

Response of Batter Piles Subjected to Static and Seismic Loading: Review Study

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ABSTRACT

Battered piles are beneficial when used as foundations where significant lateral resistance is required, which could result from extreme water waves, winds, soil pressures, massive hits of explosions, or earthquakes. Experimental and numerical research must focus on that direction to reveal how these foundations behave under different loading conditions. The present study reviews the investigations conducted on the performance of batter pile foundations and attempts to understand and cover various aspects related to this issue; after conducting the review, the results indicate that the negative battered piles provide an efficient lateral stiffness corresponding to positive battered piles and a vertical one. Also, lateral bearing capacity improved with the inclusion of battered piles. Moreover, batter piles respond better than vertical piles in liquefiable soil under seismic excitation. The current study also showed that the pullout capacity of batter piles increased with the batter angle.

Keywords: Batter pile, Seismic loading, Static loading.

1. INTRODUCTION

Pile foundations represent one type of deep foundation. When the weak soils present in shallow depth beneath the structure, they transfer the load to the stiffer deep layer of soil with a significant bearing capacity. In practical conditions, these pile foundations are not subjected only to vertical loads but also horizontal loads such as wind loads, wave loads, and earthquakes, so batter piles are used. The rapid growth in construction and expansion in seismic activity around the world encouraged attempts to provide a better comprehension of the complex relationship between the soil and foundation to mitigate building damage and economic losses that occur (**Rajeswari and Rajib, 2024**). Hence the liquefaction phenomenon of soil during earthquakes is one of the primary interests for civil engineers and the subsequent lateral spreading and settlement of soil deposits were observed during the earthquake, which further led to the complete collapse of structures. The pile foundation

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performance during the soil liquefaction represents a severe engineering challenge. When the soil liquefies, its stiffness and strength drop and the pile foundation embedded in such soil becomes susceptible to considerable lateral loading. Therefore, Batter piles are used to improve lateral stiffness. The advantage of using batter piles to support structure is their ability to transmit lateral load as an axial load instead of bending and shear, as in the case of using vertical piles alone. Many damages have occurred in structures founded on batter piles built long ago without a better knowledge of batter pile performance during seismic conditions, as known today **(Finn and Fujita, 2002)**.

The impacts of an earthquake on soil foundations should get significant attention in the future for all engineering projects built everywhere, considering the recent changes in seismic activity everywhere in the world **(Al-Taie and Albusoda, 2019)**. Also, it is worth mentioning that when piles subjected to seismic loading may show a different behavior, as studied by **(Hussein and Albusoda, 2021; Al-Jeznawi et al., 2022a; Al-Jeznawi et al., 2022b; Al-Jeznawi et al., 2023)**. The response of single and group batter piles has been studied, and their efficiency in minimizing lateral displacement and providing sufficient stiffness is indicated in literature by **(Sarkar et al., 2017; Azizkandi et al., 2020; Zhang et al., 2002; Rahimi and Bargi, 2010; Al-Neami et al., 2016)**. The battered micro-pile performance was pointed out in literature by **(Sharma et al., 2014; Sharma and Hussain, 2019; Wang and Han, 2010)**. Furthermore, the pullout capacity of battered piles placed in different soil conditions has also been studied by **(Nazir and Nasr, 2013; Singh et al., 2017; AlTememy et al., 2022)**. However, few studies have been noticed in the literature about the behavior of batter piles in soil susceptible to liquefaction. According to the lateral loading direction, the batter piles can be classified as positive and negative, as seen in **Fig. 1**. If the lateral load acts in the direction of the batter, it is called negative, and if the lateral load acts in the direction opposites to that of the batter it is called positive. Very few studies are available on this pile type, so more information and experimental data about these types of piles are needed. The focus of this paper is to summarize the literature aspect on the static and seismic performance of batter pile foundations and highlight the various features of adopting them in seismic and static design. This paper first presents the mechanisms of failure of batter piles. After that, the performances of batter piles during static and seismic conditions. Finally, the factors that influence the behavior of Batter Piles.

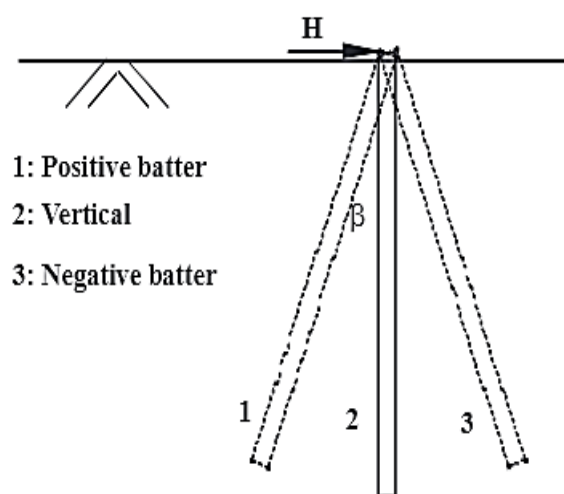


Figure 1. Types of batter piles **(Ghazavi et al., 2014)**.

