLS1	SLS2	SFAY2	SLS1	SLS2
12	527.2	717.94	719.9	216.4	377.4	380.4	79.8	129.5	133.6
11	762.9	965.6	966.1	367.2	542.6	546.8	216.2	301.1	309.0
10	926.4	1077.1	1063.2	503.5	659.9	657.0	415.4	542.1	553.3
9	988.9	1041.8	1011.0	584.7	674.0	658.9	664.7	827.3	837.8
8	1050.1	1169.7	1148.4	571.9	579.2	565.7	949.1	1133.7	1140.2
7	1072.9	1073.4	1038.9	487.1	528.8	516.7	1229.6	1407.0	1404.8
6	887.8	926.6	894.4	312.8	489.9	473.5	1442.5	1604.0	1589.6
5	555.4	862.7	832.9	78.6	427.0	391.5	**1543.0**	**1705.7**	**1675.1**
4	861.4	860.2	902.1	125.5	403.0	423.5	1500.6	1699.8	1647.3
3	1173.8	1196.4	1294.4	425.5	508.4	555.9	1350.1	1592	1514.1
2	1208.3	**1588.1**	**1587.2**	611.7	691.2	739.9	1112.1	1375.2	1277.6
1	**1482.0**	1557.5	1343.1	**614.7**	**722.4**	**754.5**	846.7	1068.1	976.5

Table 6.39b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 6.39a. and % variation with respect to SFAY2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SFAY2	1482.0	
	SLS1	1588.1	+7.1
	SLS2	1587.2	+7.0
Shear force (kN)	SFAY2	614.7	
	SLS1	722.4	+17.5
	SLS2	754.5	+22.7
Axial force (kN)	SFAY2	1543.0	
	SLS1	1705.7	+10.5
	SLS2	1675.1	+8.5



a. Bending moment b. Shear force



c. Axial force

Fig. 6.37 Variation of maximum values of(a) bending moment,(b) shear force and (c)axial force in **columns** for **layered** soil with discrete model

There is an increase of 7% for column bending moment for the two types of layering using discrete model compared to the homogeneous medium. The corresponding variations in shear force is an increase of 18% and 23% showing a variation of 5%. As for axial force it is 11% and 9% giving a variation of 2%. It has been observed that considerable variation is shown only for shear force for the two types of layering. But the responses are higher compared to the homogeneous medium.

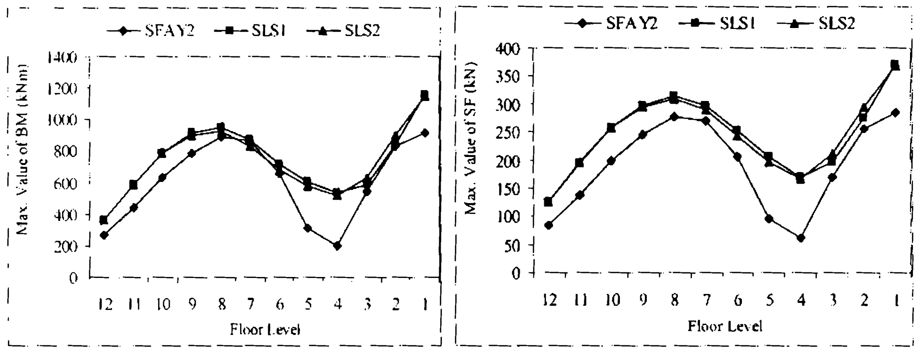
Maximum values of bending moments and shear forces in beams are reported in Table 6.40a and the percentage variations of maximum responses with respect to SFAY2 are reported in Table 6.40b. The variations along the floor level are shown in Fig. 6.38.

