Seismic Study of 400 m High RC Chimney

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Abstract – *In the era of industrialization, there is an increased need for air pollution control which has made tall RC chimneys a common structure. These chimneys help in discharging the toxic gases to higher elevation without polluting the lower atmosphere. This paper deals with dynamic analysis of RC chimney with height of 400 m using FEAST/PreWin software, general purpose finite element software developed by Vikram Sarabhai Space Centre, Thiruvanathapuram. The main purpose is to study the effect of various soil conditions on the frequency of chimney and to study the trend shown by displacement and acceleration with different earthquake excitations like El-Centro, Superstition Hills, Northridge and Loma Prieta.*

*Key Words***:** Tall RC chimney, varying cross-section, FEAST/PreWin software, 3D integrated chimney-pile-raft-soil system, varying soil types, spring simulation of soil, base excitations, displacement and acceleration.

1. INTRODUCTION

A chimney is a structure which provides a way out for the hot gases. It is usually constructed vertically for smooth flow of gases. With the rapid industrialisation, need for control of air pollution became crucial. For this, taller chimneys are becoming the need of the time.

Industrial chimneys are generally located adjacent to steam generating furnaces. The use of reinforced concrete has almost replaced brick as structural component as they are self-supporting structures which are able to withstand the different wind and earthquake loads.

Any collapse to such chimneys cause severe problem to the industries. It is thus necessary to prevent the collapse of tall chimneys. So accurate seismic studies are important in this area.

The Soil Structure Interaction (SSI) problem has become an important feature of structural and geotechnical engineering, particularly for the massive constructions on soft soils. Analysis of chimney is generally carried out assuming fixed base ignoring their foundation and flexibility of underlying soil. Many researches have now shown that flexibility of soil affects dynamic response of chimneys especially under earthquake force.

In the present paper, responses of a 400 m tall chimney with fixed base will be compared with that of same chimney with soil simulation.

Fig -1: Chimney

2. MODELING

FEAST/Prewin software is used for modeling and analysis. The dimensions of 400 m tall chimney [1] is shown in Table 1. Chimney is modeled using 3D beam elements. Studies show that, for large l/d ratio structures like chimneys, 3D beam model is adequate to capture first few lateral frequencies and associated mode shapes as in solid element model. Soil is modeled using solid elements. Piles are modeled using beam elements with appropriate geometric and material properties.

Table -1: Dimensions of Chimney

Dimensions	Base diameter (m)	Top diameter (m)
Outer dimensions	33.5	20.1
Inner dimensions	31.5	18.1

2.1 Geometric Details of the Chimney

The grade of concrete mix used is M30 for chimney and M25 for pile and raft. Corresponding modulus of elasticity value is calculated using the formula taken from the IS code. Poisson's ratio of 0.15 is used.

To model the chimney with varying cross-sectional dimensions as a beam model, the same is divided into 400 beam elements of 1 m each and are separately assigned with calculated average sectional properties for each 1 m.

2.2 Geometric Details of pile, raft and soil

RC friction piles of 20 m length and 1 m diameter were considered. s/d ratio of 3 is selected for present study, where 's' is the spacing between the piles and 'd' is the diameter of the pile. A total of 641 piles are used. The outer diameter of raft was taken as 88m nearly twice of base diameter of chimney. Raft – thickness ratio, Do/t of 22.5 is considered. Thus a thickness of 4 m is adopted for raft. Soil is idealized by single homogeneous strata of 30 m depth (location of bed rock). The boundary of soil should be placed at a sufficient distance from the structure where the static response has died out. In this study, lateral boundary of soil is placed at a distance of 4 times the width of foundation. [2]

To study the effect of SSI, 4 different soils are considered namely S1, S2, S3 and S4 which represents loose sand, medium sand, dense sand and rock respectively. The properties of soil types are shown in Table 2.

Table -2: Properties of the Soil Types

Soil Type	Elastic Modulus, E(kN/m^2)	Poisson's Ratio, μ	Unit Weight, $\gamma(kN/m^3)$
S1	108,000	0.4	16
S2	446,000	0.35	18
S3	1,910,000	0.3	20
S4	7,630,000	0.3	20

2.3 Finite Element Modeling

The integrated pile-raft-soil system was analyzed by finite element method using FEAST/PreWin software. The 400 m tall chimney is modeled using solid element up to 4 m height from bottom and beam element of 1 m each subsequently. The transition of 3D to 1D is done using a rigid link connection which provides a smooth transition and connection without offering any stiffness of its own. This is shown in Fig. 2.

