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# Influence of Vertical Acceleration on Seismic Response of End-bearing Pile Foundations

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***Abstract: -*** The behavior of pile foundations under earthquake loading is an important factor as it affects the performance of structures. Transient dynamic analysis is conducted on pile foundation in homogenous cohesive soft soil and homogenous cohesive stiff soil. In addition to horizontal acceleration an attempt is made to study the influence of vertical acceleration on response of pile foundation. MSC Patran and MSC Marc have been used as pre and post processor and MSC Marc Mentat as solver. The acceleration time history of Kobe earthquake has been taken as input acceleration and response displacement, velocity and accelerations are noted. Three set of time history analyses namely (i) free field response analysis, (ii) subjected to horizontal excitation alone and (iii) subjected to combined horizontal and vertical accelerations are conducted on each soil type. The study indicates that the response displacement and acceleration of stiff soil is greater than the corresponding values of soft soil. Vertical acceleration causes a reduction in response acceleration and response displacement.

***Keywords: -*** *Acceleration time history, Kobe earthquake, Pile Foundation, Response quantity Vertical acceleration.*

## I.    INTRODUCTION

Seismic soil structure interaction analysis involving pile foundations is one of the most complex problems in earthquake engineering. The pile foundations for buildings are often used in the region where a soft surface ground rests on the bedrock. It is easily fit for complex geologic settings and all kinds of load conditions, especially for soft subsoil condition. The behavior of pile foundations under earthquake loading is an important issue that affects the performance of structures supported on it.

Three dimensional analysis of pile foundation involves modeling soil-pile-structure interaction, the effect of the pile cap, nonlinear soil response, and in many cases incorporate seismically induced pore water pressure. Many recent earthquakes have caused the collapse of important massive structures such as power plants, bridge, dams, off shore structures and heavy oil tanks owing to the failure of foundation as many of these massive structures are founded on pile foundations [1].

**Dynamic Soil structure interaction**

Dynamic interaction between the structural foundation and soil plays an important role in their dynamic behavior under the action of either external forces or seismic waves. The nature and amount of this interaction depends not only on soil stiffness, but also on the stiffness and mass properties of the structure. The seismic soil structure interaction problem involves two major components. The first is the response of the soil as seismic waves travel through the soil deposit. The second is the coupled foundation–superstructure response, which is usually assumed to be (i) superposition of the response of the pile foundation itself to the excitation in the absence of the superstructure, known as kinematic response (ii) the effect of the additional flexibility caused by the foundation to the response of the superstructure known as inertial response [2].

**Influence of Vertical acceleration on structures**

In reality ground is simultaneously subjected to shaking in both horizontal and vertical directions and attention to vertical ground motion is quite limited and hence available understanding is much less than that for horizontal ground motions. Now the trend is towards giving vertical accelerations more attention because [3]

a) observations of strong motions earthquake records and reports on destructive earthquakes show that the effect of vertical accelerations can no longer be ignored
b) there are problems arising in the design of structures that cannot be solved only by considering the horizontal component alone
c) investigations of previous earthquake records, showed that even if the peak horizontal accelerations may not occur at exactly the same time as the peak vertical accelerations, they do occur within the same general time.

Several recorded ground motions during 1994 Northridge earthquake indicate that the vertical component was much larger than is usually considered normal in design [4]. In the Northridge earthquake (1994) in California and Hyogo –ken – Nanbu earthquake (1995) in Kobe, Japan shear damage and failure of columns were prevalent since reduction of shear strength was caused by vertical ground motion effects. The vertical members of RC structures are subjected not only to axial action due to dead and live loads but also combined varying axial force, moment and shear when excited by earthquake ground shaking. The combined effect of overturning and multi axial input leads to significant variation in axial load on columns [5].

The time histories of the 6 April 2009 L'Aquila(Italy) earthquake which was generated by normal fault with north – west/ South – East trend, shows that the vertical component tend to exceed the horizontal one up to an epicentral distance of about 30km, i.e., near field strong motions. It has been observed that the ratio of vertical to horizontal peak ground accelerations can be larger in near fault than far fault records [6].

## II.     EARTHQUAKE GROUND MOTIONS

Time history method of dynamic analysis was adopted in this study. Acceleration time history of Kobe earthquake (1995), recorded at Shin – Osaka center for duration of 40.96 s, which had a Richter magnitude of 7.2 was considered for the study, since it produced significant damages to buildings and these damages were mainly due to failure of underlying soil [7]. The Kobe earthquake has the characteristics peak ground acceleration of 2.386m/sec$^2$ at 15.16s. Acceleration time history of Kobe earthquake is given in Fig.1.
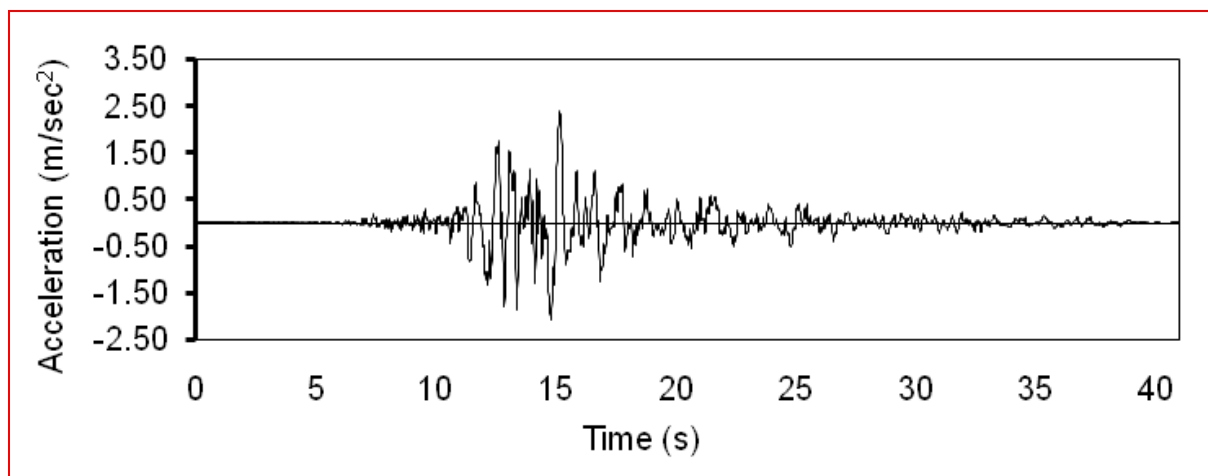


