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DYNAMIC RESPONSE OF BATTER PILES

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Abstract

Batter or raked piles have been used, especially in offshore structures, bridges, and towers to resist large lateral loads generated due to winds, tidal waves, soil pressure etc. From the past experience, the performance of batter piles were found poor for seismic resistance, resulting in bad reputation. In some cases, the key reason for the poor performance of batter piles was due to large shear force and moment induced at the pile head. Many researchers also suggested to avoid the use of batter piles in seismic prone areas, due to subsequent poor performance of batter piles during earthquakes. Several codes also recommends to avoid batter piles in moderate to severe seismic prone area. Various attempts have been made by engineers and researchers to improve the seismic performance of batter piles and to modify the existing design strategies to overcome these problems. Past studies also showed that the use of batter and vertical piles together in a pile-soil system increases its overall efficiency. Researchers also reported that in particular cases, the use of batter pile groups is advantageous in supporting lateral loading.

The emphasis of this study is to understand the dynamic lateral behavior of single batter piles under machine induced vibrations. The piles are excited in both horizontal directions, (*viz*., along batter and across batter). To simulate the vertical and batter piles, 3D dynamic implicit Finite Element Analyses were carried out using ABAQUS (with state-of-art pre and post processor). Soil mass, pile, pile cap and machine were modelled using 4-node linear tetrahedron element (C3D4). Lateral soil boundary has been simulated after performing the sensitivity analysis for soil mass. Soil pile interaction has been taken into account in terms of tangential and normal contact properties at the soil pile interface. Separation of soil mass has been allowed at the normal contact interface. Parametric study has been performed considering different pile inclinations (*i.e.* 10˚ and 20˚ from the vertical) and varying force levels of excitation (with varying excitation frequency and eccentricity of the oscillator). Responses of vertical and batter piles were estimated in terms of lateral displacement at the pile cap. This study shows that batter piles have performed very well than the vertical pile under moderate to heavy machine induced vibrations. Hence, batter piles with critical inclination significantly improve the performance of foundations subjected to lateral loads.

Keywords: Batter Pile; FEM; Dynamic Response

1. Introduction

Batter piles or raked piles have been used in offshore structures, bridges, towers to resist large lateral loads from winds, water waves, soil pressure and impacts since long time. Batter piles can carry lateral loads primarily in axial compression and/or tension while vertical piles can carry lateral loads in shear and bending. Due to poor performance of batter piles in some earthquakes, they lost their good reputation. After a series of poor performance many researchers thought use of batter piles in seismic prone areas may be detrimental and several codes wanted batter piles to be avoided.

The French seismic code [1] said, "*Inclined piles should not be used to resist seismic loads*". The seismic Euro code [2], is less restrictive, "*It is recommended that no inclined piles be used for transmitting lateral loads to the soil. If, in any case, such piles are used, they must be designed to carry safely axial as well as bending loading*". "*The use of batter piles at ports is typically not encouraged because of their poor seismic performance during past earthquakes*" advised [3]. In some cases, large shear force and moment induced at the pile head were the key source of poor performance of batter piles. However, engineers adopted strategies to develop the performance of batter piles once the reason for poor performance was identified. Thus, batter piles once again became an important weapon for foundations subjected to lateral loads. Use of batter and vertical piles in a pile-soil system increases the overall efficiency of the system. Later, [4, 5] provided evidences portraying advantages of using batter pile groups in supporting lateral loading in particular seismic cases. The presence of inclined piles offered the necessary lateral stiffness to the pile groups supporting the bridge at the Pier of Landing Road Bridge during 1987 Edgecumbe earthquake of 6.3 Magnitude [6]. The quay walls of Maya Wharf reported that inclined piles withstood severe seismic during 1995 Kobe earthquake of 6.9 Magnitude [7].

