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Earthquake Response Of Structures Under Different Soil Conditions

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Abstract

Earthquake is a spasm of ground shaking caused by sudden release of energy in the earth's lithosphere. It is an endogenous natural hazard which occurs sudden and destruction takes place within a short period of time. History and geological evidences show that the rate of occurrence of earthquakes has become a frequently recurring phenomenon all over the world. Bitter experiences left by past earthquakes, especially in urban regions; reveal the importance of terrain evaluation and influence of soil-structure interaction on response of structures during earthquakes.

In the present study, a part of Vijayawada city, located on eastern side of the state Andhra Pradesh, India, covered by many high rise buildings supported on different type of soils, is chosen as study area. A conventional three storied building when rests on different soils is chosen for the study. Earthquake analysis is carried out using mode superposition method as given in IS 1893 – 2002[5] and the response parameters like; frequencies, time periods, base shears and displacements are obtained when the structure rests on different soils or rocks. The influence of soil-structure interaction is compared with the results obtained when the structure is assumed to be fixed at the base. In the present study, it is observed that the fundamental natural frequencies increase and base shears decrease with the increase of soil stiffness and this change is found more in soft soils. In general, it is seen that the displacements increase with the decrease of soil stiffness, which is mainly attributed due to rocking effect of the soil. Hence soil–structure interaction cannot be ignored while designing important structures like nuclear power plants, liquid storage structures, dams etc., against expected earthquake forces.

1. Introduction

Though the land, air and water of the planet earth provides cradle for the existence of life , they also cause disasters in the form of earthquakes, wind storms and floods leading to a large scale loss of life and property. Earthquakes are the most devastating phenomena as they occur sudden and bulk of destruction takes place in few seconds. They occur due to the movements along faults that have evolved through geologic and tectonic processes. These earthquakes have been occurring since formation of earth and will continue in future also causing deep anguish in the minds of the people. Most of the loss of life during an earthquake is due to total or partial collapse of manmade structures.

After Killari (1993), Jabalpur (1997) and Bhuj (2001) earthquakes, it is well recognized that no part of India, can be considered to be free of seismic hazard. Subsequently, IS-1893 code was modified in 2002 deleting Zone-I from seismic zone map of India. Advanced countries like USA, Japan are already constructing structures to resist earthquakes of magnitude 7 and above and these structures were found to be safe during earthquakes. Unfortunately, in India, not much awareness has been created in the minds of people on the importance of constructing earthquake resistant structures. Very recently some parts of southern peninsula of Indian sub continent are also subjected to minor to moderate earthquake tremors ranging from M 3.0 to M 4.5 magnitude. Vijayawada, a growing city, covered by many variety of buildings like; apartments with cellar floors, office buildings, godowns etc., supported on different types of soils is situated in seismic zone –III. Influence of soil-structure interaction plays vital role when structures with different configurations under different soil conditions are subjected to earthquake forces. Hence, vulnerability of cities like Hyderabad, Vijayawada etc., against earthquake forces, should be a cause of concern.

2. Soil-Structure Interaction

Usually, when earthquake occurs, seismic waves travel through different rock and soil media and reach the foundation layer causing the structure to vibrate. It has been generally recognized that interaction between soil and the structure can indeed affect the response of structures, especially founded on relatively flexible soils. In the study of soil-structure interaction problem apart from the design parameters of the structure and type of ground excitation, the dynamic properties of soil also play important role in obtaining seismic response.

