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Dynamic Response of Vertical and Batter Piles

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DYNAMIC RESPONSE OF VERTICAL AND BATTER PILES

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ABSTRACT

The lateral forced vibration test was carried out on driven cast in-situ concrete vertical piles of 500 mm diameter in a petrochemical complex site in Paradip, India. The site predominantly consists of silty sand for the top 3 m with shear wave velocity of 200 m/s and it is followed by clayey sand with shear velocity increases from 415 m/s to 460 m/s over pile termination depth of about 17 m . The piles were subjected to a sinusoidal lateral force with magnitude of 0.3 kN to 9.5 kN in the frequency range of 5 to 30 Hz. A 3D finite element analysis was carried out on vertical piles using ABAQUS and its results are validated with the field test results. Finite element analysis was extended to batter piles (10˚and 20˚) subjected to lateral dynamic load and it was found that the peak displacement amplitude of batter piles is 15 to 25% less than the same that of vertical piles indicating better performance of batter piles under lateral dynamic loading.

INTRODUCTION

Pile foundations can be subjected to vertical or lateral or combined loads and may be of static or dynamic nature depending on the type of application for which the piles are installed. If lateral loads are dominant then pile group consisting of vertical and batter piles can be used for foundation. Though batter piles were traditionally adopted to carry large horizontal loads but due to their recent failures in series of earthquakes have paved way for their removal from foundation codes and the consideration of engineers. The main arguments that have been frequently mentioned by engineers as the real or perceived drawbacks of inclined piles include (Gerolymos et al., 2010): "Parasitic" bending stresses due to soil settlement following an earthquake and or soil consolidation before the earthquake; large forces (of alternating Sign) onto the pile cap; reduction in bending moment capacity due to seismically induced tensile forces; undesirable permanent rotation of the cap when the inclination of the piles is not symmetric and increased structural shear due to the stiffening of the system.

In the recent past, due to the improved understanding of the source of the observed poor performance during earthquakes, batter piles are re-establishing their traditional role of withstanding large horizontal loads. Some recent works which include experimental studies by Escoffier et al. (2008) and numerical investigations by Sheikhbahaei et al (2009) and Gerolymos et al (2010) provide evidence to support the use of batter piles as they can be beneficial to the structure they support as well as to themselves. Nevertheless, until today very few data are available on the response of batter piles subjected to dynamic loading particularly low strain loading as in the case of foundations for machines. This paper addresses the details of dynamic lateral load tests carried out on full scale vertical piles. A 3D finite element analysis carried on vertical and batter piles using computer code ABAQUS is also presented in this paper.

FIELD DYNAMIC TESTING OF VERTICAL PILES

Forced lateral dynamic tests were carried out on a vertical single driven cast in situ piles in a petro chemical project site at Paradip located in the eastern coast of India.

Soil Properties

The dynamic soil properties of the site was obtained by carrying out cross hole test as per ASTM D4428/D4428M-07 (2007). The site predominantly consists of silty sand in the top 3 m with a maximum shear wave velocity (V_s) of 200 m/s and maximum P wave velocity (V_p) of 425 m/s. It is followed by clayey sand upto pile termination depth with V_s and V_p linearly varying in the range of 415 m/s to 460 m/s and 1125 m/s to 1505 m/s respectively. The poisson's ratio (υ) was calculated from the V_p and V_s relation using Eqn. 1 and it varied between 0.42 to 0.45. The mass density of the soil (ρ) in the first layer was 1800 kg/m^3 and it varied between 1700 kg/m^3 at the beginning of second layer and 1900 kg/m^3 at pile termination. The maximum dynamic shear modulus (G_{max}) was obtained from the shear wave velocity using Eqn. 2 (Prakash and Puri, 1987).

$$\upsilon = 0.5 \times \frac{\left(\frac{V_p}{V_s}\right)^2 - 2}{\left(\frac{V_p}{V_s}\right)^2 - 1} \quad (1)$$

$$G_{max} = V_s^2 \rho \quad (2)$$

Pile Properties

The diameter of the test piles were 500 mm and its length below ground level and cut off level were 16.8 m and 14.8 m respectively. The pile was made of M35 grade concrete corresponding to a dynamic young's modulus (Ep) of 30000 MPa.