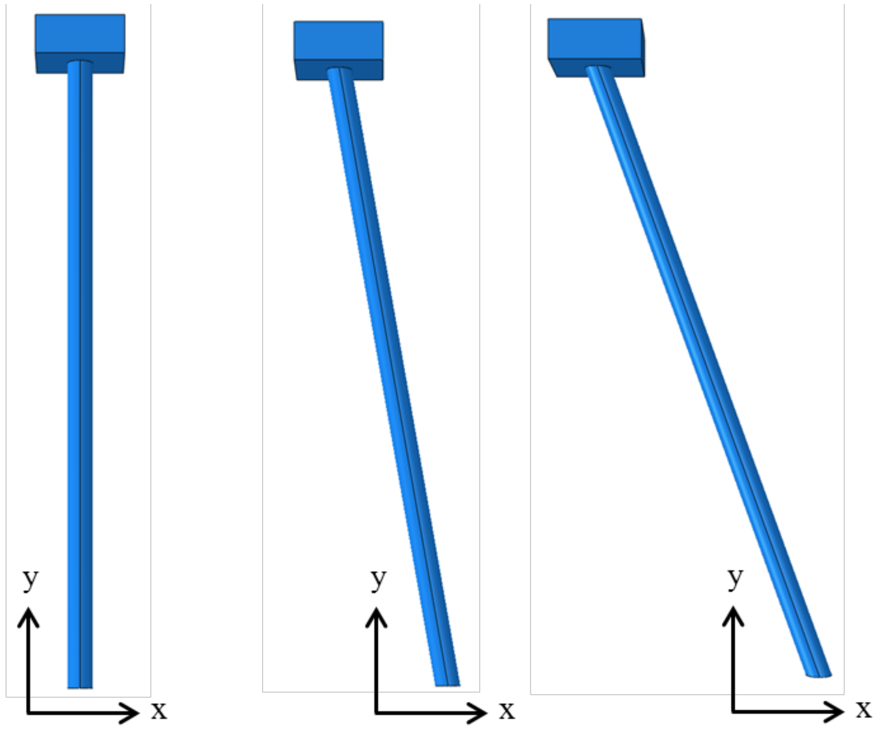
The poor performance of batter piles during some of the earthquakes was due to the design analyses which assumed the head of the pile to be "pinned", *i.e.* free to rotate, and thus was not designed to sustain any moment loading. However, pile head was subjected to large shear and moment loads, resulting in failure. Thus, the performance of batter piles could be improved by strengthening the pile head and providing sufficient ductility to the pile head or the pile-structure connection.

In the present study, the dynamic lateral behavior of batter piles subjected to machine vibrations has been studied. 3D dynamic finite element analyses have been performed using ABAQUS [8] with excellent pre and post processing features. Lateral dynamic loading is applied in both x (along batter) and z (across batter) directions in the form of sweep load to study the influence of batter direction on the behavior of soil pile system considering a range of working frequency and force levels. Twenty four different cases were considered by changing the direction and force level. The results are produced in the form of resonant frequency and resonant amplitude for all considered cases.

2. Finite Element Modelling

In this study, three different pile geometries (*viz.* vertical pile, 10º batter pile and 20º batter pile) having same length (l = 5 m) and diameter (d = 200 mm) have been considered (as shown in Fig. 1) to understand the behaviour of batter piles inclined at different angles subjected to dynamic loading in both along and across the batter direction. Due to complex geometries of soil pile system (*viz.* pile with pile cap, soil mass and machine), different parts were modelled separately in SolidWorks [9] and then imported and assembled in ABAQUS [8].

The material properties of soil (up to 10 m depth) has been selected from a particular site at the Department of Earthquake Engineering, IIT Roorkee [10]. Homogenous soil (with same Poisson's ratio, ν = 0.3 for all soil layers) has been considered for each layer (1 m thickness) as presented in Table 1. The material properties used to model the concrete pile is presented in Table 2.