The method of analysis commonly used by structural engineers assumes the structure to be attached rigidly to the ground; but as the foundation of the structure rests on the soil, it is apparent that the response depends on the properties of the structure as well as the soil. Hence the method of analysis based on soil-structure interaction gives more realistic and reasonable results. The importance of the nature of sub-soil for the seismic response of structures has been demonstrated in many earthquakes like Mexico (1957), Caracas (1967), Turkey (1970), and Bhuj (2001).The dynamic response of a structure resting on soft soils in particular, may differ substantially in amplitude and frequency content from the response of an identical structure supported on a very stiff soil or rock. However, data on many failure examples of rigid structures resting on flexible soils and intensive analytical studies in recent years [6] have made considerable advances in the field of soil-structure interaction and analytical techniques are now available. This interaction phenomenon is principally affected by the mechanism of energy exchanged between soil and the structure. The methods of estimating the basic parameters like, shear wave velocity, poison's ratio, shear modulus and damping ratio, are suggested by Whitman and Richart[2] and typical values of these parameters are given in table.1.

Type	Description of soil or rock	Shear wave velocity V_s (m/s)	Mass density ρ $\frac{KN\text{-}sec^2}{m^4}$	Poisson ratio ' ν '	Shear modulus G ($KN/m^2 \times 10^5$) = $V_s^2 * \rho$
I	Clay	150	1.85	0.40	0.42
II	Fine to Medium Sand	400	1.90	0.33	3.04
III	Weathered Rock	1250	2.10	0.30	32.81
IV	SemiWeathered Rock	2700	2.60	0.30	189.5
V	Hard Granite	150	1.85	0.40	0.42

Table 1 Types and Properties of Soil or Rock

3. Presentation of The problem

a) Soil model:

Modeling of soil requires representation of soil stiffness, mass and damping characteristics allowing for strain-dependence and variation of soil properties. The structure is assumed to rest on a uniform elastic half-space and soil spring approach [4] is used to model the soil-structure interaction. Since the structures are usually designed for gravity loads, only translational and rocking springs are considered in the analysis. These equivalent soil spring constants [2] are worked out for different classified soils based on work done by Whitman and Richart (1967) and in the present analysis, rectangular type footing is adopted for building. Damping at soil-foundation interface arises from two sources: one the material damping from the non-linear properties of the soil and the other radiation damping due to transmission of energy away from interface by radiating waves. These damping values depend upon the type of structure, foundation and stiffness of soil. The damping obtained from soil-structure interaction normally ranges from low value for flexible structures on rigid foundations to a higher value for rigid structures on flexible foundations.

Equivalent Stiffness values of soil springs are worked out as follows and presented in table 2

Type of structure	:	Building
Type of foundation	:	Rectangular
Equivalent Horizontal stiffness k_x (KN/m)	:	$2(1+\nu)G\beta_x(BL)^{1/2}$
Equivalent Rocking stiffness k_Ψ (KN/m)	:	$\frac{G}{(1-\nu)}\beta_\Psi BL^2$

Note: β_x and β_Ψ are constants that are functions of dimensional ratio L/B as shown in fig. 1

B is the width of the footing in the direction of horizontal excitation

L is the length of the footing in the direction of horizontal excitation

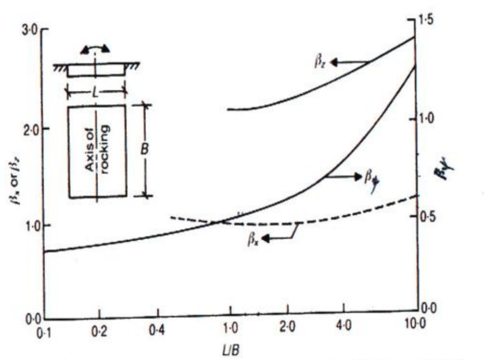

Fig1 Constants β_x, β_ψ, β_z for rectangular bases (after Whitman & Richart [1967]

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Table 2 Results of Horizontal & Rocking Stiffness values for different Soil Springs

Sl. No.	Description of Soil / Rock	Stiffness value in KN / m x 10^6	
		Horizontal k_x	Rocking k_Ψ / h^2
1	Clay	1.235	3.257
2	Fine to Medium Sand	6.434	10.129
3	Weathered Rock	40.756	50.424
4	Semi Weathered Rock	327.605	230.40
5	Hard Strata	1419.276	561.472

b) Structural Model:

