

# Seismic Response of High rise Structures Considering the Effect of Interaction between Layered Soils and the Structure

Urmila Pallepamula<sup>1</sup>, Dr. S. R. K. Reddy<sup>2</sup>

P.G. Student, Department of Civil Engineering, Gudlavalleru Engineering College, Gudlavalleru, A.P, India<sup>1</sup>

Professor, Department of Civil Engineering, Gudlavalleru Engineering College, Gudlavalleru, A.P, India<sup>2</sup>

**ABSTRACT:** Earthquakes are spasmodic disasters caused by sudden release of energy in the earth's lithosphere. Earthquakes occur sudden and bulk of destruction takes place within short duration of time. Bitter experiences left by past earthquakes reveal the importance of constructing earthquake resistant structures and influence of soil-structure interaction on the behaviour of structures during an earthquake. It has been well recognized that the interaction between flexible soil and the structure indeed affect the response of the structure apart from other parameters like ground excitation, configuration and ductility. During an earthquake, when seismic waves travel through different rocks and soil media, the values of shear wave velocity and shear modulus will be different in different layers of soil and the interaction of layered soils with the structure play vital role in obtaining the seismic response of structures, particularly in loose soils. In this project, a multi-storied building proposed to be constructed in the region of new capital, Amaravathi, Andhra Pradesh, is chosen for the study. Studies are carried out to obtain the response parameters like time period, base shear and storey displacement under seismic load conditions, when the similar structure rests on layered soil. The results are compared with those when the structure is assumed to be fixed at the base.

**KEYWORDS:** Soil structure interaction, Free vibration analysis, Layered soil, Stiffness, Time period, Story shear, Storey displacement.

## I. INTRODUCTION

Earthquakes are the most dangerous natural disasters which occur suddenly without warning and cause large scale destruction with in a very short duration of time. Earthquakes are mainly caused by rupture of geological faults, and also by other events such as volcanic activities, landslides, mine blasts and nuclear tests. Though earthquakes cannot be predicted directly, potential seismic zones can be identified using geospatial technologies.

When earthquake originates from focus, seismic waves travel through different rock / soil media and when they reach the foundation, the structure vibrates. Shear wave velocity varies from low value in case of flexible soils to a higher value for stiff soil / rock and hence the geo-technical properties of different geomorphic units will change from static to dynamic state and greatly influence on the response. It has been well established that interaction between flexible soils and the structure will greatly affect the response of the structure apart from other parameters like earthquake magnitude, configuration, ductility and construction quality. Italy(1783), Alaska(1964), Kobe(1995), Bhuj(2001), Indonesia – Sumatra(2004) and Nepal(2016) earthquakes are some of the best examples for failure of the buildings due to soil conditions.

The Southern India peninsular shield has been thought as inert to younger earth movement and the related seismicity for the past several decades. Major metropolitan cities in this region have exponential growth of population resulting construction of many high rise structures. Soil-Structure Interaction plays a major role to obtain the parameters like time period, frequency, displacements and shear of the structure which rests on the different layers of soil.

# International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Website: [www.ijirset.com](http://www.ijirset.com)

Vol. 6, Issue 5, May 2017

Most of the loss of life during an earthquake comes from the total or partial collapse of buildings. Damage sustained in recent earthquakes, have also highlighted that the seismic behaviour of a structure is highly influenced not only by the response of the superstructure, but also by the response of the foundation and the soil as well. For the seismic analysis, foundation of the structure usually assumed to be fixed at the base to simplify the analysis; but in reality, as the foundation of the structure rests on soil, the response depends upon the properties of the structure as well as soil. The interaction phenomenon is principally affected by the mechanism of energy exchanged between the soil and the structure. Shear modulus values of soil changes with the shear wave velocities travel through different soil media. Modelling of soil requires representation of soil stiffness, mass and damping characteristics allowing for strain-dependence and variation of soil properties. Hence the structures are usually designed for gravity loads, translational and rocking springs of soil.