(a) Vertical Pile (b) 10º Batter pile (c) 20º Batter pile

Fig. 1 – 3D Model for pile

Table 1 – Properties of soil [10, 11]

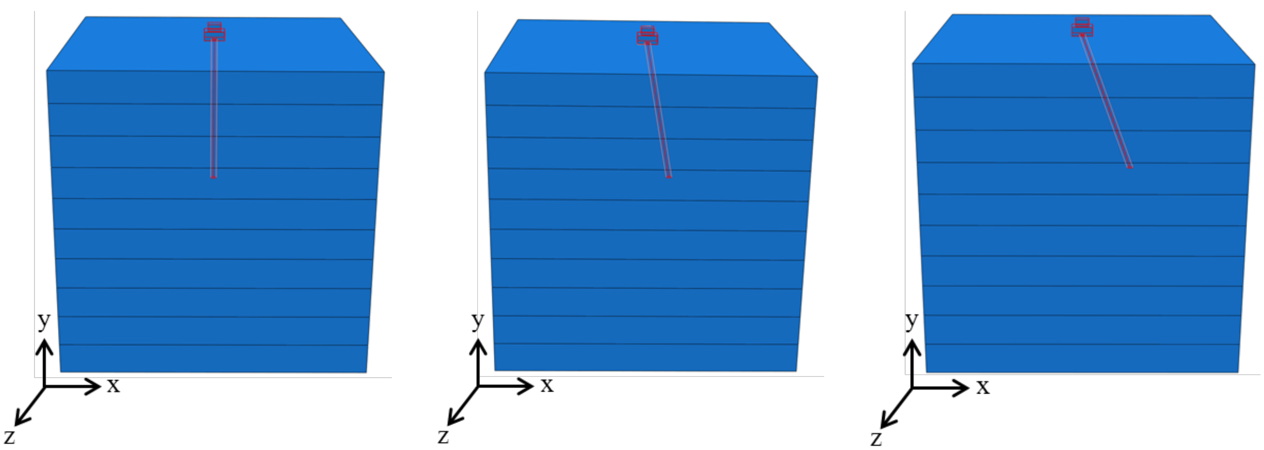
Soil Layer No.	Density, γ (kN/m^3)	Young's Modulus, E (kN/m^2)
1	15.20	8.30E+04
2	15.20	8.75E+04
3	15.20	9.65E+04
4	16.90	9.27E+04
5	16.00	1.28E+05
6	15.60	1.14E+05
7	16.00	1.10E+05
8	16.30	1.19E+05
9	16.60	1.25E+05
10	16.60	1.25E+05

Table 2 – Properties of pile [12]

Parameter	Value
Density	24 kN/m^3
Elasticity Modulus	$25x10^9$ N/m^2
Poisson's Ratio	0.15

Soil, pile, pile cap and machine were modelled as linearly elastic material with 4-node linear tetrahedron element (C3D4) available in ABAQUS element library. The soil pile machine model with different layers of soil for all three considered geometries is shown in Fig. 2. In this study, stage analyses were carried out to simulate the sequence of excavation, pile installation and dynamic loading. Initially in-situ stress has been generated by carrying out Geo-Static analysis. A small clear space of 5cm is provided in between the soil mass and the bottom of pile cap as shown in Fig. 3 to avoid the friction between the two surfaces.

Soil-pile interaction has been simulated by assigning a surface to surface contact element of zero shell thickness between master (soil) and slave (pile) parts with specific tangential (Friction coefficient, $\mu = 0.37$) and normal properties (Hard contact with allowed interface separation). The horizontal and vertical extent of the soil mass for finite element modeling has been considered through a sensitivity analysis so that the effect of boundary conditions is insignificant on considered parameters (*i.e.* displacement, stress and resonant frequency). All movements are restraint at the base of the model (*i.e.* x, y and z displacements are zero), while for lateral boundaries (*i.e.* x and z), vertical rollers are used (*i.e.* y displacement is allowed).



