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Seismic response of batter piles in liquefiable soils

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ABSTRACT: Batter piles exhibited better seismic performance compared to vertical piles in some recent earthquakes especially in case of liquefiable soil conditions. This may be due to the additional stiffness of batter piles under lateral loading conditions, making it a strong contender as alternative to vertical piles in liquefiable soil condition. In the present study, seismic behaviour of 2x1 batter pile groups supporting short (T=0.1s) and long (T=1s) period structures has been investigated through fully coupled three dimensional dynamic analyses carried out in the open source finite element software package OPENSEES. Analyses were performed considering single homogeneous and liquefiable soil layer with water table at the ground surface and superstructure load of 1000kN per pile. Three different earthquake time histories were considered as base motions. Batter pile groups with three different batter angles (0°: essentially vertical pile groups, 10° and 20°) were considered for the study. The seismic responses of the pile groups are presented in terms of bending moment, shear force, and superstructure acceleration. Numerical simulations confirm the effectiveness of batter pile groups in liquefiable ground particularly for long period structure.

1 INTRODUCTION

The seismic design of offshore structures such as wharves, bridges, and towers demands foundation that can carry large lateral loads resulting from earthquakes. Batter piles are capable of sustaining significant lateral loads since they transmit load by axial compression or tension as opposed to vertical piles (Giannakou *et al.* 2010). Due to this distinct potential of batter piles to be advantageous in such situations, it has become a favorable choice for practicing engineers especially for harbor structures (Kavazanjian (2006)). Although the use of batter piles has been restricted by many codes (AFPS 1960, Eurocode EC8/Part 5) due to its unsatisfactory or poor performance in past earthquakes (1964 Alaska earthquake, 1989 Loma Prieta earthquake, and 1991 Costa Rica earthquake), the better understanding of the actual reason behind such failures has yet again made batter piles a strong candidate for such conditions (Razavi *et al.* 2007)). A properly designed batter pile considering adequate reinforcement at pile head and strong connection between pile head and cap has proved to be effective for both piles as well as superstructure. The case studies of Maya wharf during the 1995 Kobe earthquake and New Zealand's Landing Road Bridge during the Edgecumbe earthquake have indicated the effectiveness of batter piles over vertical piles during strong earthquakes (Pender, 1993).

The beneficial or detrimental performance of batter pile during earthquakes has been studied with and without considering soil-structure interaction by many researchers (Tazoh *et al.* 2010, Isam *et al.* 2012, Li *et al.* 2015, Li *et al.* 2016). Giannakou *et al.* (2010) carried out an elastic analysis of 2x1 batter pile groups to study under which circumstances batter piles are beneficial and disastrous. Results indicated that batter piles exhibit negative response when only kinematic loading is considered. On the other hand, batter piles might be advantageous under certain conditions when inertial loading is also taken into account. Komatsu *et al.* (2004) observed that lateral stiffness of negative battered pile (inclined in direction opposite to loading) is more than that of the vertical pile while for positive battered pile (inclined in the direction of loading) lateral stiffness is less. Deng *et al.* (2007) carried out three- dimensional analysis of large pile group consisting of both vertical and batter piles and noticed that batter piles attracted larger axial loads. Gerelymos *et al.* (2008) noted that for tall slender structures, pile groups containing symmetrically inclined batter piles with hinged pile cap connection perform most satisfactorily under seismic conditions. Ghorbani *et al.* (2014) performed elasto-plastic finite element analyses and showed that increasing friction angle of soil and number, inclination, diameter, and slenderness ratio of micropile improves the seismic performance of inclined micro piles. Sarkar *et al.* (2017) highlighted the better performance of batter piles in seismic condition by conducting three-dimensional analysis on 2 x 2 vertical and batter pile groups supporting five-storied portal frame structure.