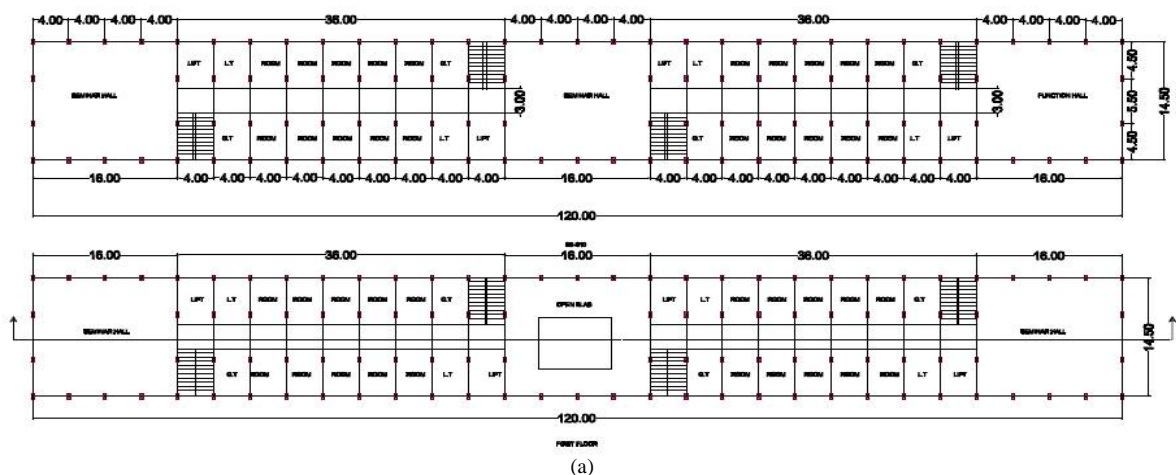
Equivalent soil spring constants are worked out for different types of soils based on the work done by Whitman and Richart (1967) for footing type foundation and work done by Novak (1974) for pile foundations. The structure and the soil can be idealized as mass-spring-dashpot system treating it one having  $n+2$  degrees of freedom where 'n' is no of storey masses idealized in the structure and the other two are spring constants represented by the soil. The response of a structure considering soil-structure interaction significantly change, particularly, when the structure rests on loose soil.

The present study focus on the analysis of the multi stories structure subjected to gravity as well as seismic loads by considering the Soil-Structure Interaction using free vibration analysis. The analysis has been carried out considering the building rests on layered soil. The results of fixed base condition are compared with the results obtained considering soil – structure interaction when the building rests on layered soils to obtain the parameters like displacements, time periods and base shears at different floor levels.

## II. PROPOSED WORK

Amaravathi which is located near the right stream side of river Krishna is announced as the new capital of Andhra Pradesh. Many multi storied structures are expected in this region. This region is mainly covered with four geomorphological units namely black cotton soil, red gravelly soils, sandy alluvial soils, saline swampy soils (Data from National Informatics Centre, Guntur). This region falls under seismic zone III. The interaction between the structure and soil plays a key role to obtain the dynamic response of the structure during earthquake.

In the present study, a twelve storied building (multi-storied building), with lower two stories for parking (soft stories) and the remaining ten stories for five star hotel resting on two different types of layered soil, is chosen for the analysis. The dimensions and properties and the structural element of the building are presented in table 1&2. Plan and elevation of building is shown in figs. 1(a), 1 (b) and 1(c).