(a) Vertical Pile (b) 10° Batter Pile (c) 20° Batter Pile

Fig. 2 – Soil pile system

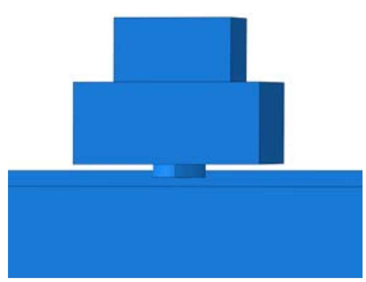
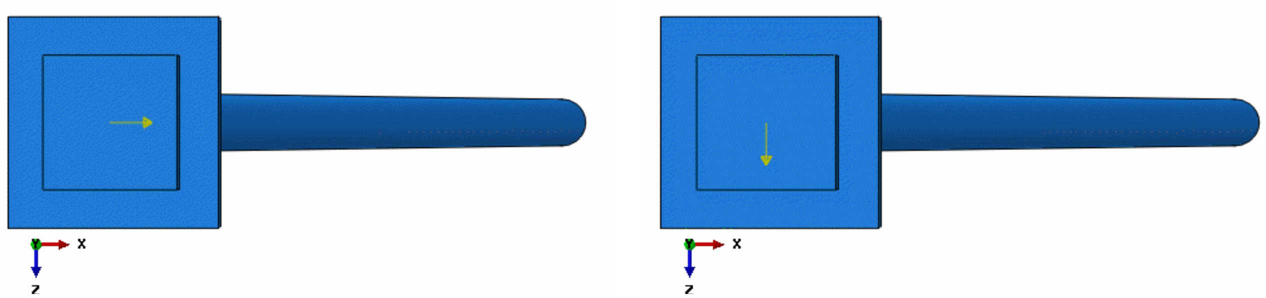


Fig. 3 – Space between soil mass and pile cap

The dynamic load pattern considered for the present study is similar to machine vibrations. In order to represent the machine, an oscillator motor assembly has been modelled as a rigid block (with high Young's Modulus to ensure no internal deformation) fixed on the top of the pile cap. The material property used to model the oscillator motor assembly is presented in Table 3. The two directions considered for dynamic loading i.e. x and z has been shown in Fig. 4 (a) and 4 (b) respectively.

Table 3 – Properties of machine [11]

Parameter	**Value**
Density, γ	78.5 kN/m^3
Young's Modulus, E	20E+12 kN/m^2
Poisson's Ratio, ν	0.30