Fig. 1 Acceleration time history of Kobe earthquake (1995)

## III.     DESCRIPTION OF SOIL AND PILE

Free field response analysis of two soil profiles namely homogenous cohesive stiff soil, and homogenous cohesive soft soil overlying rock were conducted. The properties of these considered for study are given in Table 1.

Table 1: Properties of soil and rock

| Description | Stiff Soil | Soft Soil | Rock |
|---|---|---|---|
| Young's Modulus (kN/m$^2$) | $40 \times 10^3$ | $25 \times 10^3$ | $50 \times 10^6$ |
| Poisson's Ratio | 0.3 | 0.3 | 0.24 |
| Cohesion (kN/m$^2$) | 70 | 15 | - |
| Density (kN/m$^3$) | 18 | 16.5 | 26.5 |

Single pile embedded in rock for a socketing depth of 1D, where D is the diameter of pile, is considered for soil-structure interaction study. The details of pile and pile cap are given in Table 2.

Table 2: Particulars of pile and pile cap

| Description | Value |
|---|---|
| Pile Diameter | 0.7m |
| Length of pile in soil | 9.2m |
| Socketing depth of pile into rock | 0.7m |
| Dimensions of pile cap | 1.0m x 1.0m x 0.8m |
| Young's modulus | $25 \times 10^6$ kN/m$^3$ |
| Poisson's ratio | 0.15 |
| Mass Density | 2500 kg/m$^3$ |

Sectional view of the rock, soil, pile and pile cap system considered for the study is given in Fig.2.
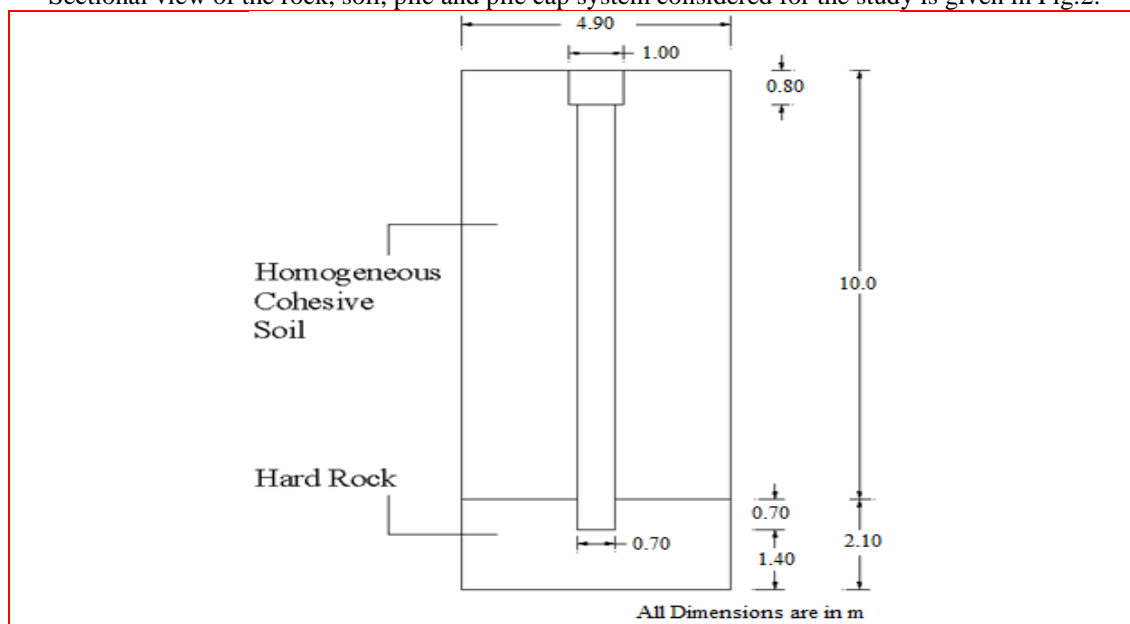


Fig. 2 Soil – structure system (Socket Depth = Dia. of pile)

## IV.    FINITE ELEMENT MODELING

In situ soils are commonly anisotropic and non-homogenous and display markedly nonlinear, irreversible and time dependent characteristics. The behavior of pile foundation subjected to seismic loading greatly depends on the soil – pile interaction. In this study, the non –linear stress strain behavior is incorporated in finite element analysis using an elasto-plastic Drucker- Prager constitutive model.  Behaviour of rock was modeled using Mohr – Coulomb constitutive model and for pile modeling, isotropic linear elastic model was chosen.