Past research has shown that the pile foundation has been the primary choice for structures and bridges founded in liquefiable soil and many literatures are available studying the response of vertical piles in liquefying condition (Finn and Fujita 2002, Cheng and Jeremic 2009, Choobbasti *et al.* 2011, Maheshwari and Sarkar 2011). However, the investigations related to the performance of batter piles in liquefiable soil are limited. Lam and Martin (1986) through their studies showed that the presence of batter piles may reduce bending moment and pile cap displacement in the liquefied soil. Wang and Orense (2014) carried out non-linear finite element analyses on fixed head batter piles and confirmed that positively inclined piles develop less moment at pile head while negatively inclined piles develop less moment at liquefied and non-liquefied soil interface when compared to vertical piles. Tazoh *et al.* (2010) noticed that batter piles reduce horizontal displacement of foundation when subjected to liquefaction-induced soil flow. Wang and Orense (2017) observed that batter piles reduce horizontal displacement of superstructure but increase shear demand in piles.

Taking into account the gap in existing literature pertaining to batter piles, the present study aims to analyze the performance of batter pile groups in the liquefiable ground. For this, three-dimensional finite element analysis of 2 x 1 fixed head batter pile groups supporting two different period structures – short (T=0.1s) and long (T=1s) is carried out in open source software package OPENSEES. The results are then compared with that of 2 x 1 vertical pile groups analyzed under same conditions. The highlights of the present study are summarized as below:

- Investigation of seismic behaviour of batter pile groups in liquefiable soil. To simulate liquefaction of soil effectively, the variability of permeability during the process of liquefaction (i.e. from build-up of pore pressure to attainment of fully liquefied stage) has been considered.
- Consideration of two different period structures to study the efficiency of batter piles in liquefiable soil conditions under earthquake loading conditions.

2 PROBLEM DEFINITION AND MODEL DESCRIPTION

A 2 x 1 batter pile group with fixed head to cap connection embedded in an uniform homogeneous Nevada sand layer (40% relative density) of 15 m thickness is considered for the study. The properties of the sand as given in Karimi and Dashti (2015) are adopted for the study. Three different batter angles - 0˚ (vertical for reference), 10˚ and 20˚ are assumed to investigate the effect of batter angle on the performance of the pile. Each pile supports a superstructure load of 1000 kN and is connected to a massless pile cap of 0.5 m thickness located 0.5m above the ground surface. The spacing to diameter ratio at the pile cap level is considered to be 3. Table 1 shows the properties of the pile. To evaluate the influence of the superstructure on the seismic response of batter pile group, two period structures – short (T=0.1s) and long (T=1s) are considered. These two time periods indicate low rise and high rise buildings in practice. Figure 1a and b show the schematic diagram of 2 x 1 vertical and batter pile group supporting the superstructure respectively. The nomenclature to be used for negative and positive batter piles for succeeding sections of the paper are shown in Figure 1b. The water table is assumed to be located at the ground surface in order to simulate fully saturated soil.

Table 1. Properties of the pile considered for the study.

Properties	Values
Diameter, d (m)	0.5
Length, l (m)	10
Modulus of elasticity, E (MPa)	2.74×10^4
Poisson's ratio, ν	0.2
Moment of inertia, I (m^4)	1.53×10^{-3}

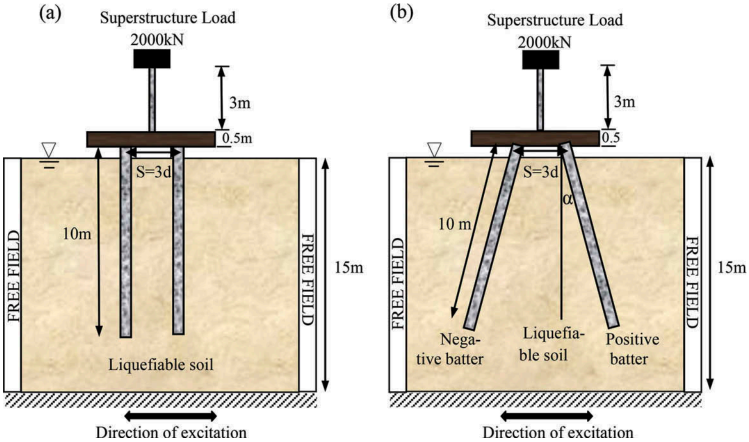

Figure 1. Schematic diagram of (a) 2 x 1Vertical pile group (b) 2 x 1 Batter pile group.