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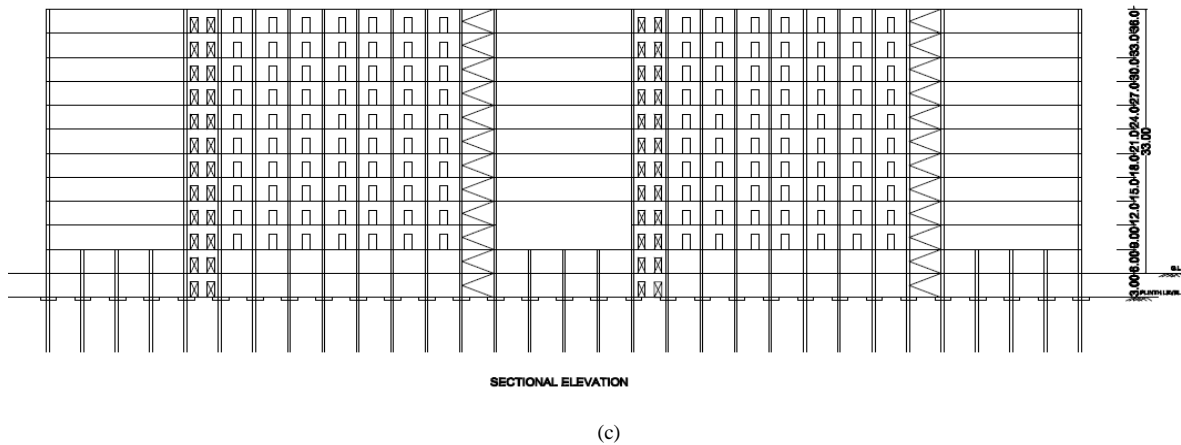
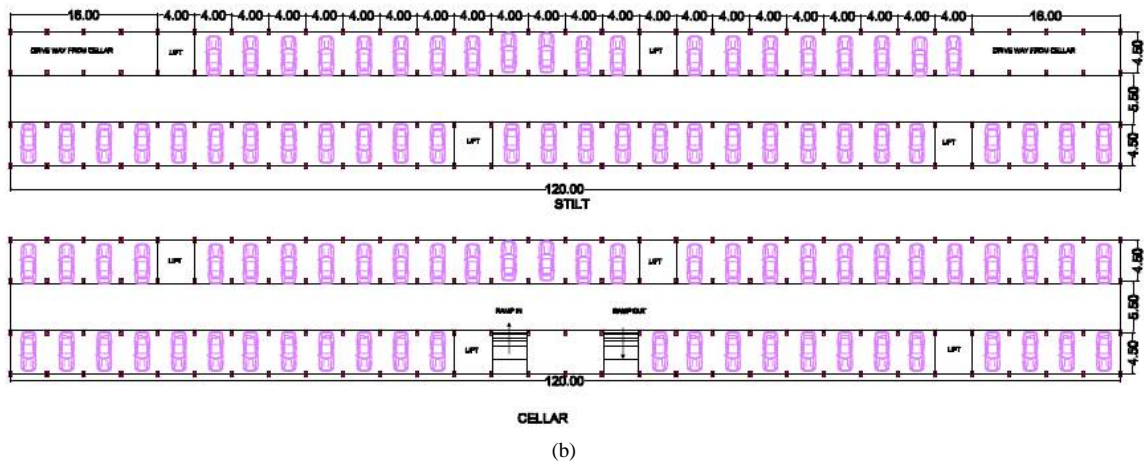


Fig. 1. Plan and elevation of the building (a) Plan of the top and first floors (b) Plan of the stilt and cellar (c) Sectional elevation of the building

## Preliminary data

Table 1. Properties of materials and different loads

Name of the property/element	Description
Grade of concrete	M25
Grade of steel	Fe 415
Unit weight of RCC	25 KN/ m <sup>3</sup>
Unit weight of brick work	19 KN/ m <sup>3</sup>

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Live load (floor)	(Seminar halls) 5.0 KN/ m <sup>2</sup>
	(Rooms) 3.0 KN/ m <sup>2</sup>
Live load (terrace)	1.50 KN/ m <sup>2</sup>
floor finish	1.0 KN/ m <sup>2</sup>
Terrace finish	1.5KN/ m <sup>2</sup>

Table 2. Dimensions of structural elements

Parameter	Dimension/s
Height of the building	36.0m
Height of each storey	3.0m
Number of stories	12(2 soft +10 )
Column size	0.3m x 0.6m
Longitudinal beams	0.23m x 0.4m
Transverse beams	0.23m x 0.45m
Plinth beams	0.23m x 0.4m
Slab thickness	0.13m
Exterior wall thickness	0.23 m
Interior wall thickness	0.115m
Grid beams	0.3m x 0.6m

### III. GEOTECHNICAL STUDIES

#### Geotechnical Classification in Study Area

The study area is covered by different types of geomorphic units/ landforms. The seismic response of similar building behaves differently in different soil units during an earthquake. Assuming the chosen building rests on deep foundations, and the soil consists of two layers in study area as given below

Layer 1 - Brownish Plastic Silty Clay [MH-CH]

Layer 2 – Yellowish brown fine to medium sand [SP]

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Vol. 6, Issue 5, May 2017

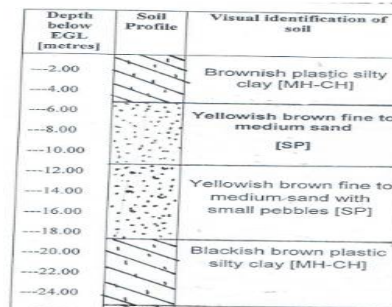


Fig.2. Soil profile of study area

Table 3. Geo-technical properties of various geomorphic units

Property of the material	Units	Layer 1	Layer 2
Shear wave velocity $V_s$	m/s	60	150
Mass density ( $\rho$ )	KN-m <sup>2</sup> /m <sup>4</sup>	1.6	1.7
Poisson's ratio ( $\mu$ )	-	0.4	0.4
Shear modulus ( $G_s$ ) = $\rho * V_s^2$	KN/m <sup>2</sup> x 10 <sup>5</sup>	5760	38250
Young's modulus ( $E_s$ )	KN/m <sup>2</sup> x 10 <sup>5</sup>	0.161	1.071

## IV. MATHEMATICAL MODEL

The structure can be treated as a mass-spring dash pot system, which is having  $n+2$  degrees of freedom, where 'n' represents the number of lumped storey masses idealised in the structure and the other two components are the spring constants of the soil namely horizontal stiffness and the rocking stiffness.