2. BATTER PILES FAILURE MECHANISMS

The batter piles performance exposed to lateral loading was first observed by (Tschebotarioof, 1953). (Yoshimi, 1964) evaluated the analysis of load–settlement of the inclined piles. (Meyerhof and Ranjan, 1973) studied the bearing capacity analysis of batter piles subjected to axial loading in sand. The study Suppose that the failure mechanisms of battered piles are the same vertical piles under axial loading. Fig. 2 displays the failure zones developed below battered piles, where (θ) is the angled of the shearing zone.

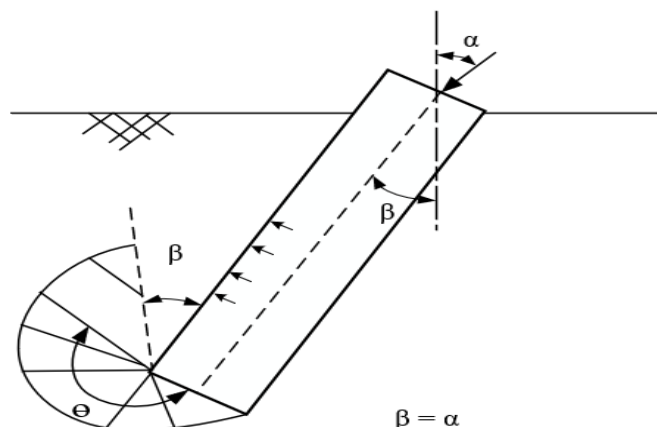


Figure 2. Failure zone below batter piles (Meyerhof and Ranjan, 1973).

As mentioned before, batter piles are classified as negative and positive. The net lateral and axial forces are equal in negative and positive batter piles if the bearing resistance of negative batter piles has been neglected. Thus, the capacity is attributed to friction only. Force analysis that acts on batter piles is shown in Fig. 3. The net axial forces act on negative batter piles in the downward direction. In contrast, the net axial force acts on positive batter piles upward. Therefore, in the case of negative batter piles, the slip surface is convex downward. Meanwhile, the slip surfaces for the positive batter piles convex upward, which explains why the shearing resistance along positive batter piles is less than negative batter piles, and the lateral capacity of positive batter piles is less than negative batter piles.

The failure mechanisms of piles under seismic loading can be summarized below:

- Bending Failure: the high load from the superstructure attributed to the failure of the piles by bending adjacent to or at the pile head.
- Shear Failure: Hollow and small diameter piles, which describe low shear capacity piles, could fail by shear.
- Buckling Failure: when piles placed in liquefiable soils are prone to failure by buckling as the critical length of the pile is less than the unsupported length of the pile in a liquefiable layer.
- Bearing Failure: When the deposit around the piles is susceptible to liquefaction under seismic circumstances, the pile exhibits significant settlement due to tip and shaft resistance failures.

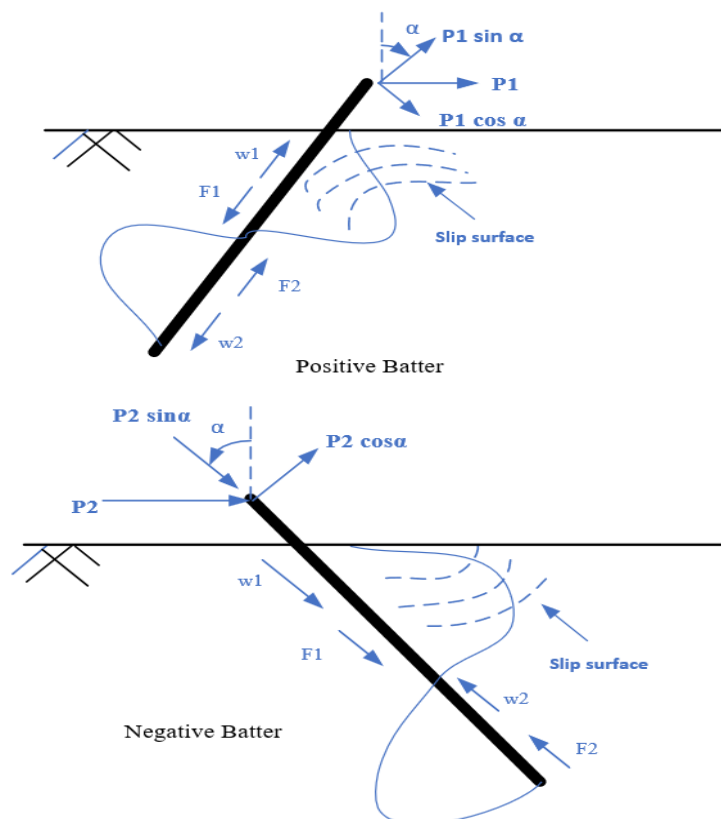


Figure 3. Force Analysis acts on batter piles (Tschebotarioof, 1953).

The prevalent failure mechanism in vertical piles is bending failure, hence considering portions of lateral loading resisted by bending. Shear failure predominates in hollow section piles and small-diameter piles (Bhattacharya, 2003). Batter piles have sufficient resistance to lateral loading corresponding to vertical piles, as the lateral loads are carried by axial tension or compression. The batter piles were reported to fail when subjected to excessive axial loading, in addition to all previous failure mechanisms. Under the exact boundaries, great axial forces are generated, contributing to insufficient behavior much prior than vertical piles (Cheng and Jeremic, 2009).