3 DETAILS OF NUMERICAL MODELING FOR SOIL-PILE-STRUCTURE SYSTEM

3.1 *Finite element model*

All the numerical analyses are performed using free finite element software package OPEN-SEES. The size of the model is chosen to be 20m x 12m x 15m for all the cases. In order to minimize any computational burden, only half of the model is analyzed. In order to ensure proper wave propagation through the soil elements, model is meshed keeping maximum element size less than one-tenth to one-eighth of wavelength associated with highest frequency of input wave (Kuhlemeyer and Lysmer, 1973). 8 noded brickUP elements are used to model soil and nonlinear beam-column elements are used for piles. The connection between the pile and the surrounding soil elements is maintained through rigid elements as Sarkar and Maheshwari (2012) observed that the soil-pile separation has nominal effect in case of liquefying soil. The pile-cap and cap-structure connections are modeled using equal-DOF command which ensures same displacements of pile and cap nodes and also cap and structure nodes at the interface. The superstructure is considered by a concentrated mass at the top of the column. Since water table is located at the ground surface, water is allowed to drain only from the top. Figure 2a, b, and c show developed finite element models of 2 x 1 vertical pile group, 10° batter pile group, and 20° batter pile group respectively for analysis in OPENSEES.

Pressure-dependent multi yield material model capable of simulating the behavior of soil in the liquefied state is utilized for modeling the sand medium. Since the permeability of sand does not remain constant when it is subjected to seismic loading, variable permeability function proposed by Shahir *et al.* (2014) as given in equation 1 is adopted for the present study.

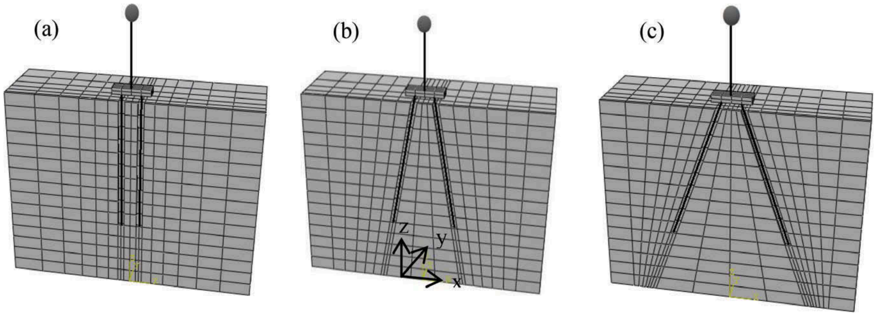

Figure 2. Finite element model of 2 x 1 (a) Vertical pile group (b) 10˚ Batter pile group (c) 20˚ Batter pile group.

$$\begin{aligned}
\frac{k_b}{k_i} &= 1 + 9r_u^2 \;\; for\ r_u < 1 \text{ Build} - \text{up phase} \\
\frac{k_l}{k_i} &= 10 \;\; for\ r_u = 1 \quad \text{Liquefaction phase} \\
\frac{k_d}{k_i} &= 1 + 9r_u^{10} \;\; for\ r_u < 1 \quad \text{Dissipation phase}
\end{aligned} \tag{1}$$

Where, k_i, k_b, k_l, k_d are initial, build up phase, liquefaction state and dissipation phase permeability coefficients and r_u is the excess pore pressure ratio.

3.2 *Stages of loading*

The entire soil-pile-structure system is developed in three stages and is explained briefly as follows:

i. Soil gravity stage: In this stage, the base of the model is completely fixed and side boundaries (parallel to y-direction) perpendicular to the excitation direction (x-direction) are connected at each depth to simulate free field condition. The other two boundaries (parallel to x-direction) are then fixed such that any out-of-plane movement is prevented. Once proper boundary conditions are ensured, soil gravity is applied to develop initial stress.
ii. Pile and superstructure gravity: Pile elements are installed in the pile zone after removing the soil elements and replacing with softer elements of small stiffness and low permeability to prevent water from flowing into the pile zone (Cheng and Jeremic, 2009). Pile mass is then distributed along the pile nodes and superstructure weight is added at the column head followed by application of gravity load.
iii. Seismic loading: Finally, earthquake time history is applied at the base of the model with the updation of permeability of soil updated in each step.