Three dimensional geometric models are created using MSC Patran software (2010). The finite element used for discretisation of the soil, rock and pile were Tet 10 elements as it can model complex curved solids more accurately with fewer elements. The coefficient of internal friction between the soil and pile is 0.3 and that between the rock and pile is 0.7.

The width of soil mass considered is seven times the diameter of single pile [8]. The depth of rock below the pile bottom is two times the diameter of pile.  The pile bottom and rock bottom surfaces are kept fixed in all three directions. The finite element model of the structure considered for time history analysis is shown in Fig.3.
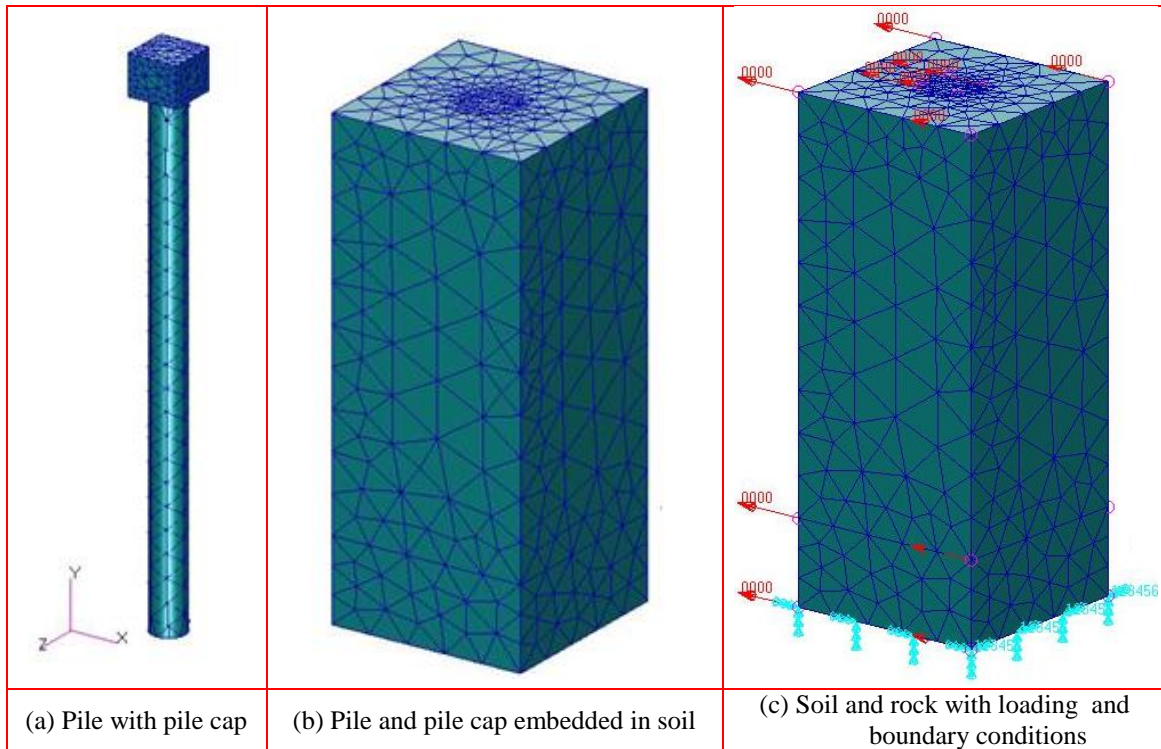
| (a) Pile with pile cap | (b) Pile and pile cap embedded in soil | (c) Soil and rock with loading and boundary conditions |
| --- | --- | --- |

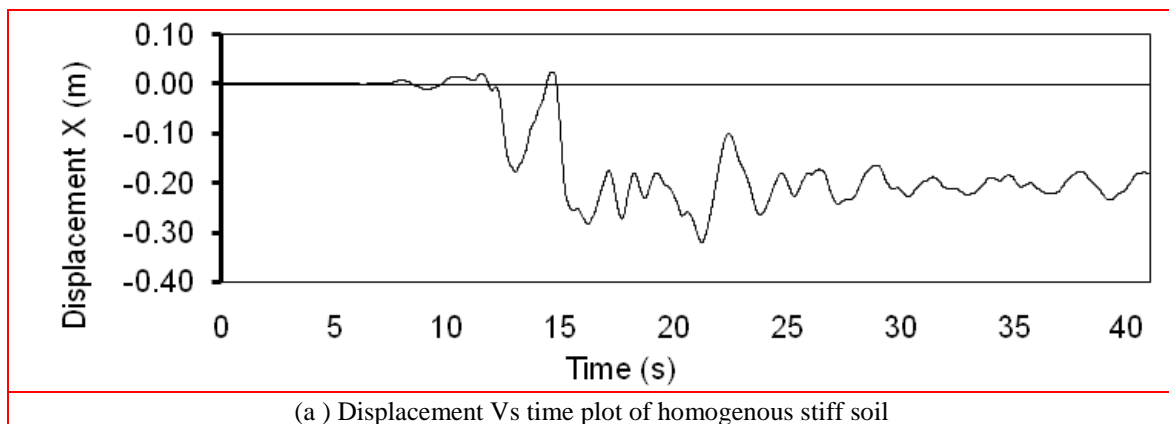Fig. 3 Discretized finite element model of soil, rock and pile