Table 6.40a Maximum values of bending moments and shear forces in **beams** for **layered** soil with discrete model

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	SFAY2	SLS1	SLS2	SFAY2	SLS1	SLS2
12	267.8	366.5	367.0	83.0	124.9	125.5
11	444	585.7	586.9	138.5	194.3	195.1
10	634.1	790.5	787.7	197.9	258.8	258.4
9	788.1	912.6	899.5	246.0	297.6	294.3
8	887.1	947.7	920.6	277.4	313.0	308.3
7	866.7	869.4	829.6	270.6	296.3	288.6
6	657.1	713.9	684.2	205.1	251.9	242.9
5	309.2	608.2	575.7	96.3	207.3	195.1
4	197.2	532.3	518.7	61.0	169.5	168.0
3	546.2	591.4	632.3	169.2	195.9	210.2
2	826.1	839.8	902.8	256.0	274.9	295.0
1	**917.2**	**1159.3**	**1151.2**	**283.7**	**369.8**	**368.4**

Table 6.40b.Maximum values of bending moments and shear forces in **beams** given in Table 6.40a.and % variation with respect to SFAY2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SFAY2	917.2	
	SLS1	1159.3	+26.3
	SLS2	1151.2	+25.5
Shear force (kN)	SFAY2	283.7	
	SLS1	369.8	+30.4
	SLS2	368.4	+29.8



a. Bending moment b. Shear force

Fig. 6.38 Variation of maximum values of (a)bending moment and(b) shear force in **beams** for **layered** soil with discrete model

When SSI effects are included using discrete model both types of layered soil showed an increase in the stresses in the beams and columns compared to the homogeneous medium. The percentage variation of maximum bending moment in beam is an increase of 26% for both types of layering when modeled using discrete elements. The corresponding variation in shear force is 30% for both the models.

6.7.4.2 Influence of SSI of layered soil with continuum model

The analytical result of SLSB1 and SLSB2 are used to study the influence of SSI using continuum model for layered soil and the results are compared with the homogeneous model SFBY2. Maximum values of bending moments, shear forces and axial forces in columns are reported in Table 6.41a. and the percentage variations of maximum responses with respect to SFBY2 are reported in Table 6.41b. The variations along the floor level are shown in Fig. 6.39.

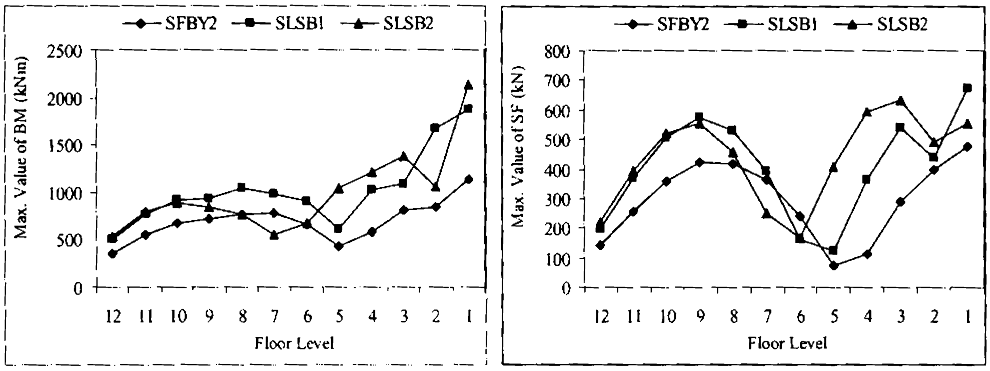
Table 6.41a. Maximum values of bending moments, shear forces and axial forces in **columns** for **layered** soil with continuum model

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)			Max values of axial force (kN)		
	SFBY2	SLSB1	SLSB2	SFBY2	SLSB1	SLSB2	SFBY2	SLSB1	SLSB2
12	356.2	500.7	535.9	141.5	198.0	218.5	58.9	81.7	136.1
11	544.6	765.9	792.4	257.5	367.4	393.9	158.1	213.0	327.5
10	668.1	916.8	896.4	358.6	507.3	522.2	303.8	406.1	579.0
9	722.0	931.9	840.9	421.5	575.9	553.2	487.7	644.2	864.5
8	760.3	1046.0	770.1	419.0	532.3	454.8	699.2	903.0	1147.3
7	786.9	980.0	558.7	362.1	393.7	249.8	910.7	1133.0	1367.9
6	661.1	904.2	673.4	239.3	162.0	165.0	1075.7	1270.1	**1468.5**
5	428.1	615.9	1043.7	72.10	123.8	408.6	**1161.2**	**1279.4**	1435.4
4	576.6	1031.0	1212.9	114.7	363.8	594.9	1143.6	1154.0	1297.2
3	813.2	1083.4	1382.6	287.5	540.7	**633.9**	1047.3	955.5	1133.5
2	836.8	1672.4	1055.2	399.6	436.3	492.9	886.6	735.0	1070.4
1	**1137.3**	**1864.5**	**2130.6**	**477.8**	**673.4**	556.3	706.2	577.1	1029.0

