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Free Vibration Analysis of Multi-Storeyed Buildings resting on different Soil / Rock Media at Hyderabad, Telangana State, India

Sunil[1*], S. S. Asadi[1] and S. R. K. Reddy[2]

[1]KL University, Vaddeswaram - 522502, Andhra Pradesh, India; camsunil_inc@yahoo.com, asadienviron.asadi@gmail.com

[2]Gudlavalleru Engineering College, Gudlavalleru, Krishna Dist - 521356, Andhra Pradesh, India; srkrsatty@gmail.com

Abstract

Earthquake is a spasm of ground shaking caused due to sudden release of energy in the earth's crust and bulk of destruction takes place within a short duration of time. Past history records reveal that rate of occurrence of earthquakes is an increasing phenomena. Bitter experiences on failure/collapse of structures, particularly in urban regions, warn the people on importance of constructing earthquake resistant buildings. Local soil conditions and interaction between soil /rock media and the structure indeed affect the response of the structure during an earthquake. In the present investigation, the western region of Hyderabad, part of the capital of Telangana, is chosen as the study area which consists of different soil/ rock profiles at different locations. Free vibration analysis of a multi-storeyed building is carried out when the foundation of similar structure rests on different soil/rock media. Frequencies and time periods are worked out for comparison when the same structure is assumed to be fixed at the base. From the results, it is observed that the variation in time period of the structure increases with decrease of soil stiffness. It is also noticed that soil-structure interaction effect on time period of the structure, particularly in loose soils, is of more significant compared to the variation in structure stiffness.

Keywords: Free vibration, Geomorphology, Shear wave velocity, Soil-structure-interaction, Spring constant, Time period

1. Introduction

Earthquakes are the most catastrophic natural hazards related to ongoing tectonic processes which occur sudden and destruction takes place in few minutes. Usually, 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 geotechnical properties of different geomorphic units will change from static to dynamic state and greatly influence on the response. The seismic response also depends upon the earthquake magnitude, configuration, ductility and construction quality.

The earthquakes of Alaska & Nigata in 1994, Kobe in 1995, Bhuj in 2001 and Indonesia in 2004 are illustrations for failure of buildings due to soil conditions.

Major metropolitan cities in India have registered exponential growth of population resulting construction of many high-rise buildings. When these structures rest on different soils in different regions, the Soil-Structure Interaction (SSI) effect influences the parameters like fundamental time period and frequency of the structure.

2. Study Area

Hyderabad city, the capital of Telangana state is situated in the central part of Deccan Plateau of Indian sub-continent. The study area covering western part of the city is

*Author for correspondence

witnessing enormous growth in the recent past with the construction of very high rise structures, service reservoirs, metro lines, flyovers and other typical structures. The area is bounded by 17° 21' to 17° 31' north latitudes and 78°16' to 78°26' east longitudes. The location map of the study area is as shown in Figure 1. The construction activities are so intensive and extending to even highly vulnerable valley fill zones, tank-bed area, hill-slopes, which are sensitive to the soil-structure interaction. Seismotectonically, the study area is situated in a seismically more active Dharwar Craton of Indian Peninsular Shield, which is being subjected to medium to major earthquakes. The morpho-structural zoning and the isoseismal maps of Hyderabad and its environs are shown in the Figure.2 respectively. Morpho-structurally, the Hyderabad region is classified as a circular morpho-structure and represents a bowl-like depression with elevated margins with altitudes varying from 300 to 600m. above msl. This may be attributed to the behaviour of river Manjira in NW and Krishna in SE, which have taken diversion because of up-liftment of bowl structure of Hyderabad granites.

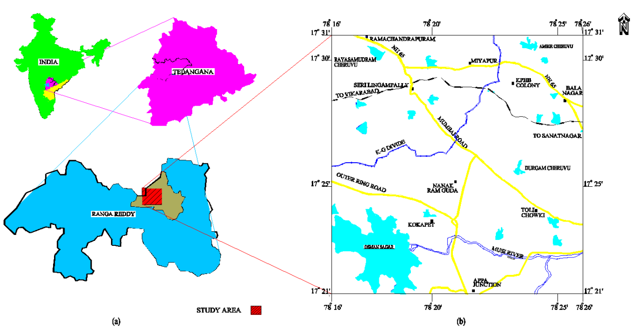


Figure 1. Study area Location.