The initial 4 m part of chimney is modeled using solid elements and integrally connected to the raft which is also modeled using solid elements. 641 numbers of 20m long piles are modeled using beam elements of 2m length totaling 10 elements per pile. The soil is modeled using solid elements and its meshing is in such a way that pile node coincides with soil nodes at appropriate location. Thus the soil and piles are connected integrally.
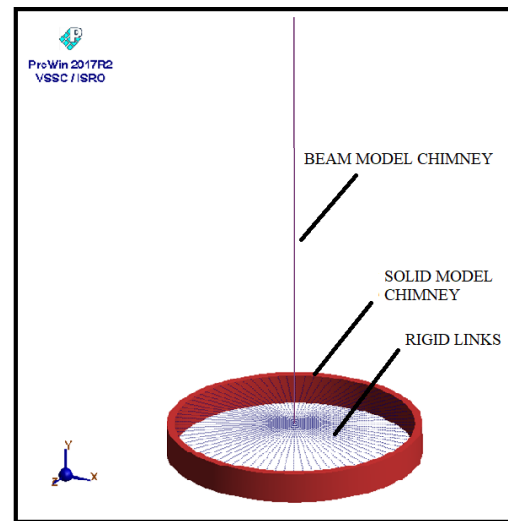

Fig -2: 3D to 1D model transition using rigid links

The pile and raft are given concrete properties (M25) and soil properties are varied to obtain various soil types 1 to 4 using the values given in Table 2. The boundary conditions to soil are given by arresting the lateral movements at the soil boundaries and vertical movements at the bed rock level. Figure 3 shows the integrated chimney-pile-raft-soil system.
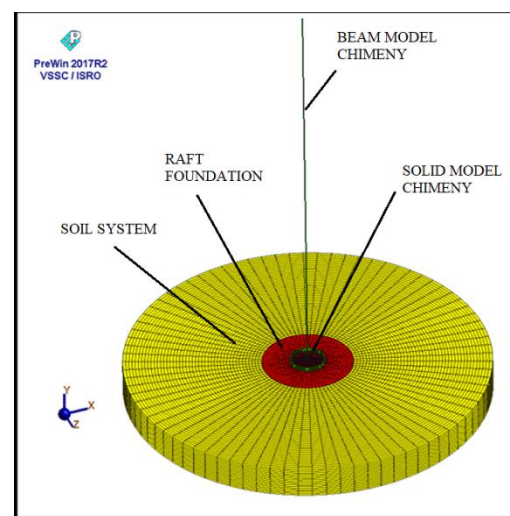

Fig -3: Integrated chimney-pile-raft-soil system.

Free vibration analysis of integrated chimney-pile-raft-pile model by varying soil types were carried out. First lateral frequency of 0.158 Hz, 0.167 Hz, 0.172 Hz, and 0.174 Hz were obtained for soil types 1, 2, 3 and 4 respectively. To reduce this running time, the effect of soil is simulated by modeling spring element at base of chimney which is represented by 3D beam element. One node of the spring is connected to the bottom of the chimney and the other node is fixed. The spring stiffness is arrived to reproduce the first lateral frequency

corresponding to each soil type. The spring constants corresponding to three translations and

rotation about its own axis (Tx, Ty, Tz and Ry) were taken as 1e+14 N/m, 1e+14 N/m, 1e+14 N/m and 1e+14 N/m respectively. Joint rotational stiffness about X and Y axis (Rx and Rz) are assumed to be same for each soil type. They are 9e+12 N-m, 1.7e+13 N-m, 3e+13 N-m, and 4e+13 N-m for soil type1, 2, 3 and 4 respectively.