Table 6.41b. Maximum values of bending moments, shear forces and axial forces in **columns** given in Table 6.41a.. and % variation with respect to SFBY2

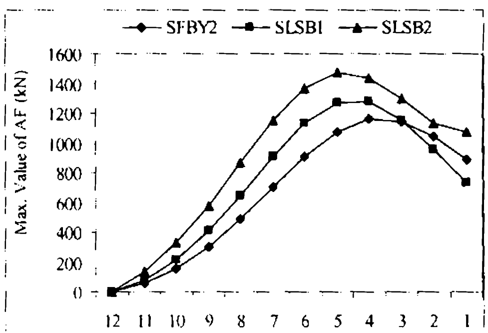
Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SFBY2	1137.3	
	SLSB1	1864.5	+63.9
	SLSB2	2130.6	+87.3
Shear force (kN)	SFBY2	477.89	
	SLSB1	673.4	+40.9
	SLSB2	633.9	+32.6
Axial force (kN)	SFBY2	1161.2	
	SLSB1	1279.4	+10.1
	SLSB2	1468.5	+26.4

There is an increase of 64% for column bending moment for the first type of layering and 87% for the second type giving a variation of 23% for the two models. The corresponding variations in shear force is 41% and 33% showing a variation of 8%. As for axial force it is 10% and 26% giving a variation of 16%. With continuum modeling the responses in the columns are observed to be upper bound than the homogeneous model.



a. Bending moment

b. Shear force



c. Axial Force

Fig. 6.39 Variation of maximum values of (a)bending moment,(b) shear force and (c)axial force in **columns** for **layered** soil with continuum model

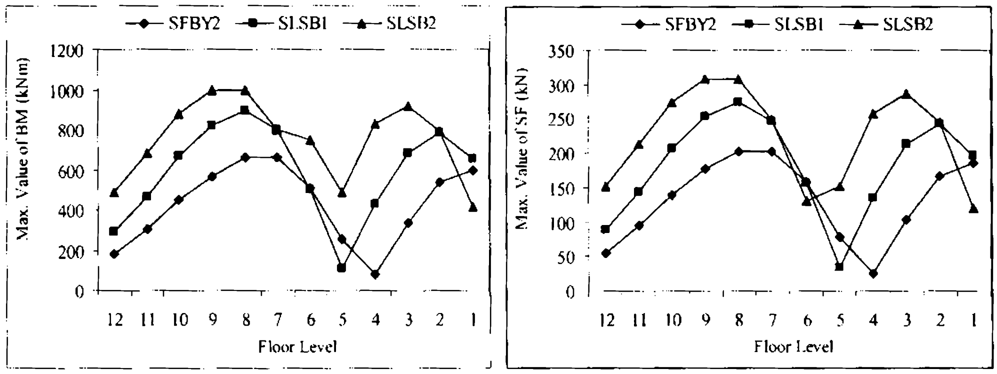
Maximum values of bending moments and shear forces in beams are reported in Table 6.42a. and the percentage variations of maximum responses with respect to SFBY2 are reported in Table 6.42b. The variations along the floor level are shown in Fig. 6.40.