## V. DYNAMIC ANALYSIS

Non linear three dimensional finite element method of analysis was adopted using MSC Softwares. MSC Patran and MSC Marc were used as pre and post processor and MSC Marc Mentat as solver. Transient dynamic analyses were conducted using the acceleration time history of Kobe earthquake (1995). The transient dynamic analyses conducted are (i) Free field response analysis of the soil (ii) analysis of the soil – rock – pile system subjected to horizontal acceleration and (iii) analysis of the soil – rock – pile system subjected to combined horizontal and vertical accelerations. To study the combined effect of vertical and horizontal accelerations on pile foundation, 2/3 of horizontal acceleration is considered in vertical direction along with horizontal acceleration. These three analyses were conducted both on homogenous cohesive soft soil and on homogenous cohesive stiff soil.
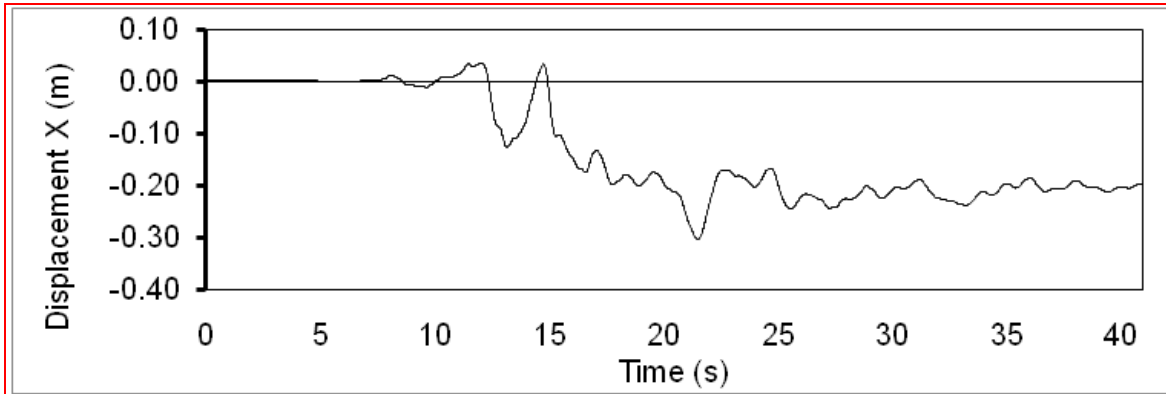
## VI. RESULTS AND DISCUSSIONS

**Free field response analysis of soil**

A control point was chosen at the centre of the finite element model of soil at the free surface. Variation of response displacement of the control point with respect to time was plotted (Fig.4) and the maximum displacement at this point was noted for two soil conditions. Also the variation of response acceleration was plotted (Fig. 5) for two soil conditions.
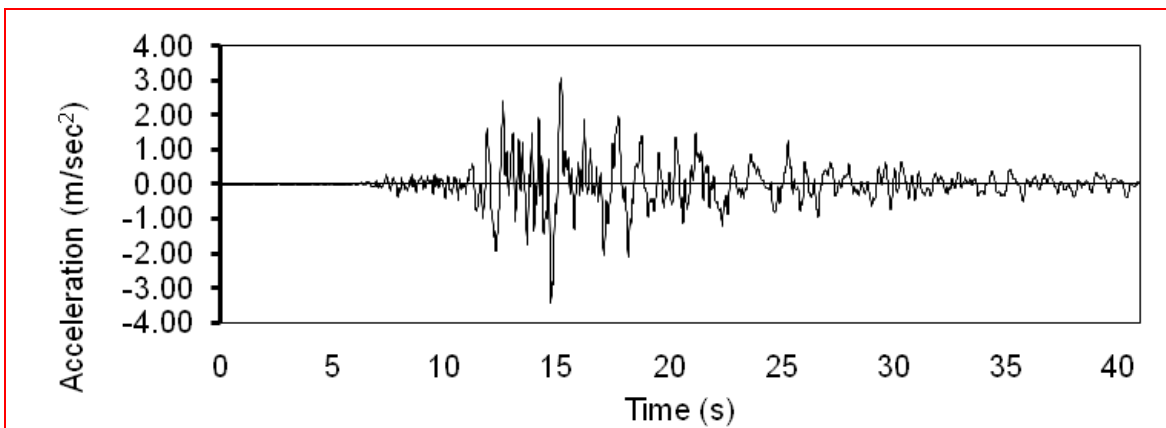