Test Procedure

The lateral forced vibration tests were carried on single vertical piles as per Indian code IS: 9716-1981.The pile was excited with a mechanical oscillator, which is mounted on the pile cap. A steady state sinusoidal force is provided by the oscillator, which uses the centrifugal force of unbalanced masses mounted on the two counter rotating shafts to generate variable alternating force in a horizontal plane. The magnitude of this force is controlled by adjusting the phase angle between the masses. The speed of the oscillator is controlled by DC motor with a speed control unit. A detailed testing procedure on vertical piles subjected to lateral dynamic loading can be found in Boominathan and Ayothiraman (2006). The tests were carried out at different settings of eccentric mass within the magnitude of 0.3 kN to 9.5 kN in the frequency range of 5 to 30 Hz.

Instrumentation and Processing

The acceleration was measured with two HBM acceleration pick-ups: one mounted at the mid height of pile cap and other to the pile at pile cut off level. Signal from pick-ups were monitored and recorded using the Data Acquisition System consisting of Digital carrier frequency amplifier system and CATMAN package installed laptop. The displacement amplitude of vibrations, A_x, was computed from the measured accelerations using Eqn. 3.

$$A_x = \frac{a_x}{4\pi^2 f^2} \quad (3)$$

Where a_x = horizontal acceleration of vibration, in mm/s^2 at frequency, f, in Hz.

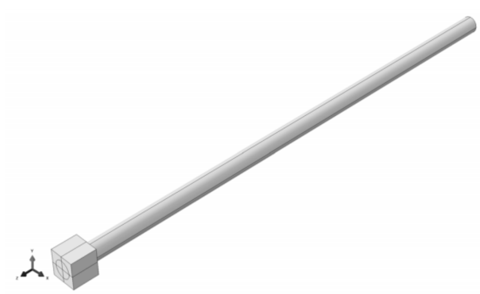
The displacement amplitude obtained from the pick-up mounted at pile cut-off level is plotted against frequency for each eccentricity level. Using the plot, the resonant frequency and peak amplitude were determined for each eccentricity level. The acceleration and displacement obtained from the pick-up mounted at mid-height of the pile cap was used to verify the values of the same obtained from the pick-up mounted at the pile cut-off level.

FINITE ELEMENT ANALYSIS

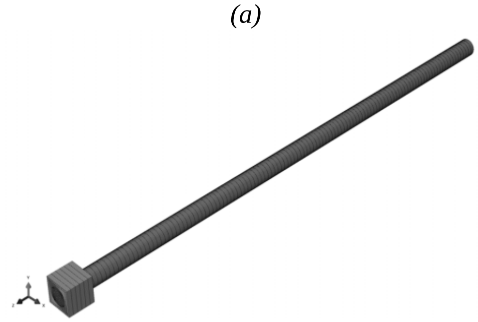
A 3D dynamic Finite element analysis was carried out on vertical and batter piles using computer code ABAQUS.

Modelling of Piles

A total of three single piles: one vertical pile and two batter piles (10˚ and 20˚) with pile dimensions equivalent to that of field piles were modelled. The piles were modelled as linear elastic material with dynamic young's modulus of 30000 MPa



(a)



(b)

Fig. 1. Modelling of piles: (a) Partition; (b) Discretization

and poisson's ratio of 0.2. Structured mesh of the piles were created by partitioning the piles effectively and the piles were discretized with solid hexahedron elements, C3D8R (Figure 1).