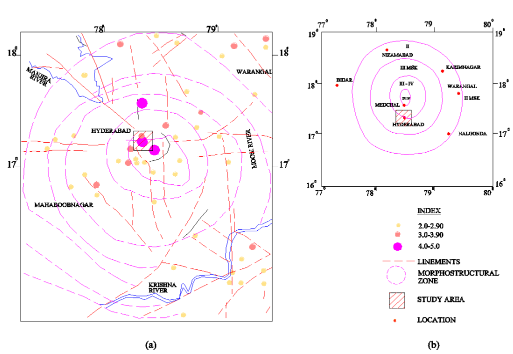


Figure 2. Morpho structural Zoning Map of Hyderabad with Lineaments (Isoseismal Map (MSK scale) of Hyderabad and its surroundings.

Some of the first order lineaments are seismically active and Hyderabad region has experienced mild tremor activity during 14th Jan 1982 to 16th October 1983 in Gandipet, Osmansagar and again in 2000 in Jubilee Hills and Medchal with earthquake intensity <5. This mild seismic activity continues as long as the upliftment of the circular structure. Hyderabad is falling in III-IV intensity on MSK intensity scale and is in the close proximity of Medchal with IV-V intensity[1].

3. Soil-Structure Interaction

The method of analysis commonly used by structural engineers assumes that the building is fixed at the base. In reality the building rests on the soil, and hence the analysis based on soil/rock conditions gives more realistic and reasonable results.

The study area is composed of various types of geomorphic units/ landforms[2] as shown in Figure 3. These units have been grouped into five categories for the purpose of analysis of geotechnical evaluation. The dynamic response of similar building behaves differently in different units during an earthquake. Assuming the chosen building rests on shallow foundation, the soil / rock units of the study area are classified into five types for the analysis as given below.

Type S1 – Silty Clay : Pediplain with moderate weathering associated with valleys and tank beds

Type S2 – Clayey sand / Colluvial soils: Valley fills associated with fractures.

Type S3 – Weathered rock : Pediplain with shallow weathering and residual mound

Type S4 – Fractured and Fissured rock/ Hard disintegrated rock: Pediment and Pediment Inselberg, rocky knobs and denudational hills.

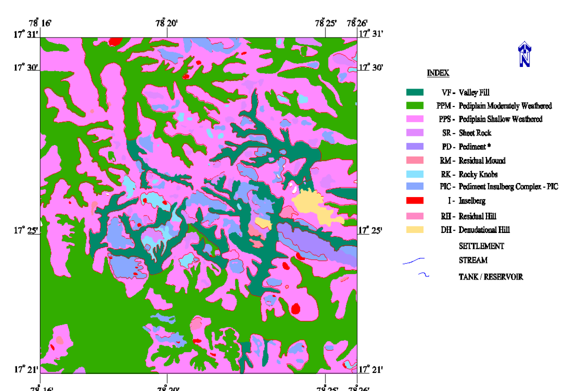


Figure 3. Geomorphological Map of the Study area.

Type S5 – Hard massive granite: Residual hills, Inselberg and Sheet rock.

4. Geotechnical Studies

In view of rapid advancements in construction technology and design of structures, the strength parameters have become pre-requisite for selection of specific soil or rock type. Before evaluating dynamic behaviour of soils, it is important to evaluate the static properties of various geomorphic units which influence the effect of SSI on response of structures. Keeping this in view, tests were conducted on different types of soil / rock samples of the study area and the properties like mass density, shear modulus, young's modulus and bearing capacity values are obtained and presented in Table 1

The values of shear wave velocity and poisson's ratio[3] of the five classified types of soil / rock units are taken for the use in the analysis and are presented in Table 1. The variation of shear modulus with respect to the shear wave velocity is presented in Figure 4.

5. Mathematical Models for the Analysis

A conventional twelve storey building is chosen for the analysis to calculate natural frequencies and time periods of the structure considering SSI effect when similar structure rests on different soils / rock media and the results are compared with the values obtained when the structure is assumed to be fixed at the base as shown in Figure 5.