### Foundation model

In present study pile foundation is the one which can be used so as to get the SSI effect due to the layered soils. A pile group consists of four piles of 0.5m diameter and 17.2m of length. Dimensions of pile cap in plan is of 3m X 3m.

### Soil model

The soil model has to represent the soil mass and soil stiffness factors which are to be allowed for the strain dependence and soil properties. The soil structure is modelled by considering that the structure is assumed to rest on a uniform elastic half space and soil-spring is used. The most common method of modelling the soil is done by considering that the soil springs are located at the base of the structure. Only horizontal and rocking springs are considered since the structures are designed for gravity loads and the plan of the building is symmetrical. The equivalent spring constant for the layered soil is worked out based on the Novak and EI-Sharnouby formula (1983).

### Equivalent stiffness of the layered soils

Calculation of stiffness of pile by using Novak and EI-Sharnouby Formulae (1983)

$$\text{Translational stiffness } k_x = \left[ \frac{Ep * Ip}{ro^3} \right] * f_{x1}$$

$$\text{Rocking stiffness } k_\phi = \left[ \frac{Ep * Ip}{ro} \right] * f_{\phi 1}$$

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Where,  $E_p$  = Modulus of elasticity of pile material  $I_p$  = moment of inertia of single pile about X or Y axis  
 $r_o$  = pile radius  $f_{x1}, f_{\phi 1}$  are Novak's coefficients

### Structure model

A twelve storey building of 120m X 14.5m size in plan, in which two soft stories are at bottom for parking and other floors are for commercial purpose, has been analysed by Free vibration analysis. It is idealised as dash- pot system treating it as one having twelve degree of freedom system with fixed base condition and fourteen degree of freedom system with SSI consideration. The dead and seismic loads are calculated according to IS 875-partIII. The inner story stiffness are worked out by adding the stiffness values of the column and stiffness of all infill walls parallel to the lateral load in each storey.

Stiffness of each column  $k_c = 12EI/L^3$

Stiffness of infill walls  $k_w = AE_m/l_d(\cos^2 \Theta)$

Where,

$E_m$  = Elastic Modulus of Masonry Wall  $E_f$  = Elastic Modulus of Frame material

$l_d$  = Diagonal length of the strut =  $\sqrt{(h+1)}$   $h$  = Height of wall

$A$  = Cross-sectional area of diagonal strut =  $W \times t$

$W$  = Width of strut  $l$  = Length of wall

$t$  = Thickness of wall  $W = 1/2(\sqrt{\alpha_h^2 + \alpha_l^2})$   $\Theta = \tan^{-1}(h/l)$

$\alpha_h$  = Contact length between wall and columns  $\alpha_l$  = Contact length between wall and beams

$\alpha_h = \pi/2((E_f l_c h) / (2 E_{mt} \sin 2\Theta))^{1/4}$   $\alpha_l = \pi((E_f l_c l) / (E_{mt} \sin 2\Theta))^{1/4}$

Table 4. Mass and stiffness values of structure

Mass(kN-sec <sup>2</sup> /m)		Stiffness(kN/m)	
m12	=1523.3	k12	=26.17x10 <sup>6</sup>
m11-4	=2020.3	k11-4	=26.17 x10 <sup>6</sup>
m3	=1780	k3	=25.6 x10 <sup>6</sup>
m1	=1138.1	k1	=12.11 x10 <sup>6</sup>
m2	=1591.3	k2	=12.11 x10 <sup>6</sup>

Table 5. Calculation of stiffness of piles

Parameter	Layer 1	Layer 2
Shear wave velocity $V_s$ (m/sec)	60	150
Soil density $\rho_s$ (kN. Sec <sup>2</sup> /m)	1.6	1.7
Depth of layer	4.5	14.5
$\mu$	0.4	0.4
$r_o$ (m)	0.5	0.5
$G_s$ (kN/m <sup>2</sup> )	5760	38250
$E_p$ (kN/m <sup>2</sup> )x10 <sup>5</sup>	274	274
$I_p$ (m <sup>4</sup> )	0.00306	0.00306
$E_p/G_s$	4747	716
$f_{x1}$	0.0042	0.0125
$k_x * 10^6$	11.178	33.27
$f_{\phi 1}$	0.233	0.388
$k_{\phi} * 10^6$	38.785	56.225