Modelling of Soil

The soil was modelled as relevance to the field conditions. A soil matrix of size 40 times the diameter of pile (D) in the direction of dynamic loading and 20D in the direction perpendicular to the direction of dynamic load applied was adopted. Material behaviour of the soil was defined using hypoelastic model. The strain rate dependent hypoelastic material properties: Young's modulus (E) and the three strain invariants (I1, I2, I3) were defined by Eqn. 4 to 7.

$$E = 2G(1+ \nu) \qquad (4)$$

$$I1= \varepsilon(1-2\nu) \qquad (5)$$

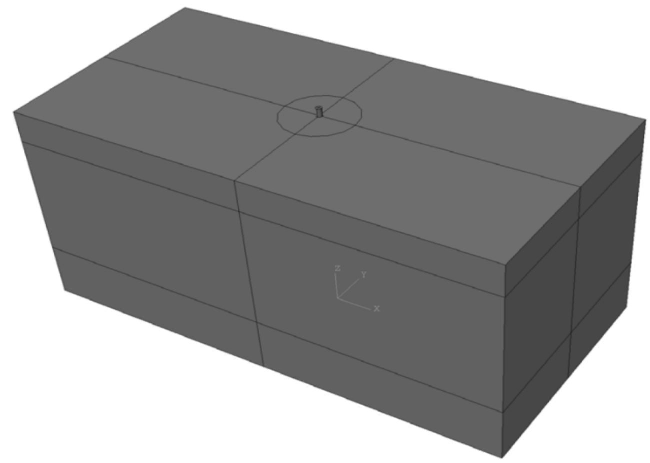
$$I2= \nu\varepsilon^2(2-\nu) \qquad (6)$$

$$I3= \nu^2\varepsilon^3 \qquad (7)$$

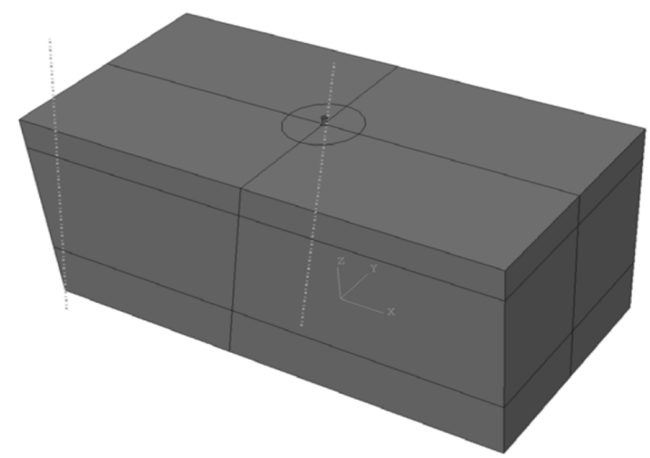
The modulus reduction curve proposed by Vucteic and Dorby were used to arrive at the strain dependent young's modulus for silty sand (first layer) and clayey sand (second layer) respectively using Eqn. 4. Shear modulus, mass density and poisson's ratio of the soil were taken as in the field. Damping was introduced in the model through Rayleigh damping coefficients: α (mass proportional) and β (stiffness proportional). The soil matrix was partitioned using different partition techniques so as to achieve a soil matrix capable of defining structured meshing. A typical partition created for soil matrix installed with vertical and batter pile is shown in Figure 2.

An inner circular zone of 6D from the center point of the pile is created with finer meshes in order to predict the response more precisely. Structured meshes generated for vertical and batter piles installed soil matrix discretized with C3D8R elements is shown in Figure 3. It could be observed in the longitudinal side of the soil matrix particularly in mesh with batter piles installed, the mesh elements are inclined towards batter angle in the centre region of the soil matrix thereby following the partition pattern as depicted in Fig. 2.

Standard boundary conditions were provided to the soil matrix. All the displacement degrees of freedom at the bottom of soil matrix were restrained to move in any directions. The lateral and longitudinal sides were fixed in X and Y directions respectively and the top surface was free to move in any directions. The pile soil interaction was created using a surface to surface contact algorithm with finite sliding. The tangential behaviour between pile and soil was established using penalty formulation with friction coefficient of 0.4. The analysis was carried out in two steps: initial and load step. In the initial step the equilibrium of the present stress state of the system was established with relevance to boundary conditions. The frequency dependent excitation applied on pile head like in field test was defined in the load step using direct steady state dynamic analysis procedure using amplitude curves.