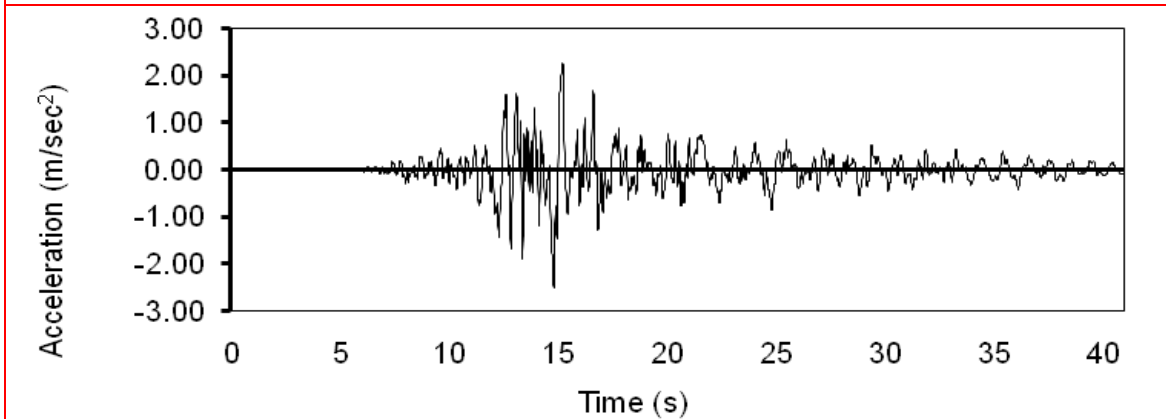(a ) Displacement Vs time plot of homogenous stiff soil

(b) Displacement Vs time plot of homogenous soft soil

Fig. 4 Free field response displacement time history of control point



(a) Acceleration Vs time plot of homogenous stiff soil



(b) Acceleration Vs time plot of homogenous soft soil

Fig. 5 Free field response acceleration of control point

The maximum values of response displacement, velocity and acceleration in the direction of loading are given in Table 3. The maximum displacement and acceleration in homogenous stiff soil is found to be more than the corresponding values in homogenous soft soil.

**Table 3:** Maximum response (displacement, velocity and acceleration) from the free field analysis of soil

| Soil Type | Max. Acceleration (m/sec$^2$) | Max. Velocity (m/sec) | Max. Displacement (m) |
|---|---|---|---|
| Homogenous Stiff Soil | 3.437 | 0.6659 | 0.3196 |
| Homogenous Soft soil | 2.508 | 0.4407 | 0.3023 |

**Pile subjected to seismic loading in horizontal direction**

Variation of response displacement of the control point with respect to time was plotted (Fig.4) and the maximum displacement at this point was noted for two soil conditions. Also the variation of response acceleration To study dynamic soil- structure interaction effects, the response of control point which is at the centre of pile cap was compared with that of free field response of the soil. The response displacement time history ( Fig. 6) and the response acceleration time history (Fig. 7) of the two soil conditions were plotted.
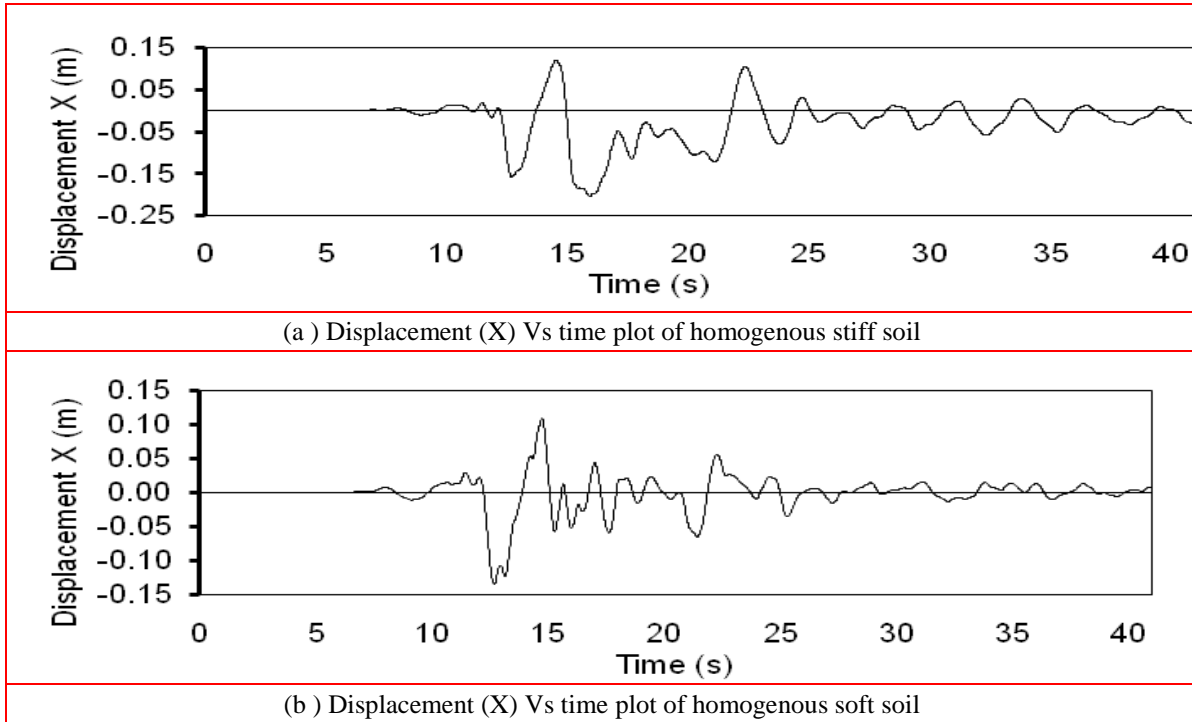
(a ) Displacement (X) Vs time plot of homogenous stiff soil

(b ) Displacement (X) Vs time plot of homogenous soft soil

Fig. 6 Response displacement time history of control point due to seismic excitation in horizontal direction

