International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2015): 6.391

Influence of Soil-Structure Interaction on Response of a Multi-Storied Building against Earthquake Forces

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Abstract: ***In the analysis of structures subjected to earthquake forces, it is usually assumed that the structure is fixed at the base to simplify the mathematical problem. This assumption leads to gross error in assessment of overall response under dynamic loads. Past history records reveal that the rate of occurrence of earthquakes is an increasing phenomenon. In recent years, many failure examples of rigid structures resisting on flexible soils made considerable advanced studies in the field of soil-structure interaction. The interaction phenomenon is principally affected by the mechanism of energy exchanged between the soil and the structure during an earthquake. In the present investigation, the location of new capital Amaravati of the state Andhra Pradesh is chosen as the study area which consists of different types of soil / rock profiles at different locations. Many high rise structures are expected in future in the new city. The influence of soil – structure interaction on seismic response of such high rise buildings is a major concern to incorporate the necessary changes in designing such structures. A twelve storied building (multi-storied building), with lower two stories for parking (soft stories) and the remaining ten stories for commercial and residential purpose, and is chosen for the analysis. This region falls under seismic zone III. Earthquake analysis is carried out when similar structure rests on different types of soils and the results of fundamental time periods, base shears and displacements are compared with the results obtained from fixed base condition. The investigation indicates the necessity of considering soil-structure interaction, particularly when the structure rests on loose soils.***

Keywords: Soil-structure-interaction, Shear wave velocity, free vibration, spring constant, Time period, Shears and Storey Displacement.

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 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. Alaska &Nigata (1964), Kobe (1995), Bhuj (2001) and Indonesia (2004) earthquakes 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, shear and displacement of the structure.

Damage sustained in earthquakes, have also highlighted that the seismic behavior 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 that it is 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. In recent years, many failure examples of rigid structures resisting on flexible soils made considerable advanced studies in the field of soil-structure interaction. 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. Modeling of soil requires representation of soil stiffness, mass and damping characteristics allowing for strain-dependence and variation of soil properties. Since the structures are usually designed for gravity loads, translational and rocking springs of soil also considered in the present study.

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.

In the present study, soil- structure interaction has been carried out for a multi storied building subjected to gravity as well as seismic loads using free vibration analysis. The analysis has been carried out considering the building rests on five different types of soils. Various combinations of dead, live and seismic loads are considered as per IS-1893 (Part-1): 2002. The results of fixed base condition are compared with the results obtained considering soil – structure interaction when the building rests on different soils to obtain the parameters like displacements, time periods and base shears at different floor levels.

1.1. Soil-Structure Interaction (SSI):

Most of the civil engineering structures involve some type of structural element with direct contact with ground. When the external forces, such as earthquakes, act on these systems, neither the structural displacements nor the ground displacements, are independent of each other. The process in which the response of the soil influences the motion of the structure and the motion of the structure influences the response of the soil is termed as soil-structure interaction (SSI). Conventional structural design methods neglect the SSI effects. Neglecting SSI is reasonable for light structures in relatively stiff soil such as low rise buildings and simple rigid retaining walls. The effect of SSI, however, becomes prominent for heavy structures resting on relatively soft soils for example nuclear power plants, high-rise buildings and elevated water tanks on soft soil.

2. Proposed Work

The location of new capital Andhra Pradesh is already established that is located near the right side down stream River Krishna covering two districts Krishna and Guntur, having latitude 15° 38' N and longitude 77° 19' E. Many high rise structures are expected in the new city in future. This area falls under seismic zone III, and covered by different types of geomorphic units like black cotton soil, silty sand, gravel under some places different types of rocky soils. The interaction of multi-storied structures with these soils plays vital role in response of such structures during an 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 commercial and residential purpose, resting on five different types of homogeneous soils, is chosen for the analysis. The dimensions and properties and the structural element of the building are presented in table 1&2. The building consists of 3 bays in X-direction and 6 bays in Z-direction, plan and elevation of building is shown in fig 1(a) and (b).