Table 6.42a Maximum values of bending moments and shear forces in **beams** for **layered** soil with continuum model

Floor Level	Max values of bending moment (kNm)			Max values of shear force (kN)		
	SFBY2	SLSB1	SLSB2	SFBY2	SLSB1	SLSB2
12	179.1	292.6	484.4	55.8	89.6	151.5
11	307.0	465.0	685.6	95.8	144.0	213.7
10	448.1	671.1	882.7	140.0	207.4	274.4
9	569.4	818.7	993.0	176.6	253.0	308.4
8	659.2	**891.0**	**993.3**	**203.2**	**275.0**	**308.6**
7	**659.7**	802.9	801.4	203.1	247.5	249.0
6	510.67	502.3	745.5	157.2	155.0	131.0
5	254.7	108.3	489.5	78.4	33.6	150.8
4	78.79	430.3	826.6	24.3	134.1	256.5
3	331.7	680.7	918.4	102.7	212.7	286.1
2	537.9	782.3	795.1	166.4	242.4	244.7
1	599.5	653.1	413.2	185.7	197.0	120.6

Table 6.42b Maximum values of bending moments and shear forces in **beams** given in Table 6.42a.and % variation with respect to SFBY2

Force response	Configuration	Max.value of force response	% variation
Bending moment (kNm)	SFBY2	659.7	
	SLSB1	891.0	+35
	SLSB2	993.3	+50.5
Shear force (kN)	SFBY2	203.2	
	SLSB1	275.0	+35.3
	SLSB2	308.6	+51.8



a. Bending moment b. Shear Force

Fig. 6.40 Variation of maximum values of (a)bending moment and(b) shear force in **beams** for **layered** soil with continuum model

There is an increase of 35% for beam bending moment for the first type of layering and 51% for the second type giving a variation of 16% for the two models. The corresponding variations in shear force is 35% and 52% showing a variation of 17%. With continuum modeling the responses in the beams are observed to be upper bound than the homogeneous model.

6.7.4.3 Influence of SSI on displacements in layered soil

The layered soil models SLS1, SLS2, SLSB1, SLSB2 and the homogeneous models SFAY2, SFBY2 have been analysed to investigate the effect of soil structure interaction on displacements in layered soil. The maximum values of horizontal and vertical displacements are reported in Table 6.43.

Table 6.43 Effect of SSI on displacements in **layered** soil

Type of soil		Max values of displacement (m)	
		Horizontal direction	Vertical direction
Homogeneous	Discrete model	0.178	0.0228
	Continuum model	0.128	0.0098
Layered 1	Discrete model	0.210	0.054
	Continuum model	0.122	0.014
Layered 2	Discrete model	0.201	0.050
	Continuum model	0.113	0.093

It has been observed that the discrete model gives upper bound values of both horizontal and vertical displacements compared to continuum models for all the three configurations of soil.

6.8 SUMMARY

Shock spectrum analysis has been conducted on the finite element model for the frame – pile – soil system for different depths of fixity, with and without soil structure interaction effects. The study has been conducted on three major soil types of Kerala viz., laterite, sand and alluvium with two soil models. The study has been extended to two types of layered soils. It has been observed that shock spectrum analysis gives wide variations of responses in the frame compared to linear elastic analysis. Interior storeys showed both increase and decrease in responses. Maximum variations are shown in the upper storeys and this may be due to the fact that the geometry of columns changes after the fourth floor. Further the positioning of the centre of mass of the structure in this region has contributed in varying the responses in this region when subjected to earthquake motion. It has also been observed that the two soil models in the present study viz., discrete and continuum, which showed good congruence in linear static analysis, shows variations in shock spectrum analysis.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 INTRODUCTION

Numerical investigations have been carried out on a four bay, twelve storeyed regular multistorey frame considering depth of fixity at ground level, at characteristic length of pile and at full length. Soil structure interaction effects have been studied by considering two finite element models for soil viz., discrete and continuum. Three types of analyses have been carried out viz., linear static analysis, free vibration analysis and shock spectrum analysis. The study has been extended to four types of soil viz., laterite, sand, alluvium and layered. The major research findings have been summerised in the subsequent sections and conclusions are given at the end.