3. EARTHQUAKES

A number of earthquakes are considered like the El-Centro Earthquake, Superstition Hills Earthquake, Northridge Earthquake and Loma Prieta Earthquake. The time v/s acceleration data of all these earthquakes were converted into Shock Response Spectrum (SRS) data using FEAST/ PreWin Software. This SRS data is used as base excitation to the chimney. The SRS plots of the above mentioned earthquakes are shown in Charts 1 to 4.
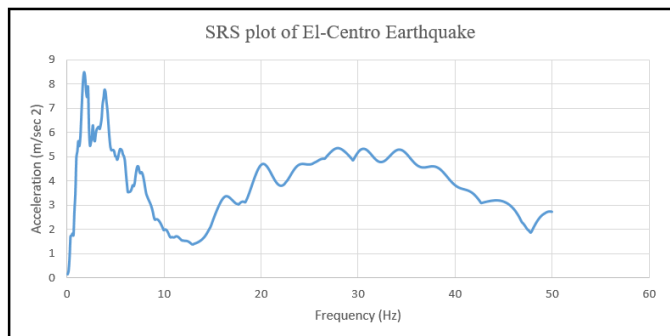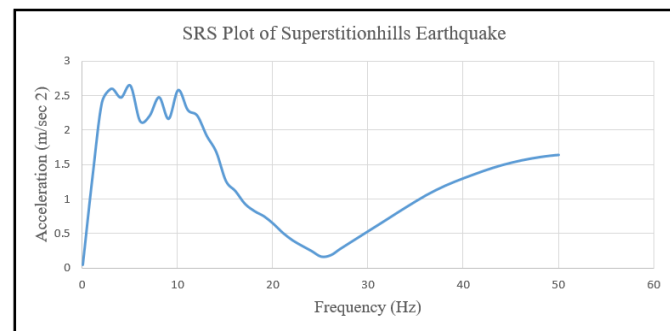

Chart 1: SRS plot of El-Centro Earthquake

Chart 2: SRS plot of Superstition Hills Earthquake

The SRS data of each earthquakes will be made into each functions in FEAST/PreWin software. These functions can be individually used as base excitation and thus the chimney can be anlysed for earthquake excitations. Thus, earthquake study on 400 m tall chimney is possible.[3]
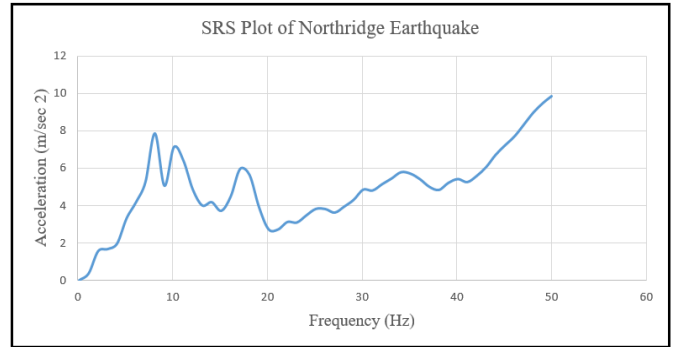

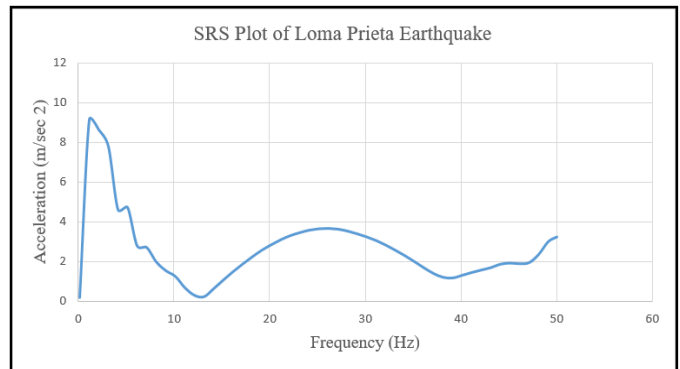
Chart 3: SRS plot of Northridge Earthquake

Chart 4: SRS plot of Loma Prieta Earthquake

4. ANALYSIS AND RESULTS

SRS corresponding to El-Centro Earthquake is applied as base excitation to the chimney and analysis was carried out. Charts 5 and 6 show the history plot for displacement and acceleration for El-Centro Earthquake. Analysis was also carried out with different soil simulations from type 1 soil to type 4 soil.
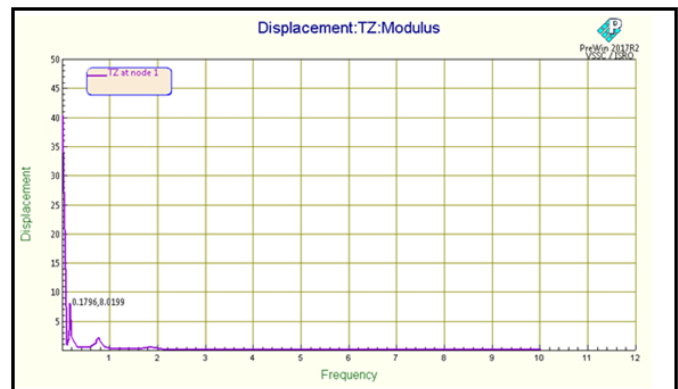