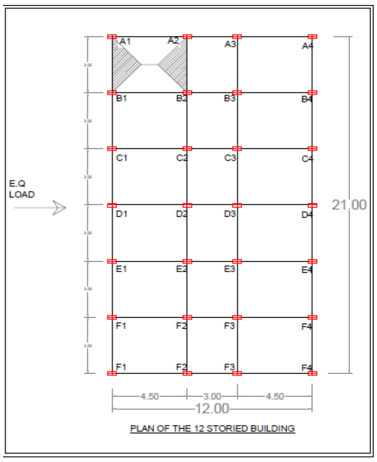


Figure 1(a): Plan of the building

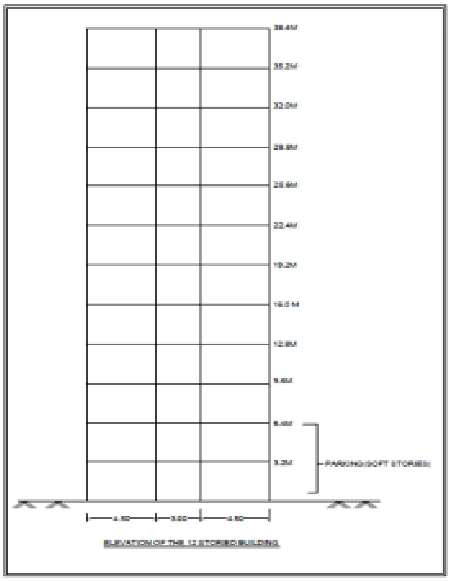


Figure 1: Elevation of the building

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 and shallow foundations, the soil / rock units of the study area are classified into five types for the analysis as given below

Type **S1** – clay
Type **S2** – stiff clay
Type **S3** – coarse gravel & murrum (soft rock)
Type **S4** – sand stone or laterite
Type **S5** – Hard rock (granite)

Table 1: Dimensions of structural elements

parameter	*Dimension/s*
Height of the building	38.4m
Height of each storey	3.2m
Number of stories	12(2 soft +10)
Column size	0.23m x 0.5m
Longitudinal beams	0.23m x 0.35m
Transverse beams	0.23m x 0.5m
Plinth beams	0.23m x o.35m
Slab thickness	0.12m
Exterior wall thickness	0.23 m
Interior wall thickness	0.115m
Parapet wall height	1m

Table 2: Properties of materials and different loads

Grade of concrete	M25
Grade of steel	Fe 415
Unit weight of RCC	25 KN/ m^3
Unit weight of brick work	19 KN/ m^3
Live load (floor)	4.00 KN/ m^2
Live load (terrace)	1.50 KN/ m^2
floor finish	1.0 KN/ m^2
Terrace finish	1.5KN/ m^2

3. Geo-Technical Properties of Various Geomorphic Units

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. The values of shear wave velocity and Poisson's ratio of the five classified types of soil / rock units, that are suggested by D.J. Dowrick are taken for the use in the analysis and are presented in Table 3.

Table 3: soil parameters

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)	$KN\text{-}m^2/m^4$	1.7	1.8	1.9	2.1	2.6
Poisson's ratio (μ)	-	0.4	0.4	0.33	0.30	0.30
Shear modulus $(G_s) = \rho * V_s^2$	$KN/m^2 x 10^5$	.0612	.405	3.04	32.812	189.54
Young's modulus (E_s)	$KN/m^2 x 10^5$	.1775	1.134	8.086	85.31	492.80
Bearing capacity (p)	KN/m^2	60	200	300	400	500

4. Mathematical model for analysis

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.

4.1 Foundation Model

In this present study five different soils are taken for the analysis, for that we have to choose appropriate foundation, at which first two soils are clayey soils where deep foundation is required, in S3soils there is overlapping due to isolated footing for that to minimize the differential settlements mat / raft foundation is chosen, for S4 and S5 soils the suitable foundation adopted is isolated footing, these are presented in table 4. Building codes such as International Building code (2006) generally permit an increase of 33% in allowable bearing capacity when earthquake loads in addition to static loads are used in design of the foundation.

Table 4: foundation details for various soils

Type of soil	*Type of foundation*
S1	Pile/Mat/footing
S2	
S3	Mat/footing
S4	footings
S5	

4.2 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 is used to model the 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 and plan of the building is symmetrical, 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 suggested by Novak and EI-Sharnouby Formulae (1983), Whitman and Richart (1967) .

4.2.1 Equivalent Stiffness of soil for footing:

1) Horizontal stiffness, k_x (kN/m) $= 2(1+\nu)\, G\beta_x\, (BL)^{½}$

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

Where

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

$\beta_x$and β_ψ - Coefficients that are functions of L/B ratio as in figure 2

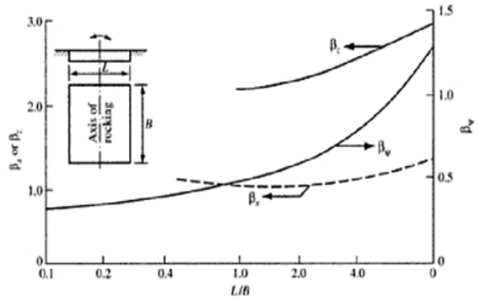


Figure 2: constants for rectangular basis (whitmen and richart)