A three storeyed office building 18.5 m x 11.5 m size in plan with a storey height each of 3.35 m resting on different types of soil is chosen for the analysis. The spacing of columns in longitudinal direction is 3.7m. An intermediate cross frame of the chosen building mentioning the beam and column sizes is shown in fig 2. In the analysis four different types of cases based on its structural configuration mentioned below are considered:

Case 1: G.F cellar and F.F & S.F floors with only outer walls.
Case 2: G.F cellar and F.F & S.F both with outer walls and inner infill walls.
Case 3: G.F, F.F&S.F are with outer walls only
Case 4: G.F, F.F&S.F are with outer walls and inner infill walls

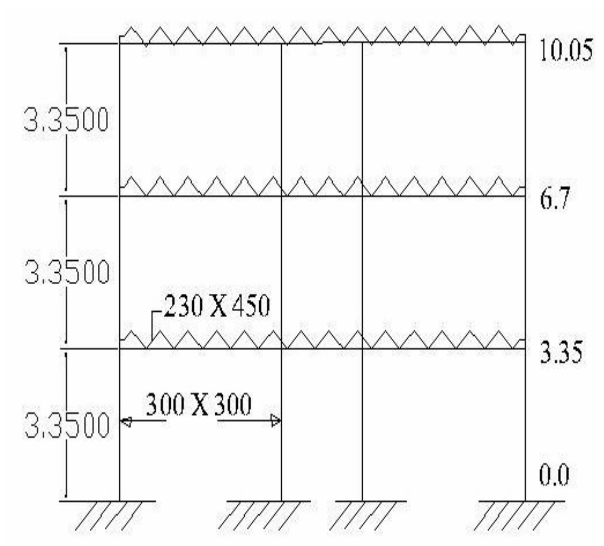

Figure 2 Intermediate Cross Frame

c) Mathematical Model of Building:

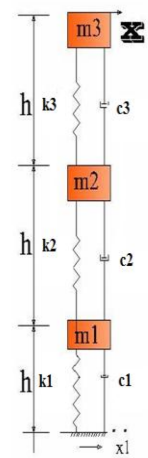

Figure 3(a)
(With Fixed base)

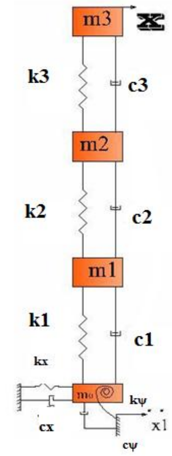

Figure 3(b)
(With Soil-Structure Interaction)

The masses are lumped at each storey level and equivalent stiffness values of all columns in each storey are represented as springs at each story level. The structure is idealized as a mass - spring - dashpot system treating it as one having three degrees of freedom with fixed base condition and five degrees of freedom when soil-structure interaction is considered as shown in fig.3(a) & 3(b). The stiffness of each storey is evaluated considering the effect of stiffness of infill walls also. In case of the storey without infill walls, each column stiffness value is taken as $k_c = 12 E_c I_c / h^2$ and the stiffness of each storey is worked out. In case of storey with infill walls, the system is modeled as a braced frame approximating the infill wall as an equivalent diagonal strut [3]. The vital approach is to determine the effective width of the equivalent diagonal strut (w_e) which depends on
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

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

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

$$k_w = \frac{A E_m \cos^2\theta}{l_d} \qquad (1)$$

In Eq. 1,

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

$$w_e = \frac{1}{2}\sqrt{\alpha_h^{\ 2} + \alpha_l^{\ 2}},$$

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 $k_x = \sum k_c + \sum k_w$.

The masses and equivalent stiffness values of each storey for each type of structure are worked out for the use in the analysis.