7.2 LINEAR STATIC ANALYSIS

It has been observed that the structural responses evaluated in the finite element analysis, viz., the bending moment, shear force and axial force in columns; and bending moment and shear force in beams, increase with increase in founding depth. This is due to the increase in cantilever action. However these responses show minimal increase beyond the characteristic length of the pile. This validates the concept of characteristic depth in the analysis. Further it has been observed that soil structure interaction effects increases the responses in the frame up to the characteristic depth and decreases when the frame has been treated for the full depth. The variations have been more pronounced in the bottom storeys of the frame. It has been observed that all the three types of soil viz., latrerite, sand and alluvium showed the same behavior. As for the layered soils, it has been observed that the inclusion of layering through a variation of modulus of elasticity reduced the bending moment in the columns but showed an increase in the other responses of the frame, compared to homogeneous medium. The two finite element models for the soil viz., discrete and continuum model showed good congruence in linear static analysis.

7.3 FREE VIBRATION ANALYSIS

Eigenvalues have been observed to be very closely spaced, especially in the higher frequency range. Further it has been observed that inclusion of soil properties through discrete model has not affected the natural properties significantly. But good variation has been observed for the different types of soil considered in the continuum model. The same behavior has been observed when the pile length is taken as characteristic depth and also when it has been taken as full depth.

7.4 SHOCK SPECTRUM ANALYSIS

It has been observed that shock spectrum analysis gives wide variation of responses in the frame compared to linear elastic analysis. Both increase and decrease in responses have been observed in the interior storeys. Storeys four to eight showed the maximum variations. This may be due to the fact that there is a change in geometry of the column above the fourth floor and also that the positioning of the centre of mass of the structure in this region has contributed in varying the responses in this region when subjected to ground motion. The good congruence shown by the two finite element models viz., discrete and continuum in linear static analysis is absent in shock spectrum analysis.

It has been observed that the maximum column bending moments were obtained when the frame has been assumed to be fixed at ground level for all types of soil for both models; the only exception being alluvial soil with discrete model. Soil structure interaction increased the responses when the pile length has been taken as characteristic depth in all cases with discrete model; but a decrease is observed in the case of alluvial soil with continuum model. Soil structure interaction reduced the responses when piles were treated for full depth in laterite; whereas mixed responses were shown in the case of sand and an increase in the case of alluvial soil.

7.5 GENERAL CONCLUSIONS

Based on the results of the numerical investigations conducted in the present study, the following general conclusions are arrived at. These conclusions give some insight into the selection of pile length and finite element model for soils in different districts of Kerala for the analysis of multistorey frames subjected to dead loads, imposed loads and seismic loads.

- It has been concluded that for linear elastic analysis using finite element method for multistorey frames with soil structure interaction effects, fixity at the characteristic length of pile can be adopted than full length, for laterite, sand and alluvium.
- It has been concluded that for shock spectrum analysis using finite element method for multistorey frames with soil structure interaction effects, fixity at characteristic length of pile can be adopted, for laterite and sand; however full length of pile has to be considered for alluvium.
- It has been concluded that discrete model predicts bending moment, shear force and axial force in columns; and bending moment and shear force in beams upper bound for laterite and sand; and shear force and axial force in columns and shear force in beams lower bound for alluvium.
- It has been concluded that continuum model predicts shear force and axial force in columns; and shear force in beams upper bound for alluvium; and bending moment, shear force and axial force in columns; and bending moment and shear force in beams lower bound for laterite and sand.
- It has been concluded that discrete model predicts bending moment, shear force and axial force in columns; and bending moment and shear force in beams upper bound for layered soil.
- It has been concluded that discrete model gives upper bound values for displacement in all cases. However continuum model has to be used if stress distribution in soil is to be studied for any of the cases.

- It has been concluded that continuum model predicts the bending moment, shear force and axial force in columns; and bending moment and shear force in beams, for the recommended lengths of pile in laterite, sand and alluvium upper bound in shock spectrum analysis using finite element method.
- It has been concluded that discrete model predicts the shear force and axial force in columns; and bending moment and shear force in beams upper bound; and bending moment in columns lower bound in layered soil in shock spectrum analysis using finite element method.
- When shock spectrum analysis is carried out for multistorey frames, it has been recommended to include soil structure interaction effects, since there is magnification of stress responses observed when seismic loads are acting on the frame.
- The usage of continuum model for modeling laterite, sand and alluvium has been recommended for shock spectrum analysis using finite element method.