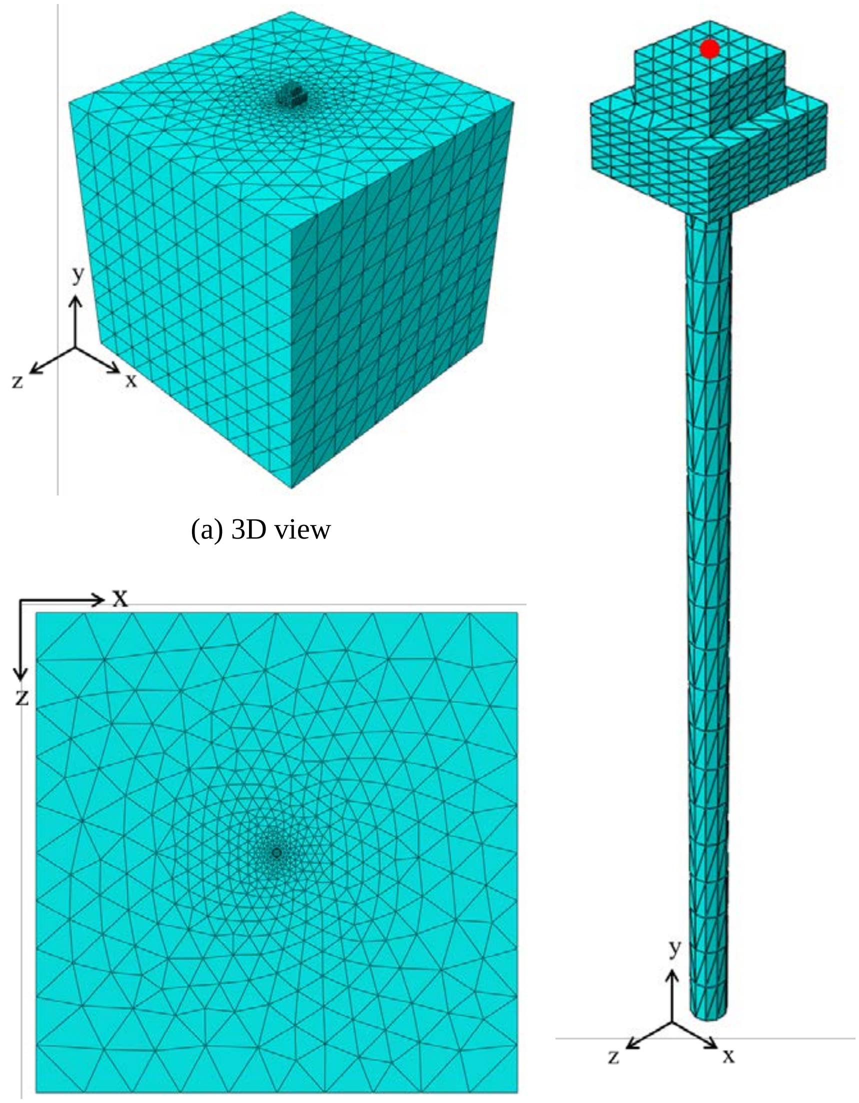


(a) x (Along batter) (b) z (Across batter)

Fig. 4 – Direction of load application

The element size of soil mass has been kept very small near the pile circumference, (*i.e.* ≈ 6 cm) and along the boundaries element of larger size (about 100 cm) has been used (as shown in Fig. 5 (a) and 5 (b)). The total number of elements for Case-I (Vertical pile) for soil mass was 43868 and total number of elements of pile was 2530. For Case-II (10º batter pile) the total number of elements of soil mass was 45300 and total number of elements of pile was 2715. Similarly, for Case-III (20º batter pile) the total number of elements of soil mass was 43797 and total number of elements of pile was 2595. Horizontal dynamic load is applied in x (along batter direction) and z (across batter *i.e.* perpendicular to the batter direction) directions separately at the node created on the rigid block as shown in Fig. 5 (c) in the form of sweep load (sinusoidal load with varying frequency and corresponding amplitude).

3D Dynamic Implicit analyses were carried out for the considered soil pile systems. The input dynamic force has been considered for a frequency range of 0 to 30 Hz depending upon the corresponding resonant frequency of the soil pile system. The horizontal dynamic loading in the form of sweep load for four different eccentricities setting (representing four different force levels) of the oscillator motor assembly for vertical pile is shown in Fig. 6.



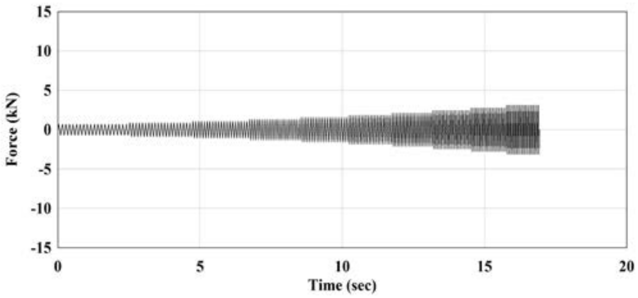
(a) 3D view

(b) Top view (c) Vertical Pile

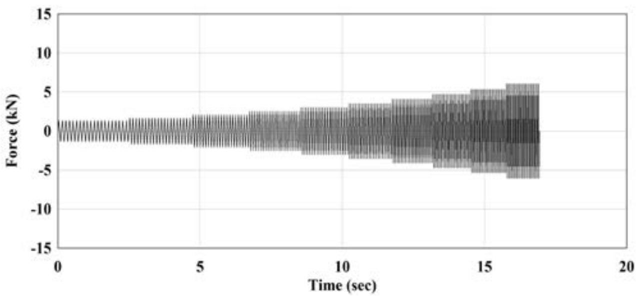
Fig. 5 – Mesh for soil pile machine system