4. Method of Analysis

In analyzing the structure subjected to time – varying forces, a mathematical model with masses and springs as explained above is used. The equation of motion for a system can be derived by considering the equilibrium of all forces acting at the nodes which can be written as

$$F_i + F_d + F_g = F(t) \qquad (2)$$

Where F_i - Inertia force vector

F_d - Damping force vector

F_g - Internal resisting force vector

F (t) - Externally applied dynamic load vector

For linear systems, these forces can be expressed as

$$F_i = [M]\{\ddot{x}\} \; ; \; F_d = [C]\{\dot{x}\} \; ; \; F_g = [K]\{x\}$$

where

[M] - Mass Matrix

[C] - Damping Matrix

[K] - Stiffness Matrix

$\{\ddot{x}\}$ - Acceleration vector relative to ground motion

$\{\dot{x}\}$ - Velocity Vector relative to ground motion

$\{x\}$ - Displacement Vector relative to ground motion

Equation (2) can be written as

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = F(t)$$

When the structure is subjected to ground acceleration $\{\ddot{y}\}$ then,

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -[M]\{\ddot{y}\} \qquad (3)$$

The dynamic analysis of linear systems of the structure requires solution of simultaneous equations, which will give rise to displacement, velocity and acceleration time history for the given time dependent load F (t).

For free vibration analysis, the natural periods and mode shapes are determined using the following equation

$$[M]\{\ddot{x}\} + [K]\{\dot{x}\} = 0$$

The equations of motion for building model with soil-structure interaction are,

i. $m_3 \ddot{x}_3 + k_3 (x_3 - x_2 - \theta h) = 0$

ii. $m_2 \ddot{x}_2 + k_2 (x_2 - x_1 - \theta h) - k_3 (x_3 - x_2 - \theta h) = 0$

iii. $m_1 \ddot{x}_1 + k_1 (x_1 - x_0 - \theta h) - k_2 (x_2 - x_1 - \theta h) = 0$

iv. $m_0 \ddot{x}_0 + k_x x_0 - k_1 (x_1 - x_0 - \theta h) = 0$

v. $I \ddot{\theta} + k_\theta \theta + m_3 \ddot{x}_3 (3h) + m_2 \ddot{x}_2 (2h) + m_1 \ddot{x}_1 (h) = 0$

where $I = I_1 + I_2 + I_3$

and I - Mass moment of inertia of all storey masses

Putting the above equation in matrix form

$$\text{Mass Matrix } [M] = \begin{pmatrix} m_3 & 0 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 & 0 \\ 0 & 0 & m_1 & 0 & 0 \\ 0 & 0 & 0 & m_0 & 0 \\ 0 & 0 & 0 & 0 & I/h^2 \end{pmatrix}$$

$$\text{Stiffness Matrix } [K] = \begin{pmatrix} k_3 & -k_3 & 0 & 0 & -k_3 \\ -k3 & k_2+k_3 & -k_2 & 0 & k_3-k_2 \\ 0 & -k_2 & k_2+k_1 & -k_1 & k_2-k_1 \\ 0 & 0 & -k_1 & k_1+k_x & k_1 \\ -k_3 & k_3-k_2 & k_2-k_1 & k_1 & k_1+k_2+k_3+(k_\Psi/h^2) \end{pmatrix}$$

Using free vibration analysis software, the fundamental natural frequencies and time periods of structures with different configurations that rest on different soils are obtained. The summarized results are given in tables 3&4. The variation of fundamental time periods and fundamental natural frequencies with shear wave velocity is shown in figures 8, 9 respectively.

Using mode super position of analysis, the base shears and displacements are obtained and presented in tables 5& 6. These results are compared with the results obtained from fixed base condition. The base shears and displacement parameters are also worked out when the structure is located in seismic zone III and the results are plotted as shown in figures 10&11. The response spectra for rock and soils as given in IS 1893-2002[5] is used in the analysis. For the calculated time periods of different cases, S_a / g values are obtained using the above response spectra and seismic zone III factor given in IS 1893-2002 code is used. In the analysis, for both interactive and non-interactive systems, a constant structural damping ratio of 5% is taken.