Table 1. Geotechnical properties of various geomorphic units

Property of the Material		Units	Soil / Rock Type				
			S1	S2	S3	S4	S5
Shear Wave Velocity	V_s	m/s	60	150	400	1250	2700
Mass Density	ρ	$KN - Sec^2 / m^4$	1.70	1.80	1.90	2.10	2.60
Poisson's ratio	μ		0.45	0.40	0.33	0.30	0.30
Shear Modulus	$Gs = \rho V s^2$	$KN / m^2 X 10^5$	0.06	0.41	.04	32.81	189.54
Young's Modulus	E_s	$KN / m^2 X 10^5$	0.18	1.13	8.09	85.31	492.80
Bearing Capacity	P	KN / m^2	60	200	300	400	450

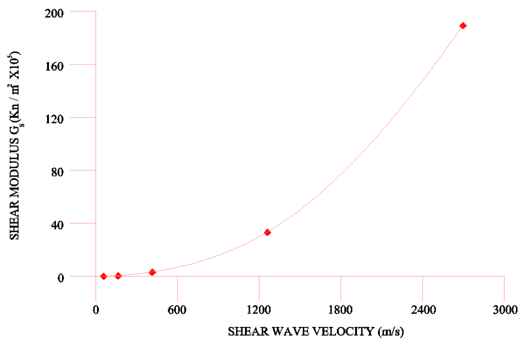


Figure 4. Variation of Shear Modulus with Shear Wave Velocity.

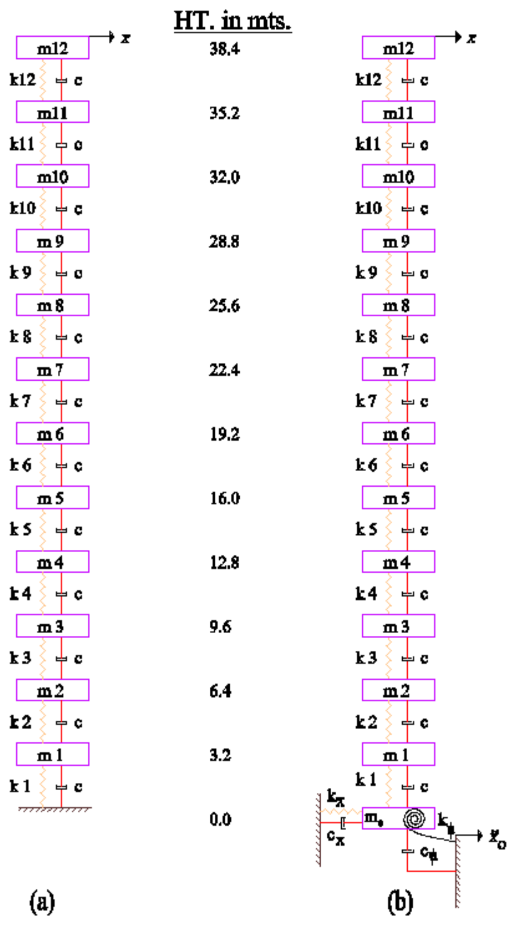


Figure 5. Building Model with (a) Fixed at Base (b) Soil Structure Interaction

5.1 Soil Model

The dynamic model of soil requires the representation of soil mass, soil stiffness and damping factors allowing for strain dependence and variation of soil properties. The structure is assumed to rest on uniform elastic half-space and soil-spring approach[4] is used to model the

Table 2. Mass and Stiffness values of structure and Soil / Rock

S .No							
			S1	S2	S3	S4	S5
1	m_1	$KN - sec^2 / m$	261	261	261	261	261
2	m_1 to m_{11}	$KN - sec^2 / m$	390	390	390	390	390
3	m_{12}	$KN - sec^2 / m$	224	224	224	224	224
4	m_0	$KN - sec^2 / m$	1238	670	520	394	311
5	k_1 & k_2	$KN / m \times 10^6$	1.16	1.16	1.16	1.16	1.16
6	k_3 to k_{12}	$KN / m \times 10^9$	4.23	4.23	4.23	4.23	4.23
7	k_x	$KN - m \times 10^5$	2.96	84.00	487.40	4468.00	22900.00
8	k_ϕ	$KN - m \times 10^5$	143.00	274.30	992.00	5239.00	27066.00
9	I	$KN - m - sec^2$	67470.00	60672.00	58860.00	57348.00	5635.00
10	I/h^2	$KN - sec^2 / m$	6589.00	5925.00	5748.00	5600.00	5503.00

soil-structure interaction. The most rudimentary method of modelling the soil is to use soil springs located at the base of the structure. Since the structures are usually designed for gravity loads only horizontal and rocking springs are considered. These equivalent spring constants for five different classified soil types of the study area are worked out based on the formulae[5] as given below and the values are presented in Table 2.