Chart 5: History plot for displacement for fixed base model subjected to El-Centro Earthquake

The responses like displacement at the tip of chimney and acceleration are estimated and are important from designer's point of view. [4]
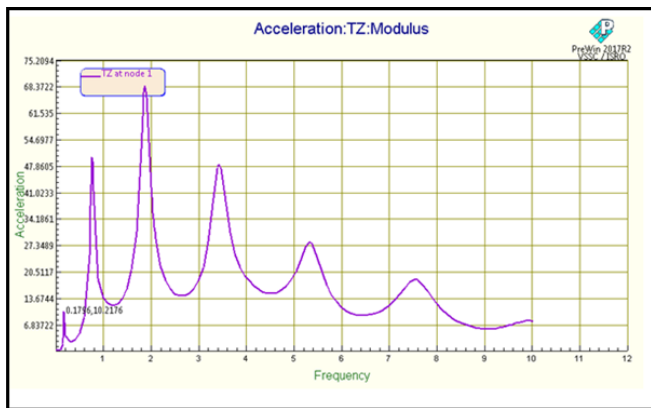
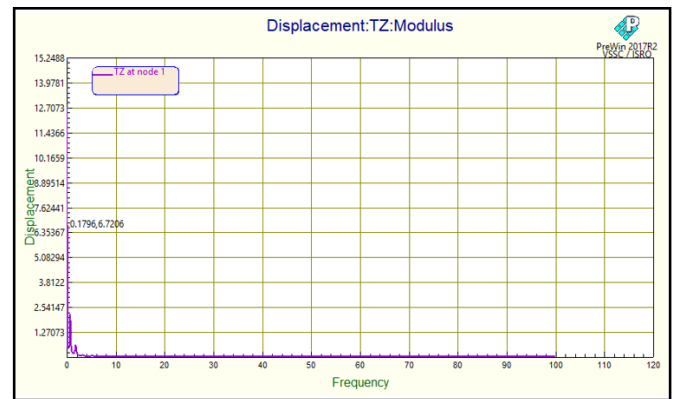**Chart 6**: History plot for acceleration for fixed base model subjected to El-Centro Earthquake

Charts 7 and 8 show the responses under Superstition Hills Earthquake.
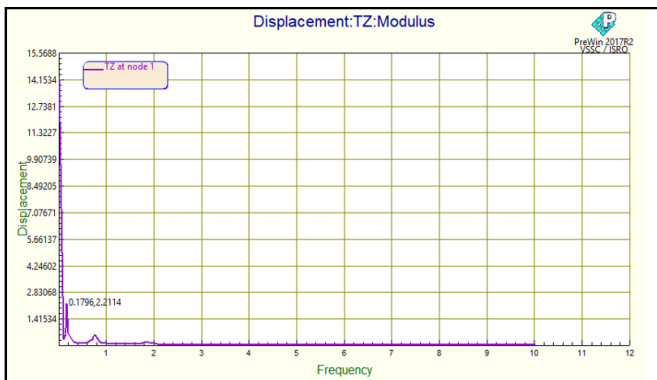

Chart 7: History plot for displacement for fixed base model subjected to Superstition Hills Earthquake
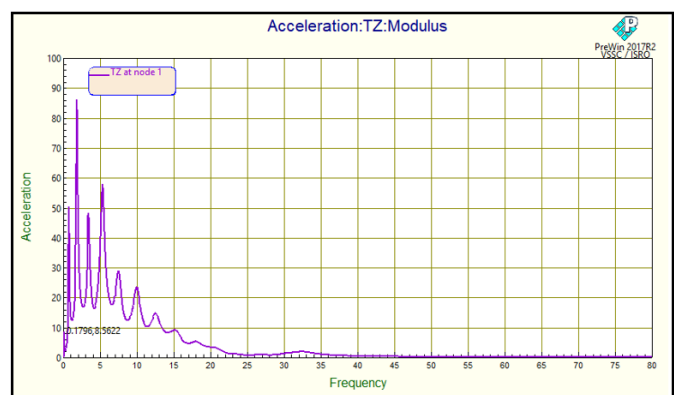

Chart 8: History plot for acceleration for fixed base model subjected to Superstition Hills Earthquake

Charts 9 and 10 show the responses of chimney under Northridge Earthquake excitation and charts 11 and 12 show the responses of chimney under Loma Prieta Earthquake excitation.