5. **Result Analysis**

In the present analysis, soil-structure interaction effect during an earthquake is considered which showed significant changes in the result on the design parameters of the structure. The shear wave velocity is an important parameter which influences the dynamic behavior of geo-technical properties like shear modulus, damping and poison's ratio. The dynamic shear modulus is found to range between 0.06× 10^5 KN/m^2 in case of loose material and 190 × 10^5 KN/m^2 for hard rock. The time periods of the structure invariably decrease with the increase in stiffness of soil / rock materials.

The time periods range in the order of 1.0 to **0.12** seconds in the buildings with different types of structure parameters and soil conditions. This indicates that time period for building varies significantly, if soil – structure interaction effect is considered. This is mainly due to the fact that buildings with high stiffness on loose soils behave differently. Base shears have shown significant variation with high values for structures resting on loose soils and low values in case of hard rock. This attributes mainly due to more absorbing energy capacity of soils when compared to rock materials. Further it is found that the displacement for buildings with cellar (Cases 1&2) are more compared to the displacement of buildings without cellar (Cases 3&4) and this variation is significant for buildings resting on hard soils.

However this variation in case of shears is insignificant irrespective of the configuration of building with or without cellar. This is mainly because the base shear depends upon the weight component.

Table 3 Results of Fundamental Natural Time Periods

Sl. No.	Description of Soil / Rock	Building (Fundamental Natural Time Periods) in			
		Case 1	Case 2	Case 3	Case 4
1	Clay	0.93	0.98	0.87	0.91
2	Fine to Medium Sand	0.61	0.64	0.50	0.51
3	Weathered Rock	0.47	0.49	0.26	0.24
4	Semi-Weathered Rock	0.44	0.46	0.18	0.15
5	Hard Granite	0.44	0.46	0.17	0.13
6	Fixed at Base	0.44	0.45	0.16	0.11

Table 4 Results of Fundamental Natural Frequencies

Sl. No.	Description of Soil / Rock	Building (Fundamental Natural Frequencies) in rad			
		Case 1	Case 2	Case 3	Case 4
1	Clay	6.71	6.39	7.14	6.84
2	Fine to Medium Sand	10.15	9.71	12.56	12.21
3	Weathered Rock	13.18	12.65	24.02	25.44
4	Semi-Weathered Rock	14.0	13.4	33.3	41.70
5	Hard Granite	14.1	13.6	35.7	48.2
6	Fixed at Base	14.23	13.67	37.66	54.14

Table 5 Results of Base Shears

Sl. No .	Description of Soil / Rock	Base Shears in KN			
		Case 1	Case 2	Case 3	Case 4
1	Clay	191.4	198.4	199.6	208.5
2	Fine to medium	141.3	148.2	171.6	187.1
3	Weathered Rock	116.4	130.7	138.4	153.7
4	SemiWeathered Rock	87.52	93.02	105.2	124.3
5	Hard Granite	82.66	92.01	94.23	110.3
6	Fixed at Base	75.68	81.10	82.83	93.30

Table 6 Results of Displacements

Sl. No .	Description of Soil / Rock	Displacements in mm			
		Case 1	Case 2	Case 3	Case 4
1	Clay	4.3	4.5	3.6	3.8
2	Fine to Medium	2.48	2.6	1.579	1.644
3	Weathered Rock	1.749	1.905	0.470	0.402
4	SemiWeathered Rock	1.369	1.427	0.257	0.162
5	Hard Granite	1.352	1.408	0.222	0.123
6	Fixed at Base	1.34	1.395	0.198	0.096