(Sadek and Isam, 2004) studied the performance of various structures constructed on vertical and inclined piles. Fig. 4 illustrates the failure mechanism of these types of foundations when subjected to lateral load. The figure shows that when the primary load comes from the structure, it is the inertia shear force; thus, the piles supporting it resist that load by shear force in addition to the moment developed at the pile head due to persistence. It is clear to notice the axial force added to such forces in the case of batter piles.

3. BEHAVIOUR OF BATTER PILES SUBJECTED TO STATIC LOADING

(Zhang et al., 1999) investigate the impact of batter pile and unit weight of soil on lateral resistance. It was carried out by applying lateral load on a single square pile with different angles of inclinations constructed in loose and medium sand. The battered angle and density of soil influence were examined. Sufficient performance of batter pile on lateral stiffness was conducted in dense sand, while less effect was noticed in loose conditions.

(Zhang et al., 2002) evaluate the performance of the pile group susceptible to lateral load. Pile configuration, angle of batter, and ground density were considered in this study. Various

lateral test loads were applied on (3 × 3) and (4 × 4) inclined pile groups. Results demonstrate that lateral capacity provided by the (3 × 3) group pile does not depend on varying vertical load. While for (4 × 4), pile groups greatly influence it.

(Adel and Nguyen, 2003) The shaft capacity of battered and vertical piles constructed in cohesionless deposits under axial compression loading has been investigated experimentally. Batter Piles model tests designed with different angles of inclinations varied from zero to 30° were considered. Results indicate that increasing the angle of inclination exhibits a slight decrease in the corresponding maximum shaft resistance. Also, the study points out that shaft resistance is governed by soil properties cohesion (c) and angle of internal friction (ϕ), slenderness ratio, and the diameter of piles.

(Rahimi and Bargi, 2010) Evaluate the impact of constructing battered pile groups with various angles of inclination and positions on the performance of wharf structure through a finite element dimension model. Bending moment, displacement, and load distribution were considered in this study. Results revealed pile forces and moment distribution influenced by the angle and position of the battered pile.

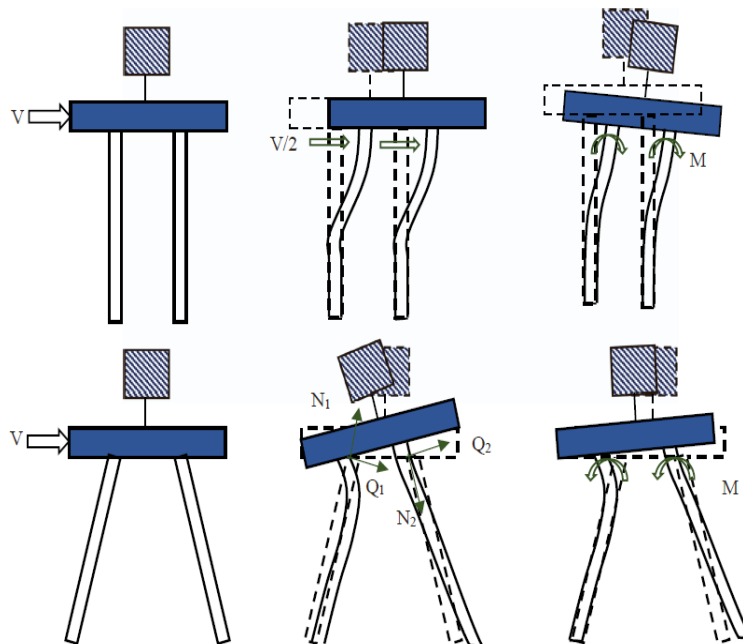


Figure 4. Vertical and battered piles load transmission **(Sadek and Isam, 2004).**

(Nazir and Nasr, 2013) They examined raked piles' maximum uplift shaft resistance through a steel pile model placed in various sandy soil conditions (loose, medium, and dense), as shown in **Fig. 5**, with different battered angles and slenderness ratios. The results revealed that the peak pullout capacity of raked piles placed in medium or dense sand increased corresponding to the inclined angle, reaching its maximum magnitude and decreasing. In contrast, loose sand's pullout capacity value decreased while the pile battered angle increased. **Fig. 6** illustrates the variation of batter angle with pullout capacity. The optimal batter angle gives the ultimate pullout capacity equal to 20°, which exceeds the capacity of the vertical pile.

(Sharma et al., 2014) studied the behavior of batter and vertical micro piles with different slenderness ratios under horizontal and vertical loading. Results indicate that the carrying capacity increased as the slenderness ratio increased. Furthermore, the maximum load



carrying and failure mode were governed by the inclination angle, the direction of the batter, and the slenderness ratio.

(Zhang and Zhuo, 2014) investigate the impact of inclination angle and piles on the mechanical properties of battered piles subjected to oblique loads. Through finite element three dimensions model. Constitutive elastic modeling has been employed for the pile material, while an elastic-plastic model is adopted to simulate the soil material. Results indicate that the interaction between the pile and soil has a sufficient impact on the ultimate loads of batter piles with various inclination angles. However, battered pile stiffness depends on lateral and axial stiffness in the case of small oblique loads. Also, as the angle of inclination increases, the axial force tends to decrease. In addition, the bending moment is affected significantly by the load inclination angle.