Chart 9: History plot for displacement for fixed base model subjected to Northridge Earthquake

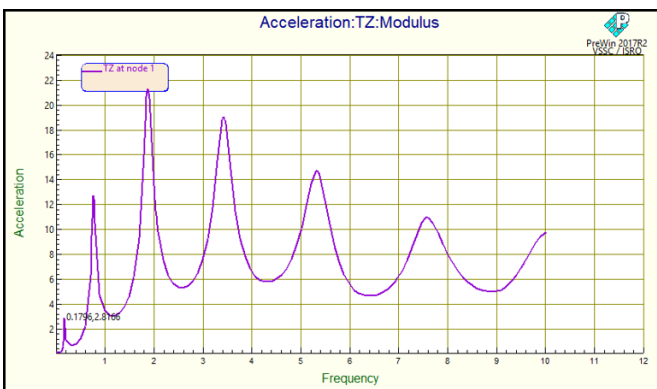**Chart 10**: History plot for acceleration for fixed base model subjected to Northridge Earthquake
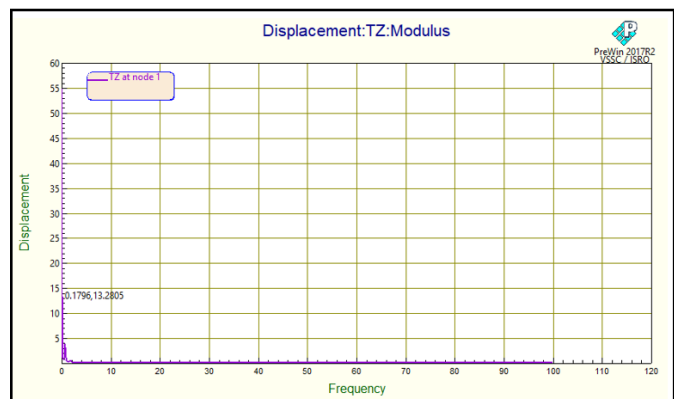

Chart 11: History plot for displacement for fixed base model subjected to Loma Prieta Earthquake

The responses on fixed base chimney are summarized in Table 3. In a similar way, each earthquake excitation is applied to chimney models with soil type 1, 2, 3 and 4. It's corresponding responses in terms of displacement and acceleration are given in Table 4 and Table 5 respectively.
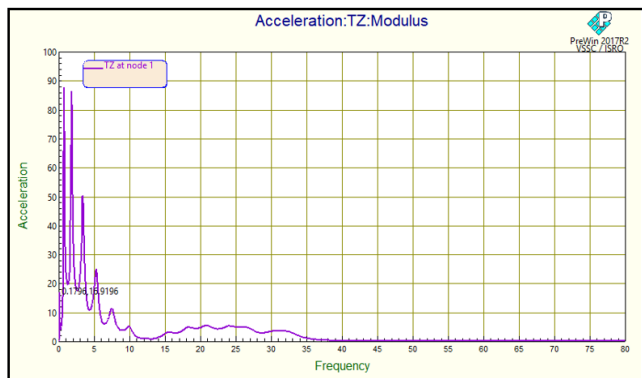
Chart 12: History plot for acceleration for fixed base model subjected to Loma Prieta Earthquake

Table -3: Response of Fixed Base Chimney to Various Earthquakes

Name of Earthquake	Displacement (m)	Acceleration (m/sec^2)
El-Centro	8.01	10.217
Superstition Hills	2.21	2.81
Northridge	6.72	8.56
Loma Prieta	13.28	16.92

Table -4: Displacement in meter of Chimney to Various Earthquakes

Types	El-Centro	Superstition Hills	Northridge	Loma Prieta
S1	8.34	2.36	6.82	13.59
S2	8.23	2.29	6.76	13.52
S3	8.15	2.26	6.72	13.44
S4	8.12	2.25	6.72	13.4

The plot showing variation of deflection at the tip of chimney with the change in flexibility or due to effect of SSI is shown in chart 12 and the variation of acceleration is shown in chart 13.