Equivalent stiffness values of soil springs are:

i) Horizontal stiffness,

k_x (kN/m) = $2(1+\nu)\, G\beta_x\, (BL)^{1/2}$

ii) Rocking stiffness,

k_ψ (kN-m) = $\frac{G}{1-\nu}\beta_\psi\, BL^2$

Where

B and L - Width and length of footing perpendicular and along the direction of excitation

β_x and β_ψ - Coefficients that are functions of L/B ratio as in Figure 6.

The variation of horizontal and rocking spring constant values (k_x & k_ψ) with respect to shear wave velocity are shown in Figure. 7

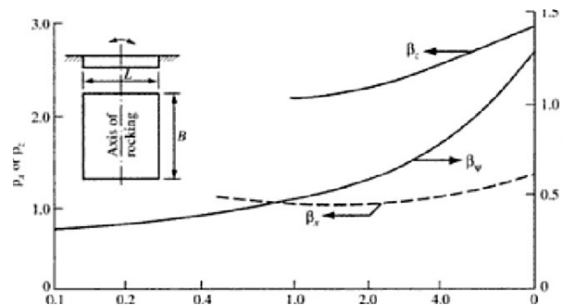


Figure 6. Constants β_x, β_ϕ, β_z for rectangular bases (after Whitman and Richart)

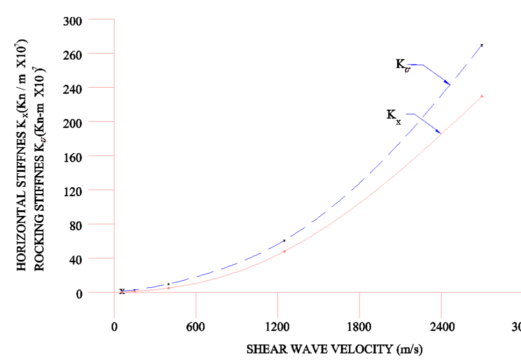


Figure 7. Variation of Horizontal/ Rocking stiffness with Shear wave velocity

5.2 Structure Model

A twelve storey building 21m x12m size in plan, with two soft stories at bottom for car parking and other floors for office purpose, has been choosen for free vibration analysis. It is idealized as mass-spring-dash pot system treating it as one having twelve degrees of freedom with fixed base condition and fourteen degrees of freedom when SSI is considered. The loads are lumped at the nodes of each floor level. According to IS 1893 (2002) code, live load is reduced by 25% and no live load is considered at terrace roof. The inter storey stiffness 'k' is worked out by adding the stiffness values of all columns (Σk_c) and stiffness of all in-fill walls parallel to the direction of lateral loads (Σk_w) in each storey.

Stiffness of each column is calculated by taking $k_c = 12E_cI_c/h^2$

In case of infilled walls, the system is modelled as a braced frame approximating the infill wall as an equivalent diagonal strut. The vital approach[4] to determine the effective width of equivalent diagonal strut (we) which depends upon

i) The length of contact between the wall and the column, αh and

ii) The length of contact between the wall and the beam, αl.

where

$$\alpha_h = \frac{\pi}{2}\left[\frac{E_c I_c h}{2E_m t \sin 2\theta}\right]^{1/4} \text{ and } \alpha_l = \pi\left[\frac{E_c I_b l}{E_m t \sin 2\theta}\right] \quad \text{Eq (1)}$$

The formulations of Stafford Smith (1966) given below are used to calculate stiffness of infill wall, k_w, where $k_w = \frac{AE_m \cos^2\theta}{l_d}$

in which,

$l_d = \sqrt{h^2 + l^2}$; $\theta = tan^{-1}\left[\frac{h}{l}\right]$, A = w_ex t and $w_e = \frac{1}{2}\sqrt{\alpha_h^2 + \alpha_l^2}$,

Where,

A– Area of cross section of the member

E_c– Young's modulus value of reinforced cement concrete

h – Height of the wall/column

E_m – Young's modulus value of masonry

I_b – Moment of inertia of beam element

I_c– Moment of inertia of column element

L – Length of the wall

t – Thickness of the wall

The total equivalent stiffness of each storey is taken as, $k = \sum k_c + \sum k_w$.[6]

The soil mass (m_0) for each type of soil is worked out considering the weight of the footing and the weight soil above it.