(a ) Acceleration (X) Vs time plot of homogenous stiff soil

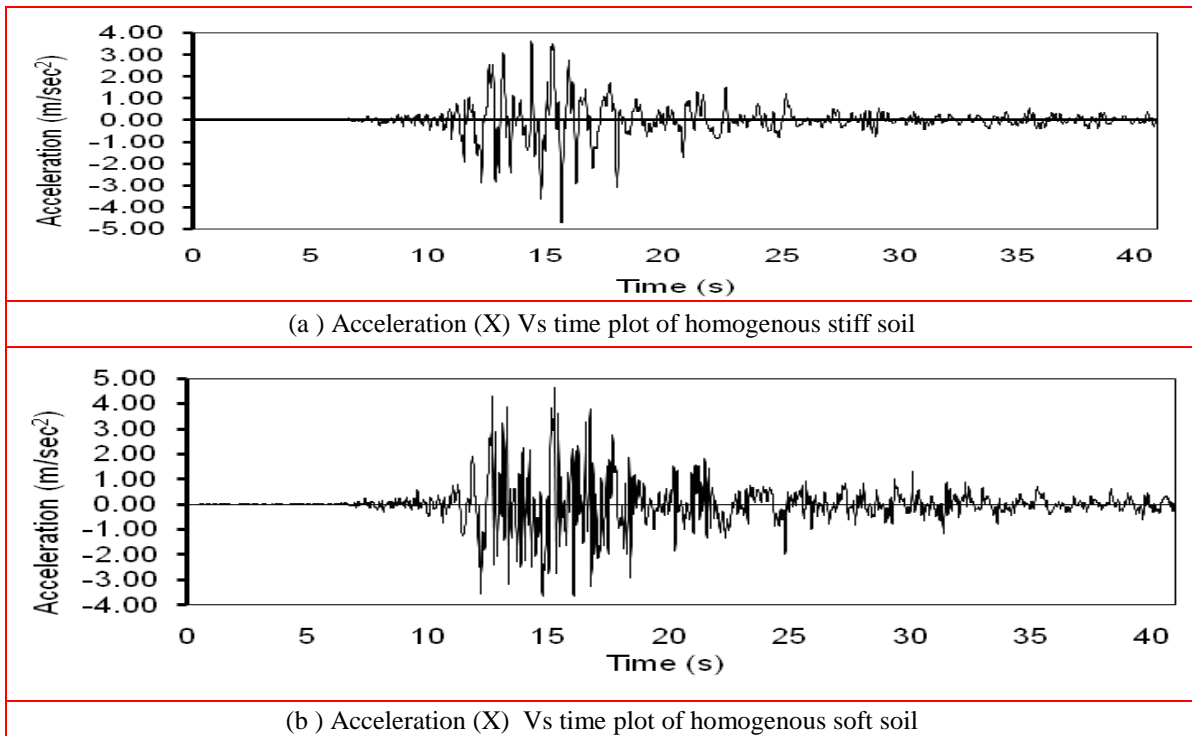(b ) Acceleration (X)  Vs time plot of homogenous soft soil

Fig. 7 Response acceleration time history of control point due to seismic excitation in horizontal direction

It can be observed that for both stiff soil and soft soil, magnitude of response displacement, get reduced when the pile is founded into the soil while response velocity and acceleration get increased. As in the case of free field response analysis, maximum lateral displacement and acceleration in the direction of loading is found to be more in the case of homogenous stiff soil than in homogenous soft soil. The maximum values of displacement, velocity and acceleration are tabulated in Table 4.

Table 4: Maximum response (displacement, velocity and acceleration) due to seismic loading in horizontal direction

| Soil Type | Maximum Acceleration (m/sec$^2$) | Maximum Velocity (m/sec) | Maximum Displacement (X) (m) | Maximum Displacement (Z) (m) | Maximum Displacement (Y) (m) |
|---|---|---|---|---|---|
| Homogenous Stiff Soil | 4.732 | 0.7846 | 0.2051 | $1.816 \times 10^{-3}$ | $2.432 \times 10^{-3}$ |
| Homogenous Soft Soil | 4.642 | 0.4691 | 0.1353 | $4.164 \times 10^{-3}$ | $1.076 \times 10^{-3}$ |