(Hazzar et al., 2016) Evaluate the effect of axial loading on battered pile response embedded in clayey and sandy soils. Through finite difference analysis with varied inclination angles and soil stiffness, results indicate that the lateral resistance of inclined piles placed in sandy soil is affected by the angle of inclinations and soil density. However, in clayey soil, the lateral capacity is governed by only the inclinations angle, while lateral bearing capacity increases as the inclinations increase.

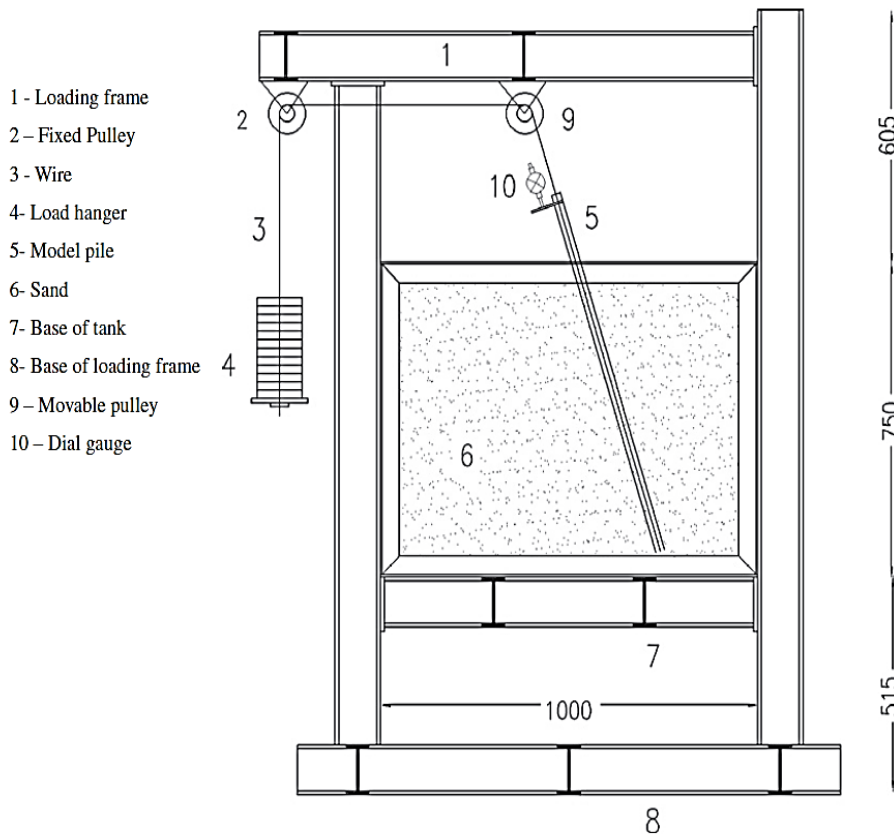


Figure 5. Schematic view of the apparatus **(Nazir and Nasr, 2013)**

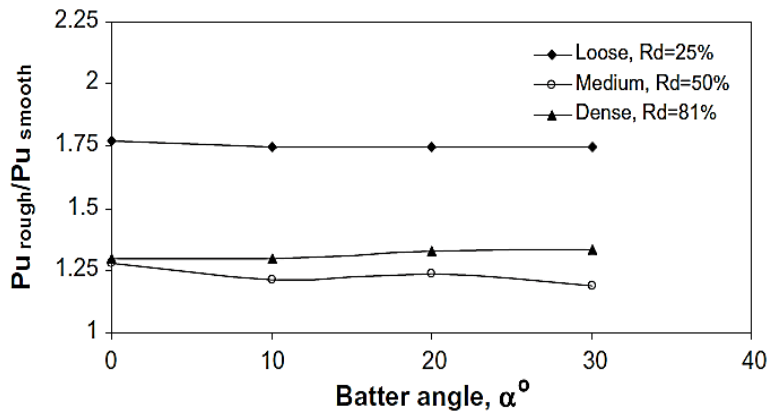


Figure 6. Variation of pullout capacity with the batter angle (Nazir and Nasr, 2013)

(Al-Neami et al., 2016) They studied the impact of the single pile on loading capacity. The test was carried out using a steel model, and three lengths of piles were selected with three different embedded ratios. The battered piles were constructed in three different relative densities of sandy soil. A particular hydraulic device was used to apply a monotonic load. The results report that the maximum loading capacity is indicated with an inclination angle equal to 20°. Load capacity is governed by relative density, as presented in Figs. 7 and 8.

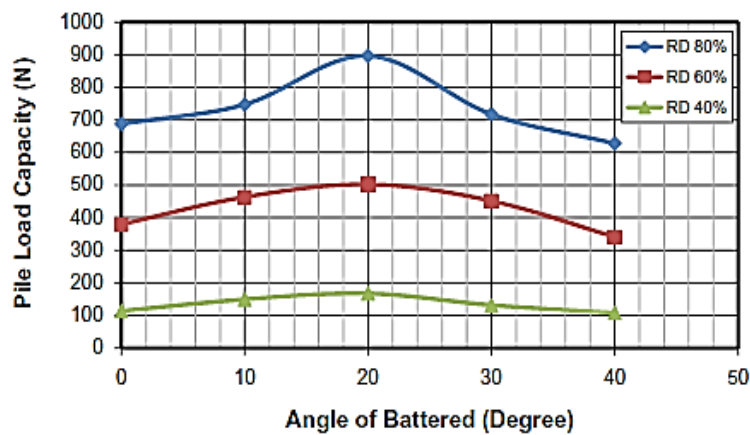


Figure 7. Relation between loading capacity and angle of batter with different relative density (RD) for L/D: 15, (L: length of pile, D: diameter of the pile) (Al-Neami et al., 2016)