7.6 SUGGESTIONS FOR FUTURE WORK

Simplifying assumptions of soil linearity and the perfect bonding at the pile – soil interface has been made in the present model. These limitations can be over come with future studies, with models based on nonlinearities.

Frames of regular configuration have been considered in this study and the work can be extended to frames with different configurations and irregularities.

In the case of pile foundations, the studies can be extended to piles of different cross section as well as by considering pile group effect.

REFERENCES

[1] **Ambraseys, N. N. and Douglas, J.**, *Near field horizontal and vertical earthquake ground motions,* Soil Dynamics and Earthquake Engineering 23(2003) pp1-18.

[2] **Anandarajah, A., Zhang, J. and Ealy, C.**, *Calibration of dynamic analysis methods from field test data*, Soil Dynamics and Earthquake Engineering 25 (2005) pp.763-772.

[3] **Arlekar, J. N., Jain, S. K. and Murty, C. V. R.**, *Seismic response of RC frame buildings with soft first storeys*, Proceedings of the CBRI golden jubilee conference on national hazards in urban habitat, (1997), New Delhi.

[4] **Bathe, K.**, *Finite element procedures*, Prentice – Hall of India,(2005) New Delhi.

[5] **Boore, D.M. and Bommer, J.J.**, *Processing of strong motion accelerograms: needs, options and consequences*, Soil Dynamics and Earthquake Engineering 25 (2005) pp 93-115.

[6] **Bowles, J. E.**, *Analytical and Computer Methods in Foundation Engineering*, (1974) McGraw-Hill, New York, pp 519.

[7] **Bowles, J. E.**, *Foundation analysis and design*, McGraw-Hill,(1996) New York.

[8] **Browning, J.P.**, *Proportioning of earthquake resistant RC Building Structures*, Journal of Structural Engineering, February (2001) pp 145 – 151.

[9] **Carniel, R., Barazza, F. and Pascolo, P.**, *Improvement of Nakamura technique by singular spectrum analysis*, Soil Dynamics and Earthquake Engineering 26 (2006) pp 55-63.

[10] **Cervenka, V. and Cervenka, J.**, *Computer simulation as a design tool for concrete structures*, The second International Conference in Civil Engineering on Computer Applications, Research and Practice, April (1996), Bahrain.

[11] **Chintanapakdee, C. and Chopra, A.K.**, *Seismic Response of vertically Irregular Frames: Response History and Modal Pushover Analysis*, Journal of Structural Engineering, August (2004) pp 1177 – 1185.

[12] **Chopra, A. K.**, *Dynamics of structures, Theory and applications to earthquake engineering*, (2003) Prentice – Hall, India.

[13] **Davenne, L., Ragueneau, F., Mazars, J. and Ibrahimbegovic, A.**, *Efficient approaches to finite element analysis in earthquake engineering*, Computers and structures 81 (2003) pp 1223-1239.

[14] **Gazetas, G., Fan, K. and Kaynia, A.**, *Dynamic response of pile groups with different configurations*, Soil Dynamics and Earthquake Engineering 12(1993) pp 239-257.

[15] **Gen-shu, T. and Jin-qiao, H.**, *Seismic force modification factor for ductile structures*, Journal of Zhejiang University Science (2005) 6A (8) pp 813-825.

[16] **Ghiocel, D. M. and Ghanem, R.G.**, Stochastic finite element analysis of seismic soil structure interaction, Journal of Engineering Mechanics, January (2002), pp 66 – 77.

[17] **Guin, J. and Banerjee, P.K**, *Coupled soil-pile-structure interaction analysis under seismic excitation*, Journal of Structural Engineering, April (1998), pp 434 – 444.

[18] **Hoshiya, M. and Ishii, K.**, *Evaluation of kinematic interaction of soil-foundation systems by a stochastic model*, Soil Dynamics and Earthquake Engineering, (1983), Vol 2 No.3 pp 128 – 134.