(a) Vertical



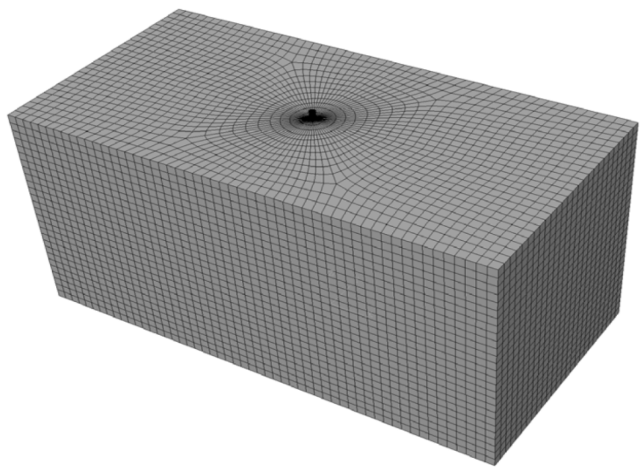
(b) Batter 10˚

Fig. 2. Partitioning of soil matrix

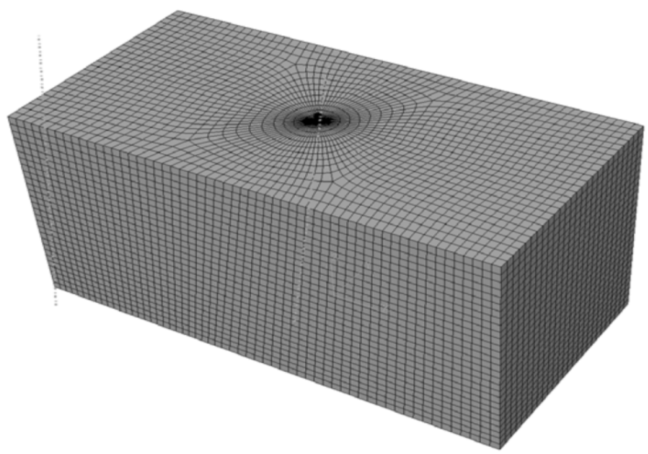
RESULTS AND DISCUSSIONS

Response of Vertical Piles

Typical displacement response curves obtained for the vertical piles are presented in Figure 4. It can be observed from the Fig. 4 that the resonant frequency of soil-pile system decreases from 22 Hz to 16 Hz with increase in magnitude of applied load. The displacement response of vertical piles obtained through finite element analysis (FEA) is also shown in Fig. 4. It could be observed that the FEA matches reasonably well with the field test results. Though there is under prediction of peak displacement by about 8 to 10 percent at resonance, the overall prediction and the trend/shape of the response curves is fairly in good agreement with the field test results.



(a) Vertical



(b) Batter 10˚

Fig. 3. Structured meshing of soil matrix

A typical sectional view of displacement contour of vertical pile embedded in soil inner circle zone along the XY plane near resonance is shown in Figure 5. To see more precisely the displacement contour of the soil alone, the pile removed circular zone is shown in Figure 6. From Fig. 6 it can be seen that high displacements occur at top soil near the pile. A typical sectional view of the circular zone in XZ plane is shown in Figure 7 and it can be observed that the soil is more stressed in X direction which is also the direction of load application when compared to Fig. 6 which shows soil in perpendicular direction to the application of load.

Response of Batter Piles

Typical sectional views of batter piles (10˚ and 20˚) are shown in Figure 8 and 9 respectively. It could be observed from Fig. 7 that for vertical piles the mesh distortion is more at the top