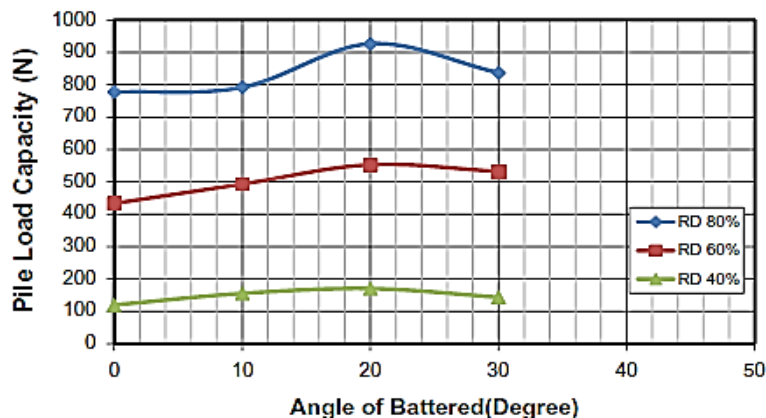


Figure 8. Relation between loading capacity and angle of batter with different relative density (RD) for L/D:25, (L: length of pile, D: diameter of the pile) (Al-Neami et al., 2016)



(Albusoda and Alsaddi, 2017) examine the performance of group piles placed in cohesionless deposits exposed to lateral loading. Various angles of inclinations, pile spacing ratio, and the effect of constructing various numbers of piles with different pile patterns were employed in this study. Results reported that the presence of batter piles provides sufficient enhancement in ultimate lateral capacity value, corresponding to the regular ones; moreover, as the pile group spacing, the group efficiency value increased. In contrast, the maximum lateral capacity of the pile group is influenced by the pile group pattern.

The influence of soil movement in the lateral direction on the batter piles was evaluated by (Chen and Hsu, 2017). Three dimensions numerical analysis using (the FLAC 3D) program, carried out on (3×3) piles consisting of inclined and vertical piles placed in clayey and sandy soil, which was employed to model lateral displacement and bending moment. Results indicate that the battered piles provide an ultimate moment value less than vertical piles under sand soil movement. While under clay movement, the pile shaft moment of battered piles is more significant than vertical piles. The study also points out a reduction in the displacement of the pile group due to the inclusion of batter piles with soil movement.

(Kumar et al., 2017) examine the performance of raked and vertical piles subjected to lateral loading. The results conclude that raked piles exhibit greater bearing capacity than vertical piles. Also, experimental and numerical tests revealed that negative-raked piles have less lateral displacement with the same loading condition than vertical and positive-raked piles.

(Ratnam et al., 2017) Examine the vertical and raked piles with inclination angle values varying from 0° to 30° . The diameter and length of the piles were 0.75m and 45m, respectively. The finite element approach was used in the simulation. Results revealed that battered piles offer 30% to 40% more stiffness than vertical piles.

(Singh et al., 2017) investigates the pullout resistance of inclined groups pile placed in sand soil. Throughout experimental work on five models of battered and vertical pile groups. Results drawn from this study were that the battered pile's pullout resistance increased with the depth of piles, density of soil, and surface roughness of piles in addition to the inclination angle. (Vu et al., 2017) evaluates the behavior of pile foundations with batter piles carried out by a foundation model tested under an axial and combination load embedded in sandy soil. Three and six pile models were used, including batter piles and the absence of batter piles. A closed-end pile model was used in the study. Mechanical properties were obtained using the triaxial test. The results indicate that placing battered group piles increases stiffness and reduces settlement. (Xie et al., 2017) investigates the batter piles' performance exposed to lateral loading. A numerical model approach was employed, and several slopes and size sections with various force levels were considered. This study reports the individual pile formula of lateral displacement corresponding to horizontal loading. Also, there is good agreement with what was predicted theoretically.

(Rezazade and Kalantari, 2017) Demonstrate the performance of piles exposed to lateral load and placed in sandy soil, executed throughout finite element software PLAXIS. Different pile foundation types were investigated, such as vertical, negative, and positive batter piles. Results indicate that batter piles exhibit great loading capacity compared with vertical piles. Moreover, the carrying capacity increased as the batter angle increased.

(Palammal and Senthilkumar, 2018) They examined batter and vertical pile groups constructed in cohesionless ground exposed to lateral and vertical loads. The pile model was a steel rod with an 8mm diameter, considering the inclination angle and varied length-to-diameter ratio(L/D). Nonlinear variation between load and settlement was indicated for all



pile group model types under vertical and horizontal loads. Furthermore, the bearing capacity increased with the (L/D) ratio increased, as shown in **Tables 1 and 2** below.