3. Results and Discussions

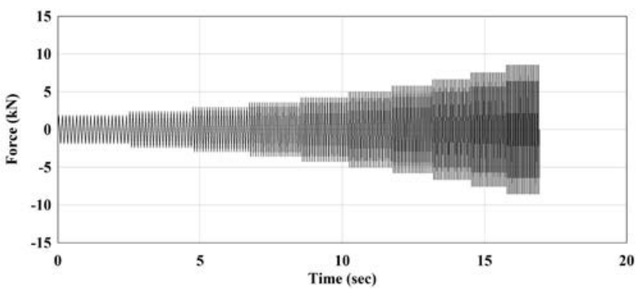
The resonant frequency of vertical pile was 25 Hz whereas for 10º and 20º batter piles it has b 16 Hz and 15 Hz respectively. The displacement time history obtained for different eccentricity setting of the oscillator for 20° pile when excited in z direction (*i.e.* across batter) is presented in Fig. 7. The displacement time history represents the displacement due to sinusoidal sweep load. Similarly the displacement time histories were obtained for all considered cases at the pile head. It has been observed that the resonant frequency of vertical, 10° and 20° batter pile remained same with increasing force level as linear soil pile system was considered for analyses. The variation of maximum displacement at the pile head with force level is presented in Fig. 8 and 9 for all considered piles excited in x and z direction respectively. The percentage decrease in the horizontal displacement amplitude of batter piles compared to vertical pile in both the direction (*i.e.* x and z) is presented in Table 4.