4.2.2 Equivalent Stiffness of soil-pile

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

Translational stiffness $K_x=[\frac{Ep * Ip}{ro^3}] *f_{x1}$

Rocking stiffness $K_\psi= [\frac{Ep * Ip}{ro}] *f_{\psi1}$

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

$f_{x1}, f_{\psi1}$ are Novak's coefficients

4.3 Structure Model

A twelve storey building 21m x12m size in plan, with two soft stories at bottom for parking and other floors for office residential and commercial purpose ,has been chosen 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 (10), 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 infill walls, the system is modeled as a braced frame approximating the infill wall as an equivalent diagonal strut.

The vital approach to determine the effective width of equivalent diagonal strut (w_e) which depends upon

The length of contact between the wall and the column, α_h and the length of contact between the wall and the beam, α_l.

where

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

The formulations of Stafford Smith (1966) given below are used to calculate stiffness of infill wall, k_w.

$k_w = \frac{AE_m \cos^2\theta}{l_d}$ in which, $l_d = \sqrt{h^2 + l^2}$; $\theta = \tan^{-1}\left[\frac{h}{l}\right]$, $A = w_e x\, t$ 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, $k = \sum k_c + \sum k_w$.

The soil mass (m_0) for each type of soil is worked out considering the weight of the foundation and the weight soil above it. The mass, stiffness values of structure and soil are presented in the table5 & 6.

Table 5: Mass and stiffness values of structure

Stiffness (KN/m)x10^6	$k_{1,2}$	1.02
	$k_{3\text{-}12}$	5.11
*Mass (KN-**sec**^{2}/m)*	m_1	206.3
	m_2	276
	$m_{3\text{-}11}$	3433
	m_{12}	226

Table 6: mass and stiffness values of soil/rock

parameter		*Type of foundation*	*Mo*	*I*	k_x	k_ψ
Units			KN.sec^2/m	KN.m.sec^2	KN/m*10^6	KN.m*10^6
Type of soil	S1	pile	972	57242	1368	35890
	S1	mat	1110	58901	.298	19.04
	S2	Pile	863	55931	4694	54000
	S2	footing	670	53616	8.57	30.618
	S3	mat	955	57037	13.47	490.9
	S3	isolated footing	530	51937	46.1	255.3
	S4		431	50749	407	1717
	S5		401	50380	2091	5680

5. Free Vibration Analysis

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

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

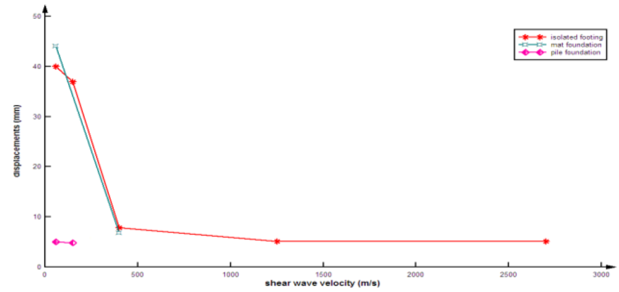
Where [m] – Mass matrix,[k] – Stiffness matrix,

$\ddot{x}$ – Horizontal acceleration, x – Horizontal displacement.

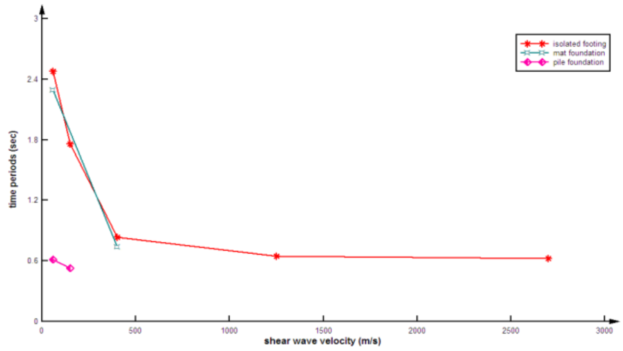
Undamped free vibration analysis is carried out to obtain the time periods, base shears, and storey displacements when the building rests on the five categorized types of soil/rock units treating the building as one with 14 degrees of freedom and also when the building is assumed to be fixed at the base treating it as one with 12 degrees of freedom. The values are tabulated in Table 7 and these values presented in graph 1 with different combinations of soil and structural parameters.