Table 1. The maximum vertical load of the pile model (**Palammal and Senthilkumar, 2018**).

| Inclined angle | Maximum Vertical Load (N) | | |
|----------------|---------------------------|----------|----------|
| | L/D = 7.5 | L/D = 15 | L/D = 22 |
| 0° | 242.57 | 503.55 | 636.96 |
| +10° | 477.54 | 518.06 | 737.67 |
| -10° | 416.97 | 442.67 | 681.06 |

Table 2. The maximum lateral load of the pile model (**Palammal and Senthilkumar, 2018**).

| Inclined angle | Maximum Lateral Load (N) | | |
|----------------|--------------------------|----------|----------|
| | L/D = 7.5 | L/D = 15 | L/D = 22 |
| 0° | 93.05 | 119.61 | 149.14 |
| +10° | 85.74 | 106.17 | 135.18 |
| -10° | 103.37 | 130.45 | 181.71 |

(**Bajaj et al., 2019a**) observed the constructed effect of battered piles on loading capacity through model tests with different soil conditions. Steel Pile inclusion in the model box under lateral loading was indicated. Artificial neural networks were also used to estimate the pile's deflection. Results suggest that negative battered piles exhibit sufficient performance corresponding to vertical and positive battered ones.

(**Bajaj et al., 2019b**) studied the behavior of batter piles placed in sand soil considering different types of loading. Parameters such as carrying capacity and horizontal and vertical displacement were considered, and a steel piles model with varying ratios of slenderness and inclination angles was employed in this test, which was constructed in sand soil. Results highlight the ultimate load-carrying capacity in negatively inclined piles compared to vertical piles with all loading cases.

(**Sharma and Hussain, 2019**) studied the behavior of battered micro-piles subjected to vertical and lateral load. They considered the angle and direction of the batter and the length-to-diameter pile ratio. The ultimate carrying capacity of negative battered piles increases with (L/D) in the case of vertical loading. Also, the stiffness was greater than that of vertical piles and positive battered piles.

(**Jamil et al., 2019**) investigate the load capacity and displacement of the pile raft footing consisting of vertical and inclined piles have been reported experimentally; two types of pile foundation models were employed, which are (the group pile model and the raft model). Less carrying capacity value for the pile mode corresponding to the raft model. In addition, the bearing capacity and settlement with installed battered piles.

(**Singh et al., 2019**) reported various approaches of modeling employed to conduct the inclined bearing capacity of inclined group piles considering smooth and rough and smooth surfaces of piles. (pile length, angle of inclination, soil density, and number of piles used) were employed in this study. Results from the study indicate that all three methods exhibit sufficient performance. Moreover, single-factor tests refer to the variation between exact and predicted values obtained from each method, which were insufficient for both pile groups (smooth and rough). Hence, the model provided by the random forest (RF) regression method with a smooth pile surface could be used to estimate the inclined bearing



capacity for both pile group types. Also, it concluded that the model tree (M5) modeling approach presents a linear relation and is simply used to find the inclined capacity of battered piles group value.

(Sabbagh et al., 2019) examine the lateral performance of inclined groups piles placed in cohesionless soil subjected to lateral soil movement effects and various pile group patterns. Considering the shear force, angle of inclination, and soil reaction. Results indicate that inclined piles respond better to lateral movement than vertical ones.

(Yan et al., 2020) conducted the lateral behavior of a wharf mounted on defected piles and placed on slope ground. Centrifuge modeling was employed in this study, and displacement, horizontal carrying capacity, and moment were considered. Also, the Linear variable displacement transducers (LVDTs) and strain gauges (SGs) were employed to measure displacements in horizontal and vertical directions and monitor the strain and moment along pile depth. The SGs were distributed on each pile, including the slope's head, bottom, and surface and the middle of the slope surface and pile head/bottom. The SGs and piles were protected with epoxy resin. The load-controlled test was employed, and incremental static lateral load was applied step-by-step. The results highlighted that batter piles exhibit less torsion when subjected to horizontal loading. The moment induced by the front inclined pile was negative and decreased with lateral loading. Positive moments were observed in backward battered piles and constant around the soil.

(Al-Neami et al., 2020) observed the carrying capacity of the battered pile groups placed in sandy soil under a monotonic load. They used a steel pile model with different lengths and diameters. Results indicate that inclined piles possess more load-carrying values than vertical ones, increasing as pile length and number increase.

(Liu et al., 2021) examined the mechanism of load transfer in battered piles under vertical loading, soil-piles interaction was considered, the effect of internal load distribution, and the mode of deformation of the piles. Reported results indicate that the loading transfer was influenced significantly by the "clamping effect" caused by pile deformation. Also, the study provides insights into the behavior of battered piles in engineering practice. Fig. 9 presented the variation of average deformation with the depth.