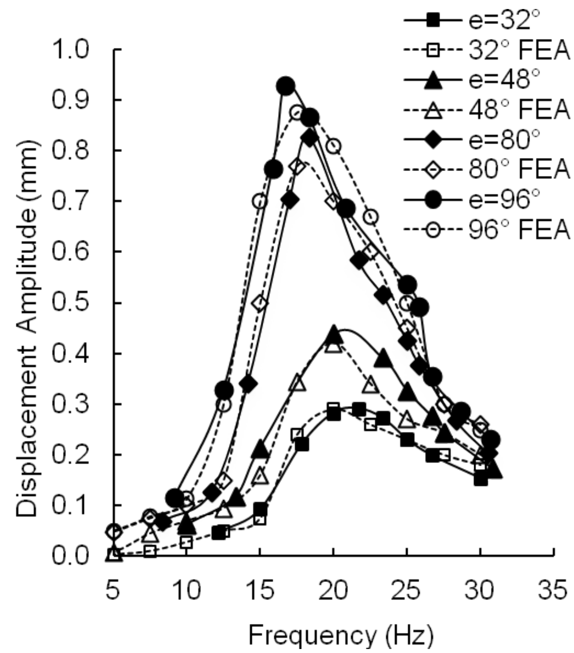


Fig. 4. Dynamic amplitude vs. frequency

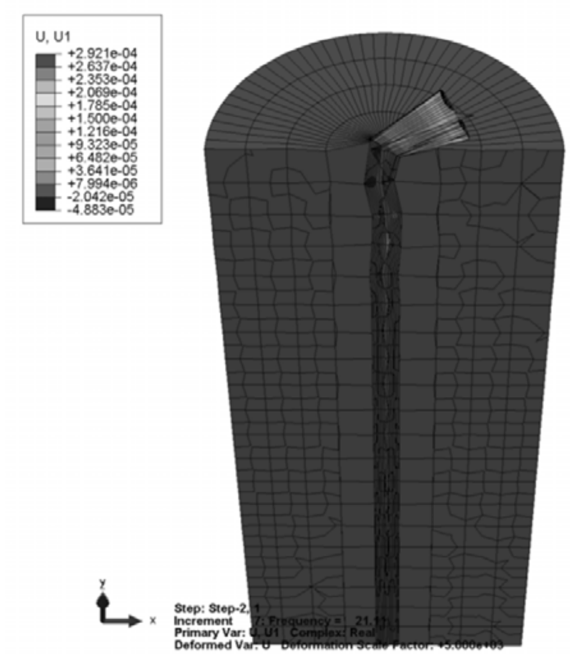


Fig. 5. Displacement contour in circular soil zone including vertical pile

whereas for batter piles (Fig. 8 and 9) it happens at the bottom. It gives an important insight as it indicates the ability of batter piles to transfer more load to the surrounding soil even at deeper depth. The mesh distortion at bottom for batter piles with some compression and expansion of soil elements indicates the capability of batter piles to transfer lateral load through partial axial compression and tension in addition to shear and bending which are the only phenomenon with which vertical piles transfer lateral load. Thus maximum mobility of the surrounding soil is utilized by batter piles.