Mass of the soil  $M_0 = 5691$  kN-sec<sup>2</sup>/m

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Mass moment of inertia of soil  $I_0 = 99711.1 \text{ m}^4$

## IV. FREE VIBRATION ANALYSIS

Using SRSS (Square Root Sum of Squares) method, the equilibrium equations are formulated and put them in matrix form and also by

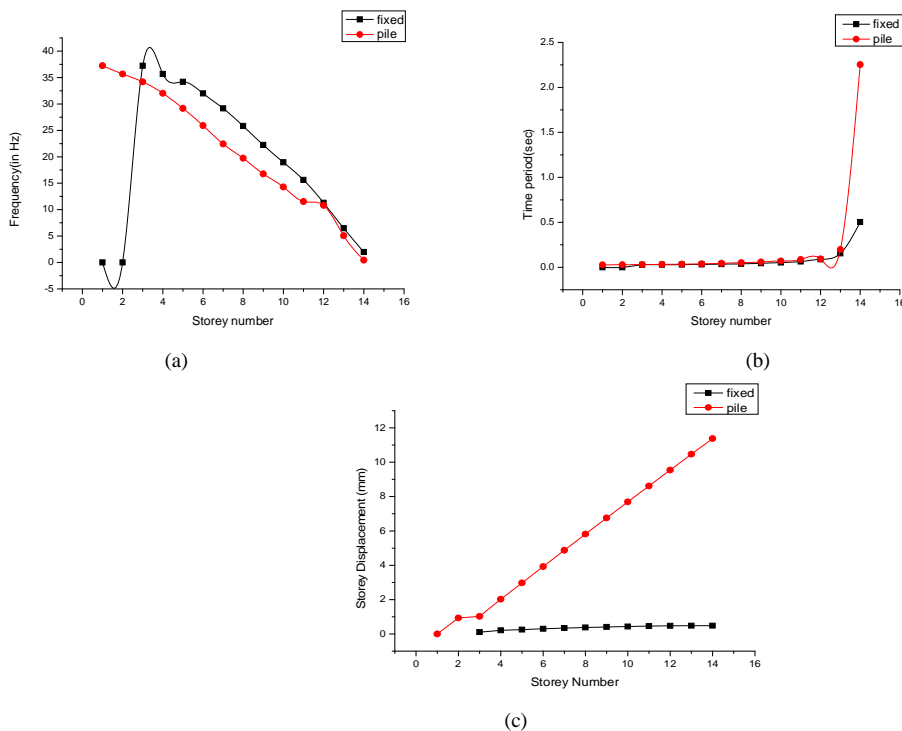
$$[m] \ddot{x} + [k] x = 0$$

Where,  $[m]$  – mass matrix,  $[k]$  – stiffness matrix,  $\ddot{x}$  – horizontal acceleration,  $x$  – horizontal displacement.

Undamped free vibration analysis is carried out to obtain the time periods, base shears, and storey displacements when the building rests on the five categorized types of soil/rock units treating the building as one with 14 degrees of freedom, the fundamental frequency and the time period are given in table 6. Seismic analysis is also carried out when the building is assumed to be fixed at the base treating it as one with 12 degrees of freedom and displacements are obtained considering soil-structure interaction effect and the results are presented in table 6.

Table 6. Comparison of results

Parameter	Frequency (Hz)	Time period (sec)	Displacements (m)
(SSI) Pile	0.444	2.253	0.080733
Fixed base	1.985	0.503	0.004417



Graph. 1. Comparison of results obtained (a) Comparison of frequency (b) Comparison of Time period (c) Comparison of displacements

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## VI.CONCLUSION

- Failure examples during past earthquakes reveal that soil structure interaction effect play vital role in response of structures, particularly when structure rests on loose soils.
- Stiffness of soil both in translation and rocking direction decreases with decrease of shear wave velocity of soil.
- It is observed that rocking spring constant value of layered soil is more than that of values obtained for horizontal spring constant.
- Time period increases with decrease of stiffness of the soil and this increase is observed more in upper storey levels. In case of buildings with soft stories at lower level, this increase is exponential.
- Frequency values in upper stories decrease compared to the decrease of frequency in lower stories.
- When soil structure interaction is considered, the displacements at different storey levels are observed more compared to the fixed base condition and this increase is found more due to rocking effect during an earthquake.

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