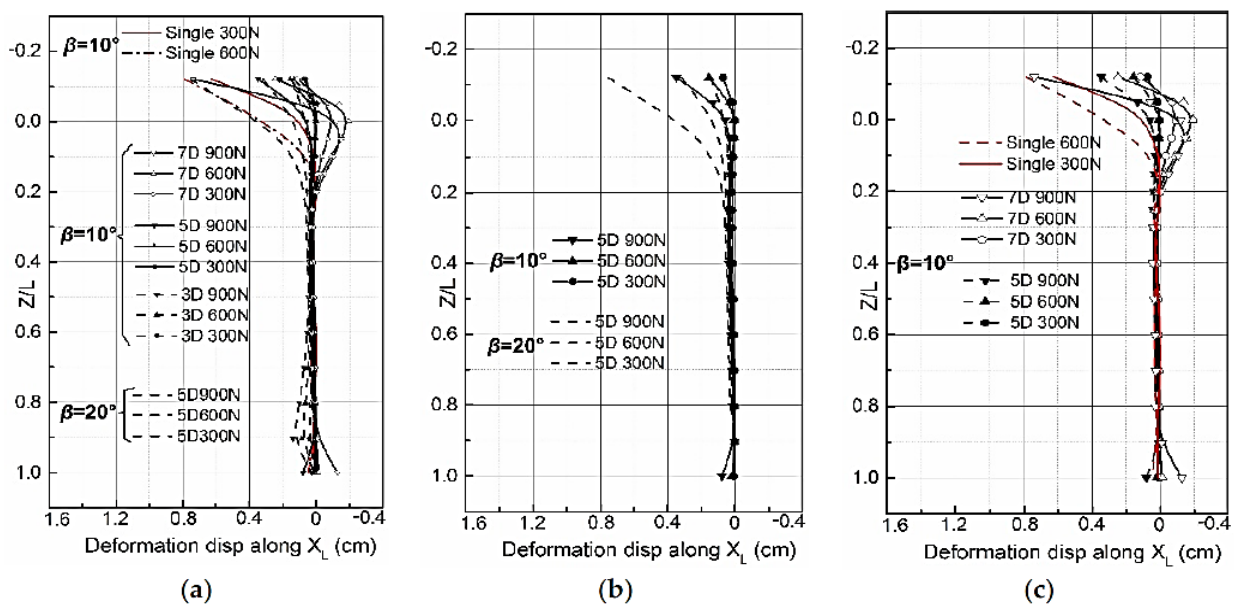


Figure 9. Deformation of batter piles with depth (a) deformation of all tests, (b) $\beta = 10^\circ$ and $\beta = 20^\circ$, (c) $\beta = 10^\circ$ (Liu et al., 2021)



(Mahalakshmi et al., 2021) They studied the impact of the direction and angle of inclination of battered piles-raft foundation systems placed in sand. A steel tank and (2 × 1) steel pile group model were used, considering length-to-diameter ratio, thickness, and pile diameter. Results revealed that the negative direction of the batter was the efficient direction corresponding with vertical and positive direction, as illustrated in Fig. 10. Also, the optimum angle of inclination in terms of lateral carrying capacity was 20° with a vertical axis. (AlTememy et al., 2022) Evaluate the pullout capacity of batter piles through PLAXIS 3D software, considering several parameters such as the angle of inclinations, soil condition, and length-to-diameter ratio. Results highlight that the pullout resistance of inclined piles increased with the battered angle ,reaching its ultimate value and then decreasing, as shown in Fig. 11. Also, the soil density and length-to-diameter ratio affect the peak pullout capacity value.

(Yadu et al., 2022) evaluated the response of vertical and battered piles placed in cohesionless soil under uplift loads. Different length-to-diameter ratios and battered angles were considered. Fig. 12 illustrates the test setup used. Ultimate uplift capacity observed with batter angle equal to 35°. Also, it was noticed from the experimental test that uplift capacity increased with increasing length-to-diameter ratio.

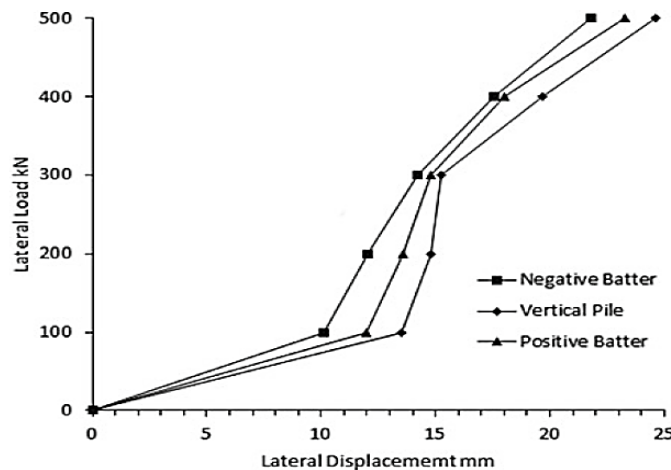


Figure 10. Effect of direction of batter (Mahalakshmi et al., 2021)

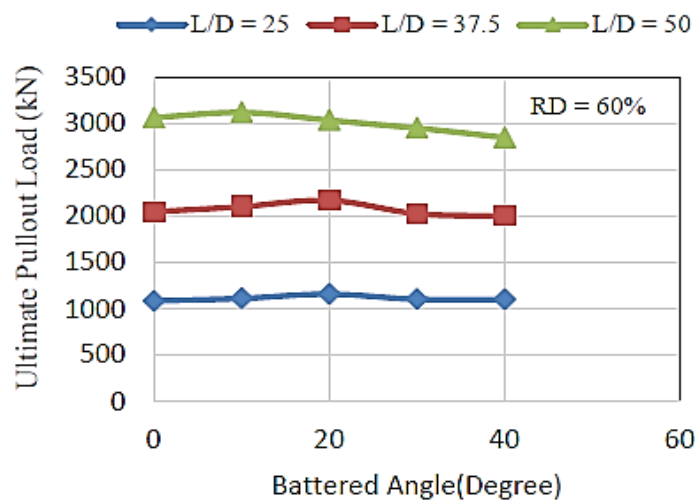


Figure 11. Pullout capacity variation with batter angles and (L/D) (AlTememy et al., 2022)