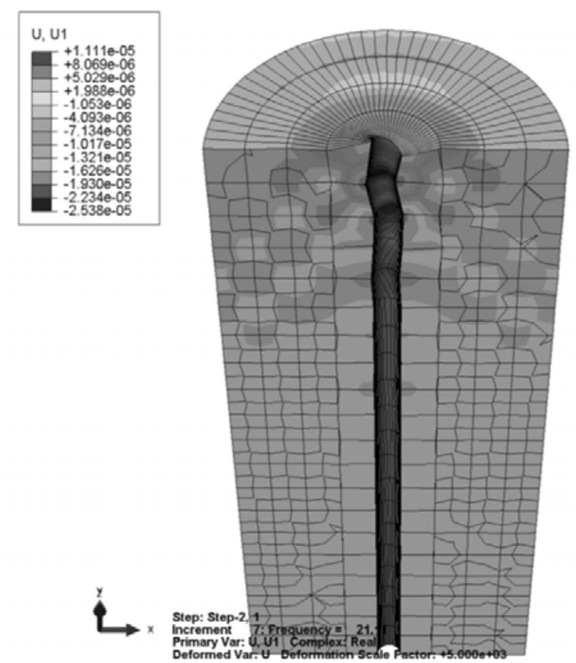


Fig. 6. Displacement contour in circular soil zone for vertical pile

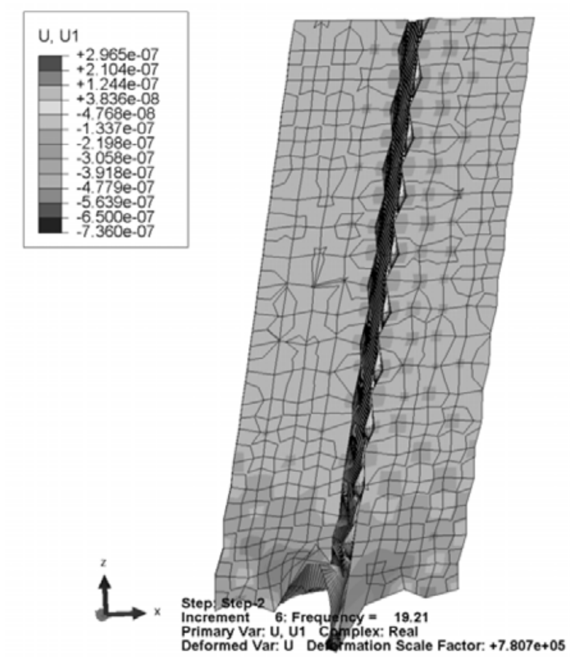


Fig. 8. Sectional view of displacement contours of circular soil zone for batter pile (10˚)

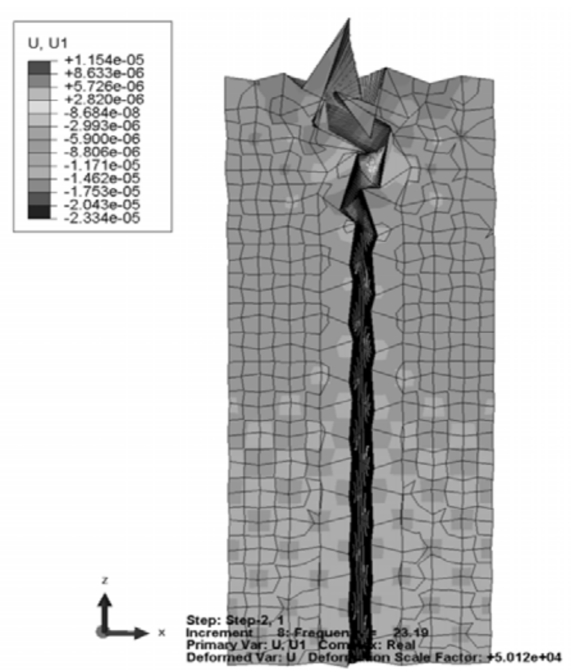


Fig. 7. Sectional view of displacement contours of circular soil zone for vertical pile

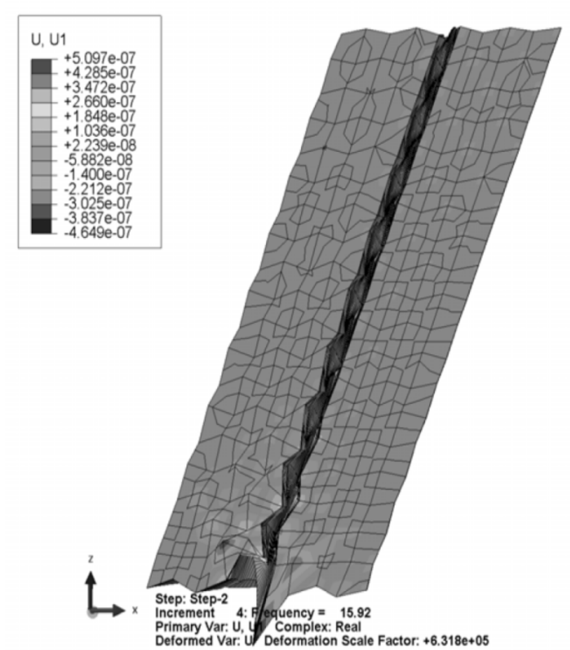


Fig. 9. Sectional view of displacement contours of circular soil zone for batter pile (20˚)

A typical displacement response of batter piles for a lower (e = 32˚) and higher (e = 80˚) magnitude of load is shown in Figure 10. Displacement response of vertical piles obtained through FEA is also shown for comparison. It can be seen that displacement amplitude is considerably reduced with increase of batter angle for the batter piles when compared to the vertical pile. A similar finding is also reported by Gerolymos et al. (2010) based on the finite element analysis carried out on batter piles.