The mass and stiffness values of each storey of the structure and soil masses & stiffness are worked out and presented in the Table 2. Free vibration[7-10] analysis is carried out for obtaining the fundamental frequencies and time periods of the building when similar structure rests on five different types of soils that are classified as given in Chapter 3.0

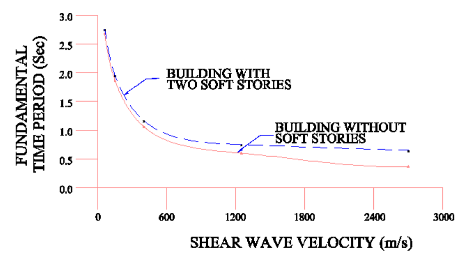
6. Method of Analysis

Using the combined mathematical model of both structure and soil with masses and springs as in Figure 5, the equilibrium equations are formulated and put them in matrix form

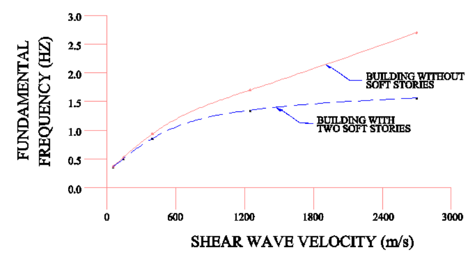
$$[M]\,\ddot{x} + [k]\,x = 0$$

Table 3. Fundamental time periods and natural frequencies

Sl. No.	Soil / Rock type	Configuration of the Building			
		Fundamental time period (seconds)		Natural Frequencies (Hz)	
		With two soft stories at lower level	Without soft stories	with two soft stories at lower level	Without soft stories
1	S1	2.75	2.68	0.36	0.37
2	S2	1.96	1.86	0.51	0.54
3	S3	1.15	1.06	0.87	0.94
4	S4	0.74	0.59	1.35	1.69
5	S5	0.62	0.37	1.56	2.70
6	Fixed base	0.62	0.35	1.61	2.86



(a)



(b)

Figure 8. Variation of Fundamental Time period with Shear Wave velocity Variation of Fundamental Frequency with Shear Wave Velocity

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 and natural frequencies when the building rests on the five categorized types of soil/rock units treating the building as one with 14 degrees of freedom and also when the building is assumed to be fixed at the base treating it as one with 12 degrees of freedom. The values are tabulated in Table 3.

The variation of fundamental time periods and natural frequencies with respect to the shear wave velocity are presented in Figure 8.

7. Result Analysis

The shear wave velocity of the soil is an important parameter which influences the dynamic behaviour of geotechnical properties like shear modulus, damping coefficient and poisson's ratio.

Generally, shear wave velocity increases with the stiffness of soil and varies between 60m/s for loose soils and 2700 m/s for hard rock. Accordingly, the dynamic shear modulus value is observed to range between 0.06 x 10^5 KN/m^2 for silty clayey soils and 190 x 10^5 KN/m^2 for hard granite rock. This exponential increase is due to the multiplication of soil density with the square of shear wave velocity. Similarly, the horizontal and rocking spring constant values of the soil / rock units increase in range between 3.0 and 143.0 x10^5 for loose soils and 22.9 to 27.1 x 10^8 KN/m for hard rock respectively. The time period of the building in general decreases with the increase of stiffness of the soil. The time period of the building with two bottom soft stories ranges from 2.75 sec. for clayey soils to 0.62 sec. for hard rock; whereas for building without soft stories, it varies from 2.68 sec. for clayey soils to 0.35 sec for hard rock. This attributes that the variation in time period of the building with or without soft stories at lower level is insignificant when the building rests on loose soils; however this variation is observed significant when the building rests on stiff soils / hard rock. From the above, it can be concluded that the variation in response is less when the flexible structures rest on stiff soils / rock and is more when rigid structures rest on flexible soils.

8. Conclusions

- From present study, it is observed that structures resting on hard rock or firm soil behave well during an earthquake than the structures resting on loose soils.
- It is noticed that shear wave velocity influences significantly the change in shear modulus of soil and accordingly the horizontal and rocking spring constant values increase exponentially from loose soil to hard rock.
- The fundamental time period of the building invariably decreases with the increase of soil stiffness. However, for buildings with cellar floors this variation is not much in case of loose soils; whereas for similar buildings without cellars this variation is significant when they rest on stiff / hard rock.
- The fundamental frequency and time period values of the building when it is assumed to rest on hard rock (Type S5) are very close to the values obtained when the building is assumed fixed at the base. This shows that the SSI effect when the structure rest on stiff soil / hard rock is insignificant and can be neglected.

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