The maximum displacement in the direction of loading in homogenous cohesive stiff soil with pile is only 64.17% of free field response of the soil whereas the in homogenous cohesive soft soil, maximum displacement in the direction of loading is 44.76 % of corresponding free field response of soil. The maximum velocity and acceleration get increased by insertion of pile into soil. The increase in maximum velocity is by 17.83 % in stiff soil and is 6.44 % in soft soil. The increase in maximum acceleration is by 37.68% in stiff soil and is 85.09% in soft soil. The displacement contour of pile showing the maximum displacement is shown in Fig.8. It can be seen that for both pile in homogenous stiff cohesive soil and soft soil, maximum displacement from mean position is at the pile cap.
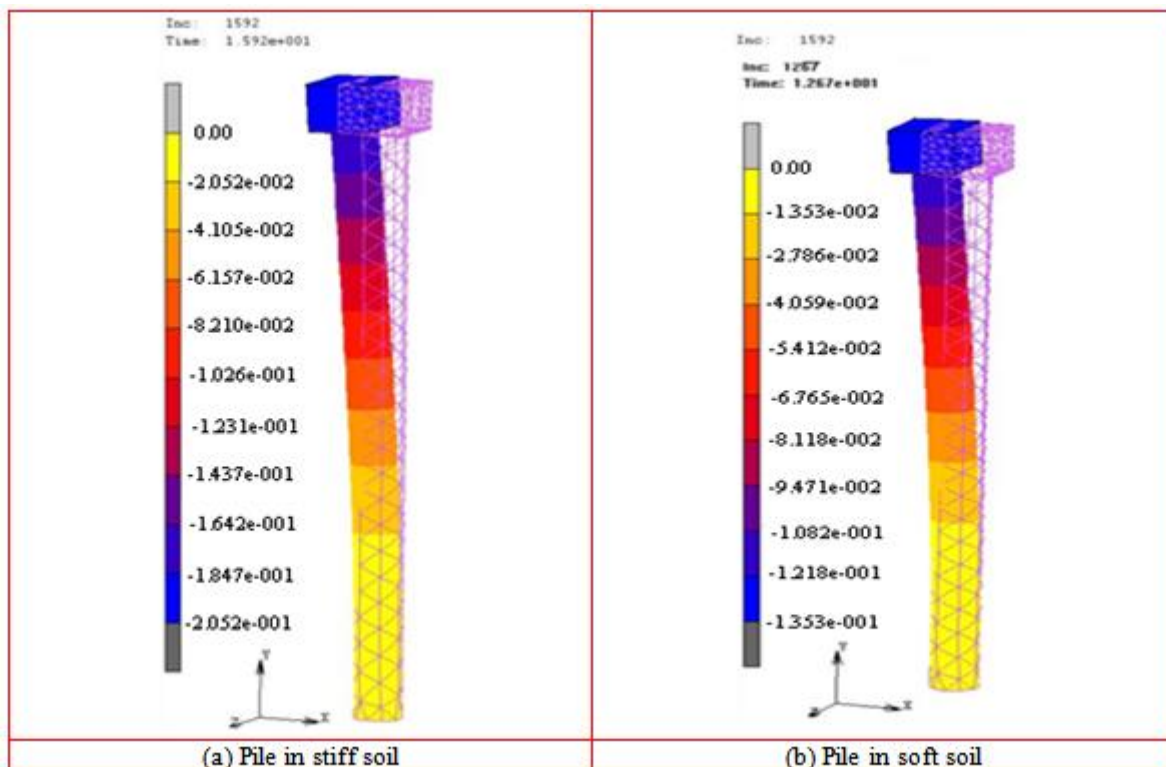


(a) Pile in stiff soil          (b) Pile in soft soil

Fig. 8 Displacement contour of pile subjected to seismic excitation in horizontal direction

**6.3.  Pile subjected to seismic loading in horizontal and vertical direction**
Recent studies show that presence of vertical ground motion can enhance the destructive process of the the horizontal ground motion on the structure[9]. In order to study the influence of vertical acceleration on pile foundations, the pile in homogenous stiff soil and soft soil which were subjected to seismic loading in both horizontal and vertical directions simulatneously were analysed and the response displacement, velocity and accelerations were noted. The maximum values of response displacment, velocity and accelerations are tabulated in Table 5.

Table 5 Maximum displacement, velocity and acceleration when subjected to seismic loading in both horizontal and vertical directions

| Soil Type | Maximum Acceleration (m/sec$^2$) | Maximum Velocity (m/sec) | Maximum Displacement (X) (m) | Maximum Displacement (Z) (m) | Maximum Displacement (Y)(m) |
|---|---|---|---|---|---|
| Homogenous Stiff Soil | 4.379 | 0.6556 | 0.1946 | $8.255 \times 10^{-4}$ | $2.2 \times 10^{-3}$ |
| Homogenous Soft Soil | 3.37 | 0.4887 | 0.1248 | $3.531 \times 10^{-3}$ | $8.837 \times 10^{-4}$ |

Comparison of results in Table 4 and 5 indicates that for both stiff soil and soft soil, magnitude of response displacement, and acceleration get reduced when the effect of vertcial acceleration is considered along with horizontal acceleration. In this case also, maximum displacement (both lateral and vertical) and acceleration in the direction of loading is found to be more in the case of homogenous stiff soil than in homogenous soft soil. But we can not conclude that, in all soil conditions, the seismic response decreases when the effect of seismic excitation in vertical direction is considered along with horizontal excitation. Detailed study is required in this field as the response of pile depends on various factors such as amplitude and frquency parameters of input motion, properties of soil etc.