Table -5: Acceleration in (m/sec^2) of Chimney to Various Earthquakes

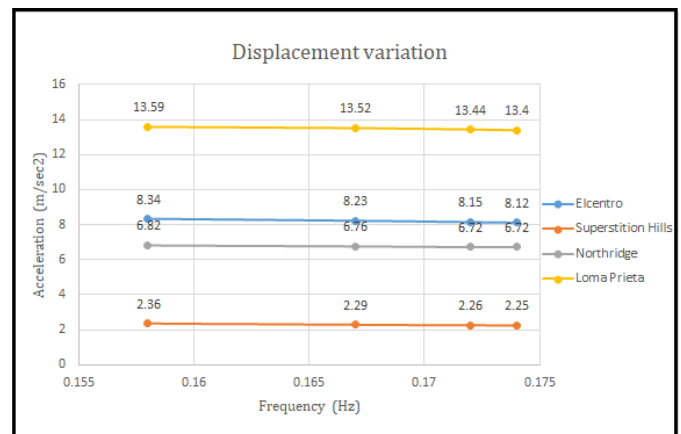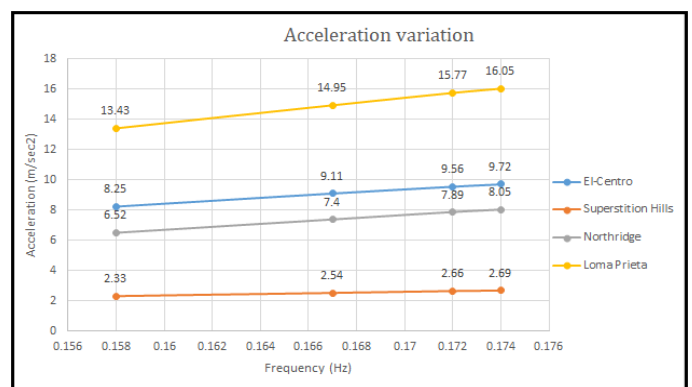| Soil Types	El-Centro	Superstition Hills	Northridge	Loma Prieta
S1	8.25	2.33	6.52	13.43
S2	9.11	2.54	7.4	14.95
S3	9.56	2.66	7.89	15.77
S4	9.72	2.69	8.05	16.05

Fig.16: Variation of displacement

Fig.17: Variation of acceleration

5. COMPARISONS AND DISCUSSIONS

The following comparisons and discussions were made,

- The frequency values of 0.158 Hz, 0.167 Hz, 0.172 Hz, and 0.174 Hz have been obtained for chimney with soil type 1, 2, 3 and 4 respectively and 0.179 Hz for fixed base model.

- A displacement of 8 m is obtained on exciting the chimney with El-Centro earthquake, which is well-known and prominent earthquake.

- Displacement is important from designer's point of view and 8 m tip displacement is beyond limit even for a 400 m tall chimney.

- If such a chimney has to resist big earthquakes, a redesign in terms of increase in base stiffness or an improvement in mix design is recommended.

- Further excitation of chimney with different soil conditions to different earthquake excitations were made, of which the displacement and acceleration values are studied.

- The displacement has shown a decreasing trend while acceleration has shown an increasing trend with the increase in soil stiffness.

6. CONCLUSIONS

The following conclusions were drawn from the study,

- Seismic analysis is carried out using FEAST/ PreWin software. Chimney is found to be sufficient to be modeled as beam.

- In the present study, seismic performance study on chimney is carried out considering a 400 m tall chimney.

- The SSI effect was studied by considering 4 different types of soil and the fundamental time periods are found to vary with change in soil flexibility.

- When subjected to specifically selected El-Centro earthquake a tip displacement of approximately 8 m is obtained which is beyond limits and it is suggested to redesign the structure if it has to resist such earthquakes.

- Redesign in terms of increasing the base stiffness or improving the mix design has been suggested.

- 4 different earthquake excitations are used to study the trend of displacement and accelerations.

- The displacements show a decreasing trend with increase in soil stiffness.

- The acceleration shows an increasing trend with increase in soil stiffness.

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