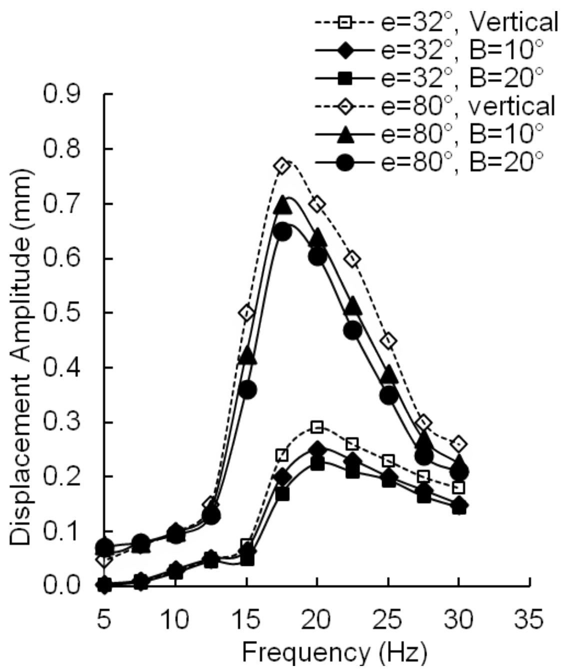


Fig. 10. Effect of angle of inclination on the response of batter piles

Table 1. Resonant Frequency and Peak Displacement of Piles subjected to Lower Force Level (e = 32˚)

Pile Inclination	Resonant Frequency Hz	Peak Displacement mm	Percentage Reduction in Displacement
0˚	20.5	0.300	0
10˚	20.0	0.255	15
20˚	20.2	0.225	25

Table 2. Resonant Frequency and Peak Displacement of Piles subjected to Higher Force Level (e = 80˚)

Pile Inclination	Resonant Frequency Hz	Peak Displacement mm	Percentage Reduction in Displacement
0˚	17.5	0.770	0
10˚	17.4	0.705	11
20˚	17.5	0.655	15

The percentage variation of peak displacement for lower and higher eccentric loads is presented in Table 1 and 2 respectively. The resonant frequency for both batter and vertical piles is almost same irrespective of the batter angle and it occurs within the range of 16 Hz to 22 Hz. For the lower magnitude of applied dynamic load the displacement of batter (20˚) piles reduce by 25% in comparison to vertical piles and for higher magnitude of load it reduces to 15%. The decrease in percentage reduction from low to high magnitude of dynamic load is attributed to the increase of non linearity of the soil pile system with increase in force level.

SUMMARY AND CONCLUSIONS

The dynamic lateral load tests carried out on vertical plies at a site in Paradip, India is reported. The displacement response of vertical piles obtained from the field tests is used to validate the 3D finite element results carried out using ABAQUS. The finite element analysis was also extended to batter piles to draw comparison of its performance with vertical piles. Based on the field and finite element studies, the following conclusions are arrived:

- In the field tests resonant frequency of vertical piles is found to be varying from 16Hz to 22 Hz depending on the magnitude of applied load.
- The displacement response of vertical piles obtained from 3D finite element analysis is in good agreement with field test results.
- For batter piles like in the case of vertical piles, the peak displacement amplitude increases but resonant frequency reduces with an increase of magnitude of applied force.
- The batter piles transfer lateral load through partial axial compression and tension in addition to shear and bending unlike vertical piles as evident from the high mesh distortion for batter piles at the bottom.
- The peak displacement amplitude of batter piles is found to be 15 to 25% less than the same that of vertical piles indicating better performance of batter piles under lateral dynamic loading.

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