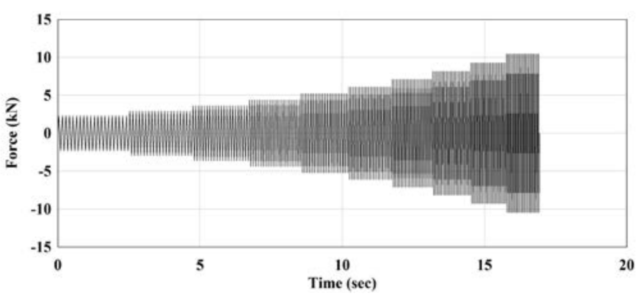
(a) 30° eccentricity



(b) 60° eccentricity

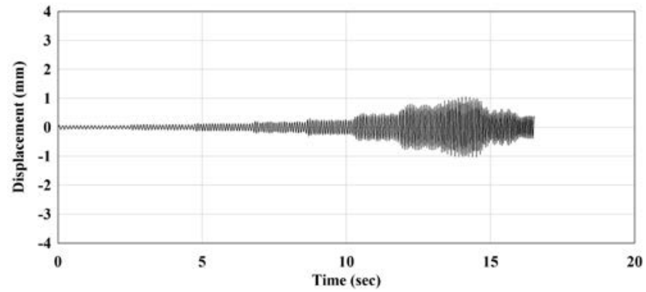


(c) 90° eccentricity

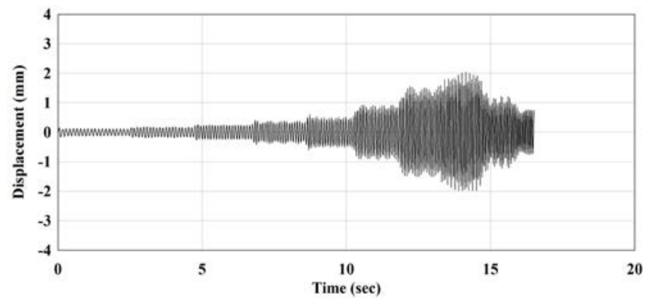


(d) 120° eccentricity

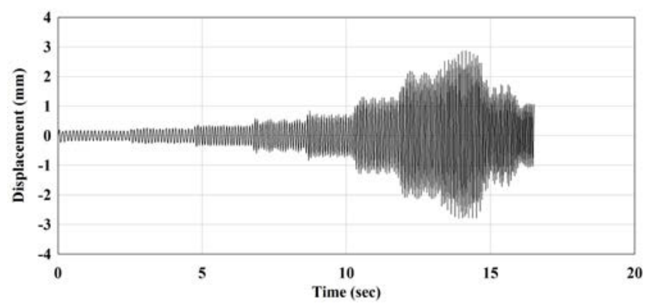
Fig. 6 – Dynamic input motion



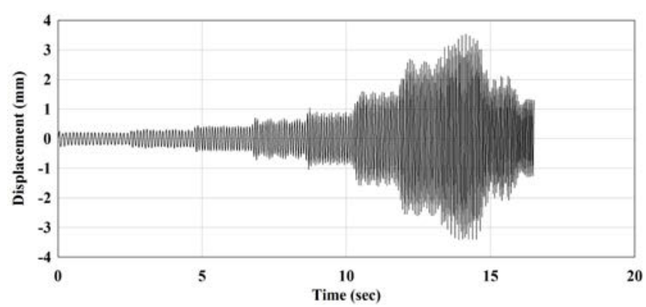
(a) 30° eccentricity



(b) 60° eccentricity



(c) 90° eccentricity



(d) 120° eccentricity

Fig. 7 – Displacement time history for 20º batter pile (z direction)

Table 4 – Percentage decrease in displacement amplitude

Excitation Direction	x (Along Batter)				z (Across Batter)			
Eccentricity (Degrees)	**30**	**60**	**90**	**120**	**30**	**60**	**90**	**120**
10˚ Batter Pile	65.88	62.00	67.76	71.52	67.80	68.48	68.72	69.72
20˚ Batter Pile	58.10	55.62	54.56	55.36	52.43	52.43	52.26	53.52

It can be observed from Table 4 that the percentage decrease in the peak displacement amplitude has reduced with the increase in the batter angle along both x and z directions. This provides an evidence for the fact that the displacement amplitude does not decrease in proportion to the increase in the batter angle. The critical batter angle for a particular case could be obtained by performing rigorous analytical studies.

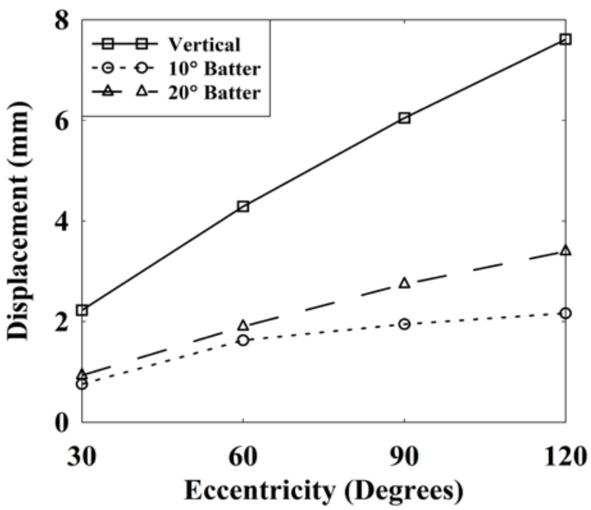


Fig. 8 – Horizontal displacement at pile cap (x direction)

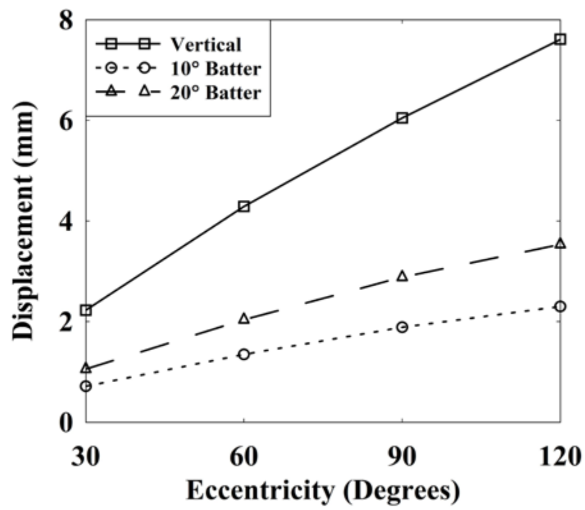


Fig. 9 – Horizontal displacement at pile cap (z direction)