3.3 *Characteristics of applied seismic motions*

Three different earthquake time histories as presented in Table 2 are considered for the present study. The motions are chosen such that a fair range of earthquake characteristics is included. All the three time histories were scaled to same PGA of 0.1g.

Table 2. Characteristics of seismic motions considered.

Earthquake	Predominant frequency (Hz)	Bracketed duration (s)	Arias intensity (m/s)
Elcentro (1940)	1.51	25.98	1.8
Taft (1952)	1.91	15.58	0.59
LomaPrieta (1989)	1.56	3.44	0.11

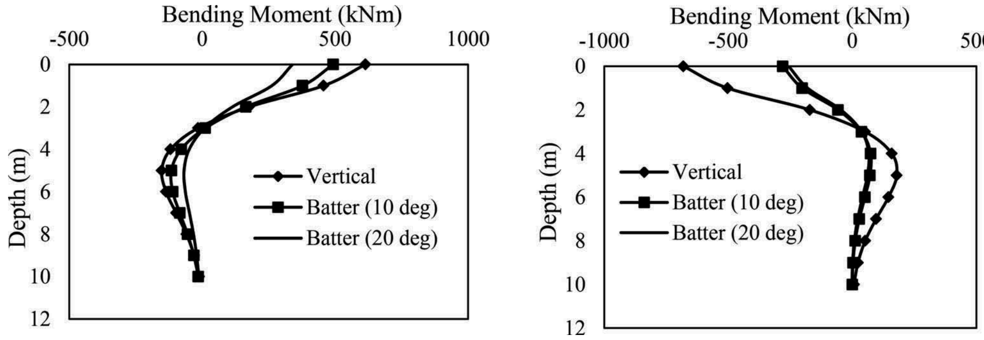

Figure 3. Bending moment profiles of vertical, 10° batter and 20° batter pile groups subjected to Elcentro earthquake (1940) for (a) Short period structure (b) Long period structure.

4 RESULTS AND DISCUSSIONS

The following section presents the results of batter pile groups (10˚ and 20˚) supporting short and long period structures subjected to seismic loading. The results are compared with corresponding vertical pile groups subjected to same earthquake time history. The results are presented in terms of pile bending moment, shear force, and superstructure acceleration. Percentage change in induced forces of batter pile groups are calculated with respect to vertical pile groups. Similarly, percentage change is calculated for superstructure acceleration.

4.1 *Comparison of bending moment of vertical and batter pile groups*

Figure 3a and b shows bending moment profiles of vertical, 10˚ batter and 20˚ batter pile groups supporting short period structure and long period structure respectively for Elcentro earthquake (1940). The bending moment profiles show that bending moment is maximum at the pile head (due to inertial loading). The bending moment is again observed to increase at the interface of liquefied ($r_u \approx 1.0$) and non-liquefied soil ($r_u \ll 1.0$) (effect of kinematic loading). It can be noted that with increase in the pile batter, there is a significant reduction in the pile bending moment especially at the pile head. Figure 4a and b show percentage reduction in maximum pile head moment for10˚ and 20˚ batter pile groups supporting short and long period structures respectively. It is observed that the effect of batter is more for pile groups supporting long period structures. Percentage reduction of up to 65% is noted in the presence of batter piles when subjected to Elcentro earthquake. For short period structure minimum