[19] **IS 456** : 2000, *Indian Standard Plain and reinforced concrete – code of practice.*

[20] **IS 875 (part 1):** 1987, *Indian Standard code of practice for design loads (other than earthquake) for buildings and structures,* part 1- Dead Load, unit weight of building materials and stored materials.

[21] **IS 875 (part 2)**: 1987, *Indian Standard code of practice for design loads (other than earthquake) for buildings and structures,* part 2 – Imposed Loads.

[22] **IS 1893 (part 1)** :2002, *Indian Standard criteria for earthquake resistant design of structures,* part 1: General Provisions and Buildings.

[23] **IS 2911 (part1)** – 1979, *Indian Standard Code of practice for design and construction of pile foundations*, part 1: Concrete Piles

[24] **IS 13920:1993** *Ductile detailing of reinforced concrete structures subjected to seismic forces – code of practice.*

[25] **Jaya, K. P.**, *Dynamic behaviour of embedded and pile foundations in layered soil using cone models*,Ph.D Thesis,(2000) IIT, Madras.

[26] **Kokusho, T.**, *Current State of Research on Flow failure considering void redistribution in liquefied deposits*, Soil Dynamics and Earthquake Engineering 23(2003) pp 585-603.

[27] **Kramer, S. L.**, *Geotechnical earthquake engineering*, Pearson education, (2007) India.

[28] **Krauthammer, T. and Chen, Y.**, *Free field earthquake ground motions: effects of various numerical simulation approaches on soil-structure interaction results*, Engineering Structures (1988),Vol 10 pp 85-93

[29] **Krishna, A.M, Madhav, M. R. and Latha, G. M.**, *Liquefaction mitigation of ground treated with granular piles: Densification effect*, ISET Journal of Earthquake Technology, December (2006), pp105 – 120.

[30] **Kurian, N. P. and Manojkumar, N. G.**, *A new continuous winkler model for soil- structure interaction*, Journal of Structural Engineering, Vol 27, No 4 January (2001) pp 269-276.

[31] **Lee, I. K. and Brown, P. T.**, *Structure – Foundation Interaction Analysis*, Journal of the Structural Division, Proceedings of the American Society of Civil Engineers, November, (1972), pp 2413 – 2431.

[32] **Lee, I. K. and Harrison, H. B.**, *Structure and Foundation Interaction Theory*, Journal of the Structural Division, Proceedings of the American Society of Civil Engineers, February, (1970), pp 177 – 197

[33] **Lu, Y.**, *Comparative study of seismic behavior of multistorey reinforced concrete framed structures*, Journal of Structural Engineering, February (2002) pp 169 – 178.

[34] **Neuss, C. F. and Maison, B. F**, *Analysis for P-Δ effects in seismic response of buildings*, Computers and Structures Vol 19, No 3, (1984) pp369-380.

[35] **Newmark, N. M.**, *Numerical Procedure for computing Deflections, Moments and Buckling Loads*, Trans. ASCE (1943), vol.108, pp. 1161 – 1234

[36] **Newmark, N. M.**, *Seismic design spectra for nuclear power plants*, J.Power Division, ASCE, 99(2), (1973) pp 287 – 303

[37] **NISA II / DISPLAY III** Manual, (1996) Engineering Mechanics Research Corporation.

[38] **Orense, R. P.**, *Assessment of liquefaction potential based on peak ground motion parameters*, Soil Dynamics and Earthquake Engineering 25 (2005) pp 225-240

[39] **Osinov, V. A.**, *Cyclic shearing and liquefaction of soil under irregular loading: an incremental model for the dynamic earthquake – induced deformation*, Soil Dynamics and Earthquake Engineering 23(2003) pp 535-548.

[40] **Paulay, T.**, *Simplicity and Confidence in Seismic Design*, The Fourth Mallet – Milne Lecture,1993, SECED, John Wiley and Sons.

[41] **Paz, M.**, *Structural Dynamics, Theory and computation*, CBS Publishers and distributors,(1987) New Delhi.