4. Conclusions

Numerical investigation has been carried out to study the lateral dynamic behaviour of single vertical and batter piles. It has been observed that; irrespective of the direction of excitation (*i.e.* x and z) as the eccentricity of the oscillator (*i.e.* force level) increases, the horizontal displacement amplitude increases for all considered cases. Linear soil pile system has been considered and hence insignificant variation was found in the resonant frequency of the soil pile system. The percentage decrease in horizontal displacement amplitude of 10º batter pile was about 67±5% in x direction (*i.e.* along batter) and 68.5±1.5% in z direction (*i.e.* across batter). Whereas, the percentage decrease in horizontal displacement amplitude of 20º batter pile was about 56±2% in x direction (*i.e.* along batter) and 53±1% in z direction (*i.e.* across batter).

Thus, providing batter pile helps in the reduction of the horizontal displacement amplitude. In authors' point of view, 10° batter pile subjected to horizontal dynamic (sinusoidal) loading, helps in significant reduction of horizontal displacement amplitude when compared to 20° batter pile. Thus the critical batter angle which helps in significant reduction of amplitude could be obtained analytically. Hence, it is favorable to use batter pile in situations where the system is subjected to heavy horizontal dynamic (sinusoidal) loads.

5. Acknowledgements

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6. References

[1] AFPS (1990), Recommendations AFPS 90, Association Française de Génie Parasismique, Presses des Ponts et Chausseés.

[2] Eurocode EC 8 (2003), "Design of structures for earthquake resistance. Part 5. Foundations, retaining structures, and geotechnical aspects", Section 5.4.2(5): Piles and Piers, pp. 23

[3] Werner, S. D. (1998), "Seismic Guidelines for Ports", American Society of Civil Engineers.

[4] Giannakou, A., Gerolymos, N., Gazetas, G., Tazoh, T. and Anastasopoulos, I. (2010), "Seismic behavior of batter piles: Elastic response", *Journal of Geotechnical and Geoenvironmental Engineering*, 136(9), pp. 1187-1199.

[5] Gerolymos, N., Giannakou, A., Anastasopoulos, I. and Gazetas, G. (2008), "Evidence of beneficial role of inclined piles: Observations and summary of numerical analyses", *Bulletin of Earthquake Engineering*, **6**(4), pp. 705-722.

[6] Berrill, J.B., Christensen, S.A., Keenan, R.P., Okada, W. and Pettinga, J.R. (1997), "Lateral spreading loads on a piled bridge foundation", International Conference on Soil Mechanics and Geotechnical Engineering, Seismic Behavior of Ground and Geotechnical Structures: Special Technical Session on Earthquake Geotechnical Engineering, Balkema Publisher, Rotterdam, Netherlands, pp. 173-183.

[7] Kastranta, G., Gazetas, G. and Tazoh, T. (1998), "Performance of three quay walls in Maya Wharf: Kobe 1995", 11th European conference on Earthquake Engineering, Paris.

[8] ABAQUS (2016). ABAQUS Documentation, Dassault Systèmes, Providence, RI, USA.

[9] Solidworks (2016), Dassault Systèmes, SolidWorks Corporation, Waltham, Massachusetts, USA.

[10] Muzammil M. (2013), "Influence of Pile Geometry on the Dynamic Response of Under-reamed Piles", M. Tech Thesis, Department of Earthquake Engineering, IIT Roorkee.

[11] Bharathi M, Dhiraj Raj, R.N. Dubey and S. Mukerjee (2016), Numerical Simulation of Dynamic Vertical Tests on Piles. Sixth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Delhi, India.

[12] Bharathi M., R.N. Dubey and S. Mukerjee (2014), Numerical Simulation of Horizontal Dynamic Pile Load Tests on Under-Reamed Piles. 5th Asia Conference on Earthquake Engineering, Taipei, Taiwan.