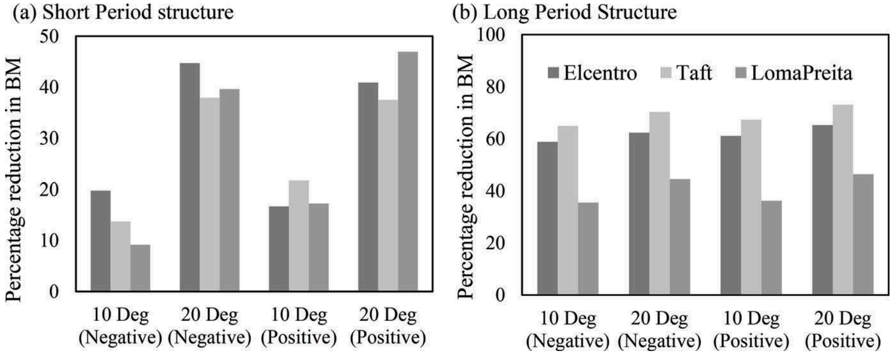

Figure 4. Percentage reduction in maximum pile head moment for10˚ and 20˚ batter pile groups supporting (a) Short period structure and (b) Long period structure.

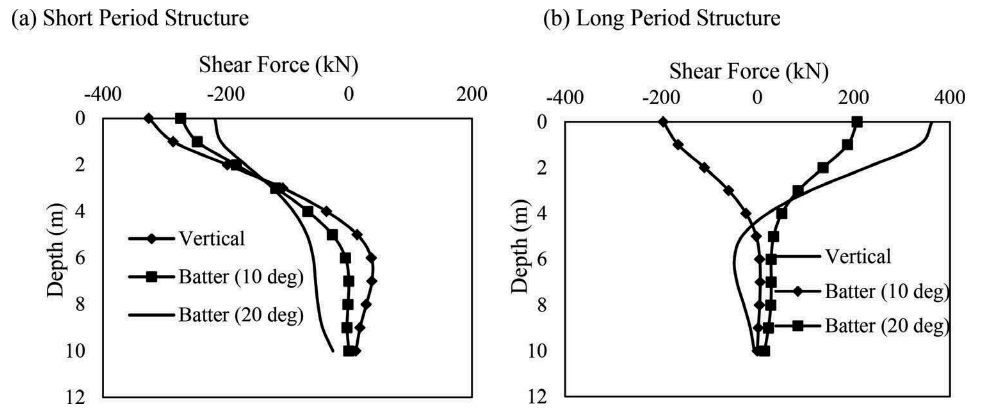

Figure 5. Shear force profiles of vertical, 10° batter and 20° batter pile groups supporting (a) Short Period structure and (b) Long Period structures subjected to Elcentro earthquake (1940).

percentage reduction is about 10% whereas for long period structure it is about 30%. For the earthquakes considered in the study, it is observed that for short period structures, batter angle influences significantly in reducing bending moment whereas for long period structures the effect of batter angle is marginal.

4.2 *Comparison of shear force of vertical and batter pile groups*

Figure 5a and b shows shear force profiles for vertical, 10˚ batter and 20˚ batter pile groups supporting short and long period structures subjected to Elcentro (1940) earthquake. It is clear that batter piles are effective in reducing shear forces developed at the pile head for both short period and long structures. Similar observations were noted for Taft (1952) and LomaPrieta (1989) earthquakes also. This may be because in vertical piles, significant amount of load is carried through shear. Figure 6a and b shows percentage reduction in shear force at pile head for 10˚ and 20˚ batter pile groups subjected to Elcentro, Taft and LomaPrieta earthquakes supporting short and long period structures respectively. Percentage reduction of up to 32% and 53% is observed when batter angle increases from 0˚ to 20˚ for short and long period structures respectively. Similar to bending moment, batter piles are found to be more effective in reducing shear force when supporting long period structure.