Table 7: frequency, time period, displacements and storey shears

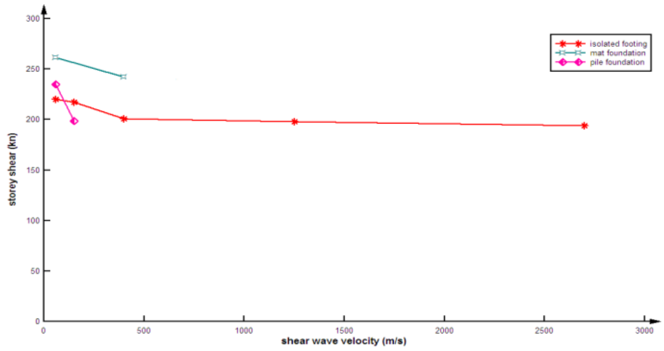
Parameter		Frequency (Hz)	Time period (sec)	Displacements (mm)	Storey shear (KN)
S1	pile	1.628	.614	5	224.2
	mat	.436	2.29	6.4	261.2
S2	pile	1.629	.6138	5.2	214.1
	Footing	.558	1.79	3.72	217
S3	mat	1.35	.7394	7.78	242
	Footing	1.2	.8332	7.8	201
S4		1.54	.6485	5.1	198
S5		1.6	.6235	5.9	194
Fixed base		1.63	.6126	4.5	172



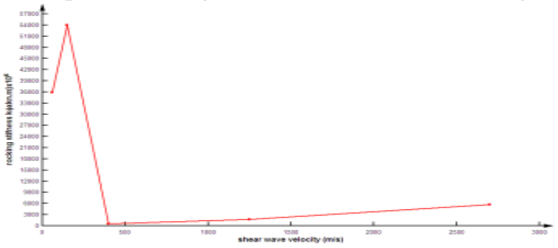
Graph 1(a) displacements Vs shear wave velocity



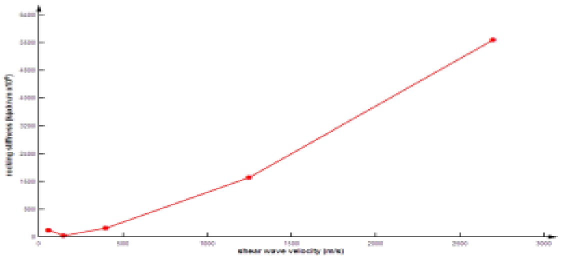
Graph 1(b) time period Vs shear wave velocity



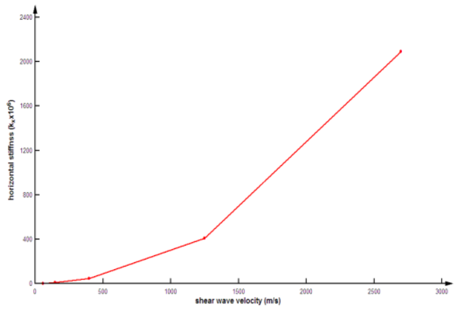
Graph 1(c) storey shear Vs shear wave velocity



Graph 1(d) rocking stiffness vs shear wave velocity(pile to footing)



Graph 1(e) rocking stiffness vs shear wave velocity (mat to footing)



Graph 1(f) horizontal stiffness vs shear wave velocity

6. Conclusions

In spite of many scientific and research advancements during last century, the threat of natural disasters, particularly earthquake and cyclones has remained untamed. Previous geological evidences and failure examples show that rate of occurrence of such events will increase in future. Rapid growth of population in capitals and other cities situated in seismic regions, the potential for massive destruction increases against future earthquakes.
From the results obtained, the following conclusions are presented below.

- The shear wave velocity influences significantly in changing the shear modulus of different soils from static to dynamic state. It is noticed that dynamic shear modulus exponentially increases with the increase of shear wave velocity.
- The horizontal and rocking soil spring constant values increase when type of soil varies from loose soil to hard rock
- It is also noticed that these values are high in case of pile foundations when compared to the isolated footing type of foundation.
- Fundamental time period of the building invariably decreases with the increase of soil stiffness. In loose soils like silty clay and silty sand, where normally pile foundations are preferred, these time period values decrease compared to the values obtained when isolated footing type foundation is provided.
- The base shear values obtained are the lateral shears transferred from soil to the base of the structure due to effect of soil – structure interaction.
- It is noticed that the shears and displacements are high in case of loose soils compared to those of very stiff/ hard soils.
- When pile or mat foundations is used in place of isolated footing, these values are observed decreasing.
- It is also noticed that the increase in shears and displacements with the decrease of soil stiffness is mainly due to the contribution from rocking spring constant compared to horizontal spring constant values of soil.
- In general, it can be concluded that structure resting on stiff soils or rock behave well during earthquake than structures resting on loose soils.

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