The maximum lateral displacement (X) in homogenous cohesive stiff soil with pile is 5.11% less in comparison with the effect of horizontal acceleration alone. The corresponding decrease in soft soil is 7.77 %. The maximum acceleration also get decresed by consideration of vertical acceleration. The decrease in maximum acceleration is by 7.46 % in stiff soil and is 27.4 % in soft soil. The displacement contour of pile showing the maximum displacement is shown in Fig.9. It can be observed that maximum displacement occurs at pile cap for both homogenous cohesive soft soil and stiff soil.
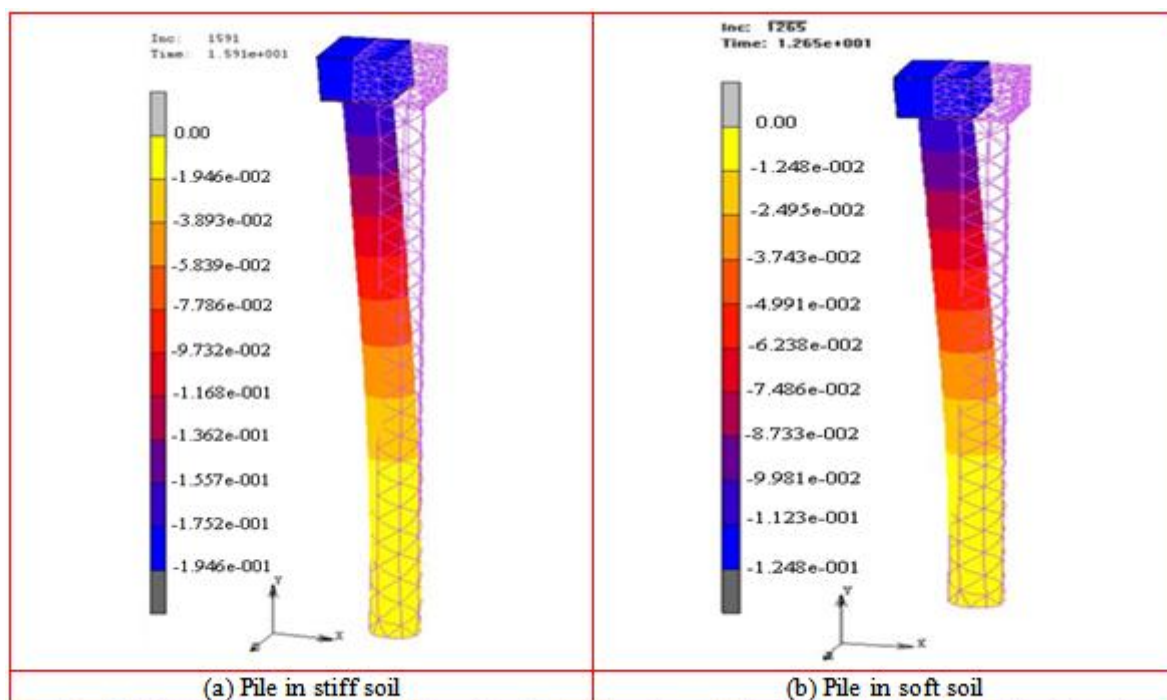


Fig. 9 Displacement contour of pile subjected to seismic excitation in horizontal and vertical directions

## VII.　CONCLUSIONS

Transient dynamic analysis of end bearing pile foundation was carried out using MSC Softwares. Seismic response of piles in two different soil conditions was examined. Free field response of the control point was compared with the response of the pile under (i) horizontal excitation alone and (ii) combined horizontal and vertical excitations. The studies show that

- When pile is modelled along with the surrounding soil, the deflection at top is found to be significantly low er in magnitude when compared to corresponding free field response analysis results. This indicate that soi l around significantly contribute to resist the lateral deformation of pile
- The response displacement and acceleration of stiff soil is greater than the corresponding values of soft soil in all the three sets of analyses conducted.

- Seismic response of pile subjected to combined horizontal and vertical acceleration is found to be less than that of pile subjected to horizontal acceleration alone. The response acceleration in the direction of horizontal excitation and response displacement in all three direction get reduced when the effect of input vertical acceleration is considered along with horizontal acceleration.
- The vibration response of pile depends on amplitude and frequency of seismic excitation and also on properties of soil. However detailed study is require to evaluate response of the pile foundation subjected to vertical acceleration

## VIII.　REFERENCES

[1]　B. K. Maheshwari and R. Sarkar, Seismic behavior of soil-pile-structure interaction in liquefiable soils: parametric study, *International Journal of Geomechanics,11(4),* 2011, 335–347.

[2]　A. Ucak and P. Tsopelas, Effect of soil–structure interaction on seismic isolated bridges, *Journal of Structural Engineering, 134(7), 2008, 1154–1164.*

[3]　A. Kadid, D. Yahiaoui and R. Chebili, Behaviour of reinforced concrete buildings under simultaneous horizontal and vertical ground motions, *Asian journal of civil engineering building and housing, 11(4),* 2010, 463-476.

[4]　A. R. Salazar and A. Haldar, Structural response considering vertical component of earthquake, *Computers and Structures, 74,* 2000, 131 -145.

[5]　S. J. Kim, C. J. Holub and A. S. Elnashai, Analytical assessment of the effect of vertical earthquake motion on RC bridge piers, *Journal of Structural Engineering, 137 (2),* 2011, 252–260.

[6]　L. Sarno, A. S. Elnashai and G. Manfredi, Assessment of R.C. Columns subjected to horizontal and vertical ground motions recorded during the 2009 L'Aquila (Italy) earthquake, *Engineering structures, 33*, 2011, 1514 -1535.

[7]　J. F. Bird, J. J. Bommer, H. Croweley, and R. Pinho, Modelling liquefaction induced building damage in earthquake loss estimation, *Journal Soil dynamics and Earthquake Engg., 26*, 2006, 15-30.

[8]　J. W. Bull, *Soil-Structure Interaction: Numerical analysis and modeling* (New Delhi: CRC Press, 1994).

[9]　C. H. Loh and M. J. Ma, Reliability assessment of structure subjected to horizontal – vertical random earthquake excitation, *Structural Safety, 19 (1),* 1997, 153 -168.