[42] **Safak, E.**, *Time – domain representation of frequency-dependent foundation impedance functions*, Soil Dynamics and Earthquake Engineering 26 (2006) pp 65-70

[43] **Spyrakos, C. and Loannidis, G.**, *Seismic behaviour of a post tensioned integral bridge including soil-structure interaction(SSI)*, Soil Dynamics and Earthquake Engineering 23 (2003) pp 53-63

[44] **Spyrakos, C. C., and Xu, C.**, *Seismic soil-structure interaction of massive flexible strip-foundations embedded in layered soils by hybrid BEM-FEM*, Soil Dynamics and Earthquake Engineering 23(2003) pp 383-389

[45] **Takewaki, I., Takeda, N. and Uetani, K.**, *Fast practical evaluation of soil-structure interaction of embedded structures*, Soil Dynamics and Earthquake Engineering 23 (2003) pp 195-202

[46] **Takewaki, I. and Kishida, A.**, *Efficient analysis of pile-group effect on seismic stiffness and strength design of buildings*, Soil Dynamics and Earthquake Engineering 25 (2005) pp 355-367

[47] **Takewaki, I.**, *Bond of earthquake input energy to soil-structure interaction systems*, Soil Dynamics and Earthquake Engineering 25 (2005) pp 741-752

[48] **Tokimatsu, K., Suzuki, H. and Sato, M.**, *Effects of inertial and kinematic interaction on seismic behavior of pile with embedded foundation*, Soil Dynamics and Earthquake Engineering 25(2005) pp 753-762.

[49] **Veletsos, A. S. and Prasad, A. M.**, *Seismic Interaction of structures and soils: Stochastic Approach*, Journal of Structural Engineering, Vol. 115, No. 4, April, 1989, pp 935 – 956

[50] **Viladkar, M. N., Godbole, P.N. and Noorzaei, J.**, *Modelling of interface for soil-structure interaction studies*, Computers and Structures, Vol. 52, No. 4, (1994) pp.765-779

[51] **Vesić, A. S.**, *Principles of Pile Foundation Design*, Soil Mechanics Series No. 38, School of Engineering, Duke University, Durham (1975)

[52] **Wegner, J. L., Yao, M. M. and Zhang, X.**, *Dynamic wave soil- structure interaction analysis in the time domain*, Computers and Structures, 83(2005), pp 2206-2214.

[53] **Wolf, J. P. and Song, C.** *Some cornerstones of dynamic soil-structure interaction*, Engineering Structures 24 (2002) pp 13-28

[54] **Wolf, J. P.**, *Dynamic soil-structure interaction*, Prentice – Hall, INC., N. J.

[55] **Wu, W.**, *Equivalent fixed base model for soil structure interaction systems*, Soil Dynamics and Earthquake Engineering ,16(1997) pp 323-336

[56] **Yang, Y., Kuo, S. and Liang, M.**, *A Simplified procedure for formulation of soil-structure interaction problems*, Computers and Structures, Vol 60, No 4 (1996) pp 513-520

[57] **Yang, J., Li, J. B. and Lin, G.**, *A simple approach to integration of accleration data for dynamic soil-structure interaction analysis,* Soil Dynamics and Earthquake Engineering (2005).

[58] **Yuan,X., Sun, R. and Shangjiu, M.**, *Effect of asymmetry and irregularity of seismic waves on earthquake- induced differential settlement of buildings on natural subsoil*, Soil Dynamics and Earthquake Engineering 23(2003) pp 107-114.

[59] http://www.asc-india.org/kerala.htm

PUBLICATIONS RELATED WITH THE RESEARCH WORK

[1] Deepa B.S. and Nandakumar C.G., " *Finite Element Analysis of Earthquake Resistant Multistorey Frames*", National Conference on Earthquake Analysis and Design of Structures, PSG College of Technology, Coimbatore, February 2006, pp A 147-154

[2] Deepa B.S. and Nandakumar C.G., "*Soil Structure Interaction Studies of Multistorey Frames using Finite Element Method*", to be published in the international journal, 'Engineering Structures'. (communicated in January 2008)

[3] Deepa B.S. and Nandakumar C.G., "Shock *Spectrum Analysis of Multistorey Frames*", to be published in the international journal, 'Earthquake Engineering & Structural Dynamics". (communicated in January 2008)