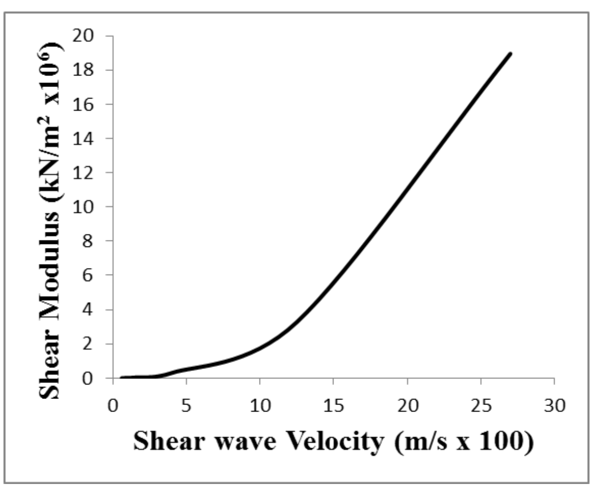

Figure 4. Variation of Shear Modulus with shear wave velocity

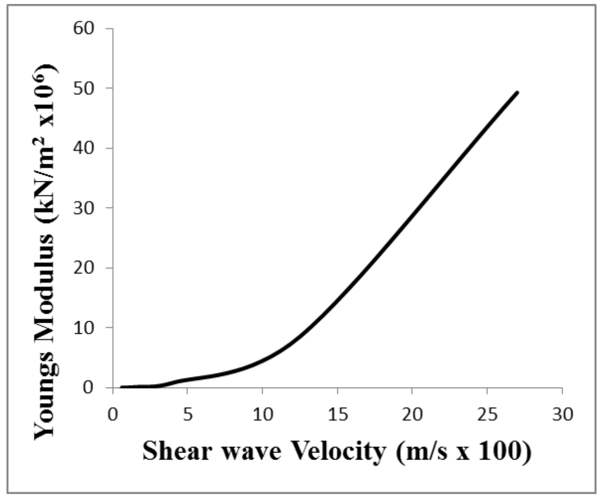

Figure 5. Variation of Young's Modulus with shear wave velocity

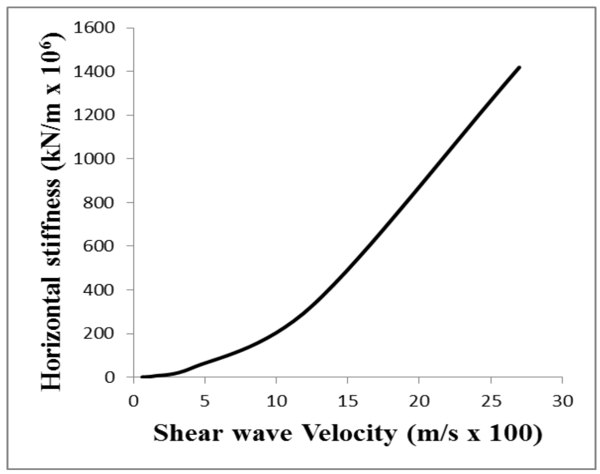

Figure 6. Variation of Horizontal stiffness with shear wave velocity

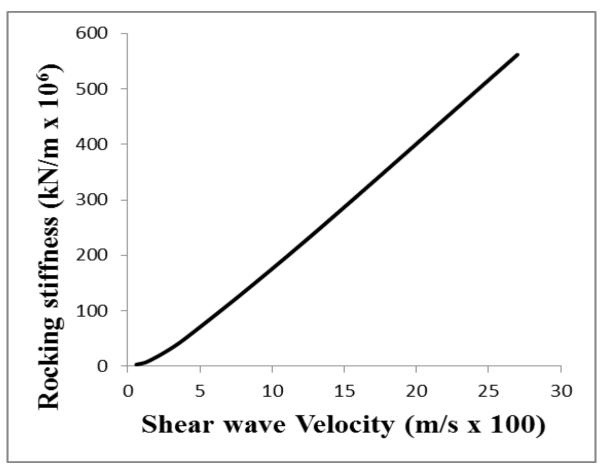

Figure 7. Variation of Rocking stiffness with shear wave velocity

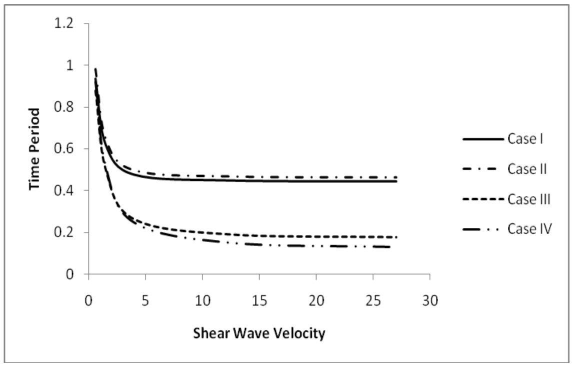

Figure 8. Variation of Time periods with shear wave velocity

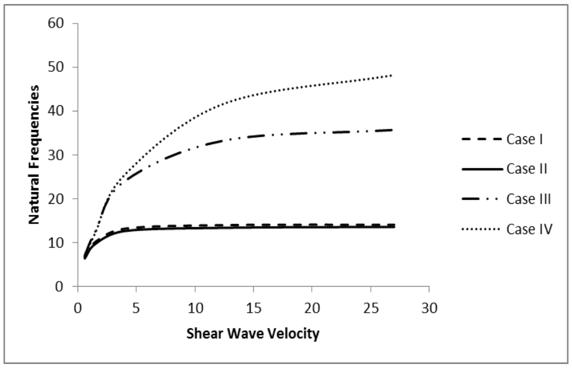

Figure 9. Variation of Natural frequencies with shear wave velocity

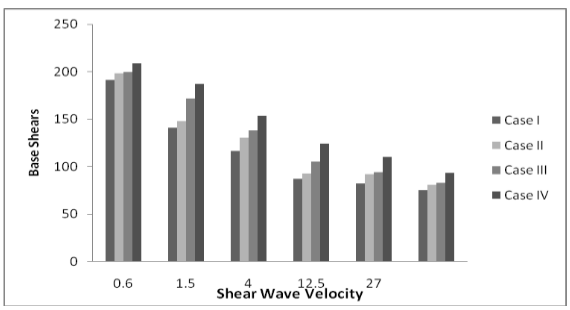

Figure 10. Variation of Base shears with shear wave velocity

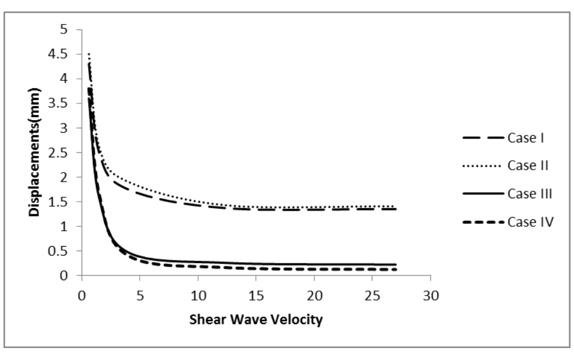

Figure 11. Variation of Displacements with shear wave velocity

6. Conclusions

i.) Time periods of the structure invariably decrease with the increase of soil stiffness. The time periods for buildings with cellar are observed more compared to the buildings without cellar.

ii.) Due to earthquake forces, base shear decreases with the increase of soil stiffness. However, the variation in shear is insignificant irrespective whether the buildings are with or without cellar.

iii.) In general, it is seen that the displacement values increase with the decrease of soil stiffness, which is mainly attributed due to the rocking effect of the soil.

iv.) It is also observed that there is a wide variation in the decrease of displacements from loose soil to hard rock at ground floor level when compared with the displacements at top storey level.

v.) The soil damping normally ranges from low value for flexible structure on rigid foundation to a high value for rigid structures on flexible foundations. Particularly for structures like nuclear power plants, which are more rigid than high rise buildings, the influence of soil-structure interaction is more significant.

vi.) It is necessary to consider soil-structure interaction effect when structures rest on loose soils.

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