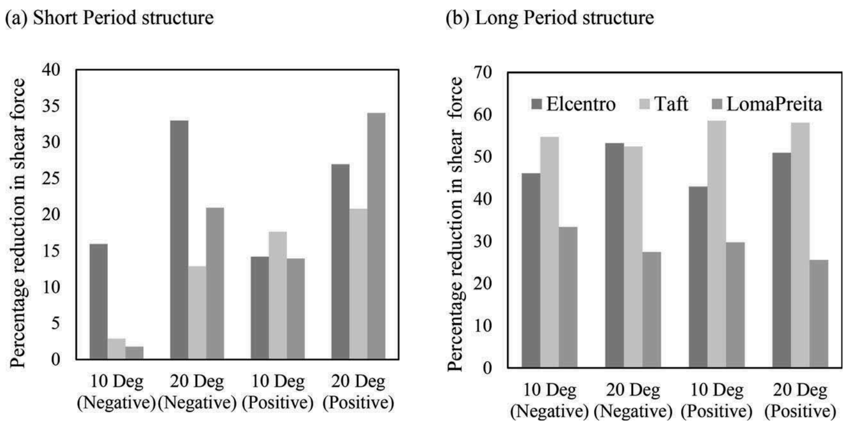

Figure 6. Percentage reduction in shear force at pile head for10˚ and 20˚ batter pile groups supporting (a) Short Period structure and (b) Long Period structure.

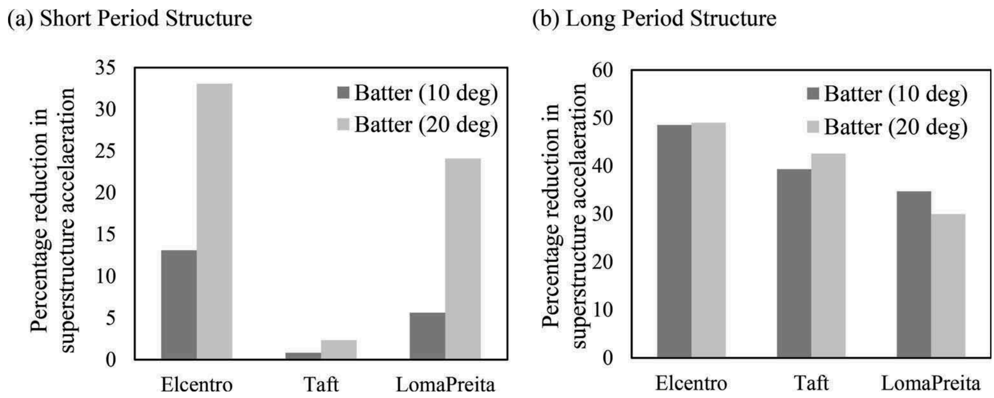

Figure 7. Percentage reduction in superstructure acceleration for10˚ and 20˚ batter pile groups supporting (a) Short Period structure (b) Long Period structure.

4.3 *Superstructure acceleration*

Figure 7 shows percentage reduction in superstructure acceleration for 10˚and 20˚ batter pile groups. The reduction in superstructure acceleration for batter pile groups supporting short period structure is comparatively less. The percentage reduction is as small as 2% for Taft earthquake. On the other hand, for long period structure, batter pile again proves its efficiency with percentage reduction going up to 48%. For short period structure, lengthening of period due to liquefaction makes overall period of system higher which in turn increases the spectral acceleration experienced by the structure. For long period structure, lengthening of period reduces the spectral acceleration of the structure as for higher periods spectrum ordinate reduces.

5 CONCLUSIONS

The present study employs three dimensional finite element analyses to study the effect of pile batter (10˚ and 20˚) on the seismic performance of 2 x 1 pile groups embedded in liquefiable soil. Analyses are carried out on pile groups supporting two different period structures: T=0.1s (short period) and T=1s (long period). Results confirm the effectiveness of batter piles in liquefiable soil due to better mobilization of axial stiffness of piles. The following major conclusions can be outlined from the study:

a. Batter piles reduce bending moment developed at both pile head and interface of liquefied and non-liquefied soil.
b. Batter pile group supporting both short and long period structures reduces shear forces developed at pile head.
c. Reduction in maximum superstructure acceleration is more for long period structure.
d. Both 10˚ and 20˚ batter pile groups are observed to have similar response on both pile and superstructure when supporting long period structure.
e. For the cases considered in the study, it may be concluded that the symmetrically inclined 2 x 1 batter pile groups are highly efficient for long period structures.

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