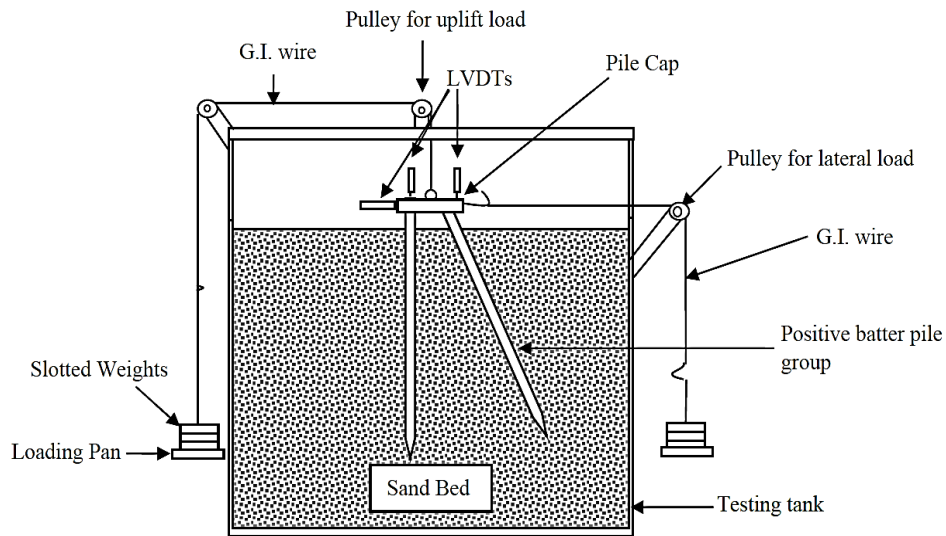


Figure 12. Schematic diagram of the test setup (Yadu et al., 2022)

4. EXPERIMENTAL AND NUMERICAL STUDIES ON THE SEISMIC RESPONSE OF BATTER PILES.

(Schlechter et al., 2004) investigates dynamic performance of wharf structures constructed on inclined piles under seismic load. Results highlight the importance of batter piles in limiting deflections from lateral loads and improving the overall stability of wharf structures. Settlement and dynamic moment reduced by the inclusion of battered piles, as shown in Fig. 13. The study emphasizes the need for more investigation on the seismic behavior of batter piles, considering their continued use, to support existing wharves. Also, it contributes to the knowledge base for designing and assessing the seismic impedance of wharf structures constructed on piles, particularly about the use of batter piles.

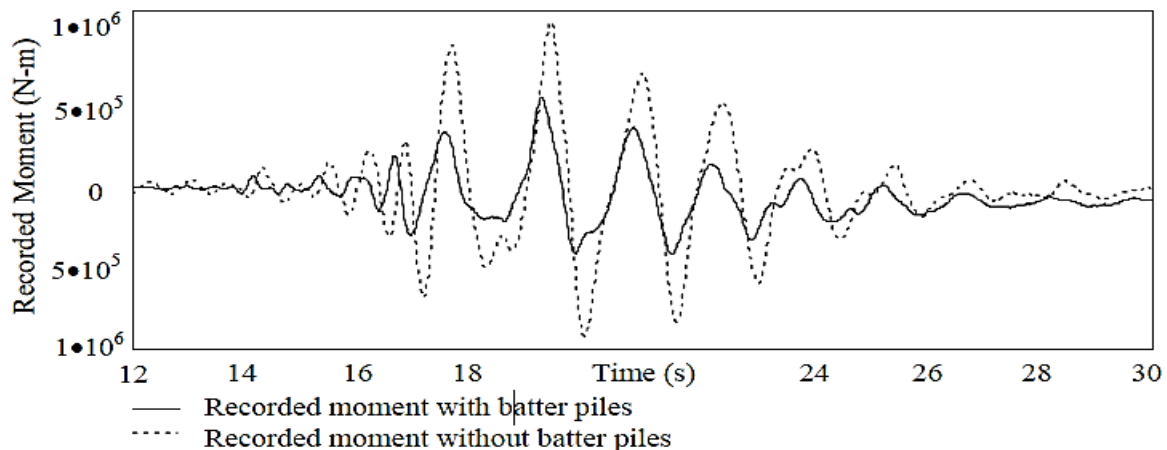


Figure 13. Moment record variation with time (Schlechter et al., 2004).

The bearing load of pile groups susceptible to seismic excitation was conducted by (Komatsu et al., 2004) to obtain economic and better design under seismic circumstances and carried out by an aluminum piles model subjected to lateral and vertical loads through an air jack. Applied load and deflection were observed using a load cell and potentiometer,

respectively. Results revealed that the number, spacing, and pile head condition influence the lateral performance of battered piles, and the vertical bearing capacity value increases, corresponding to eccentricity. Meanwhile, the vertical bearing capacity slightly decreased as the angle of inclinations of battered piles increased. However, the bearing capacity in the lateral direction increased as the angle of inclinations of battered piles increased, as demonstrated in **Fig. 14**.

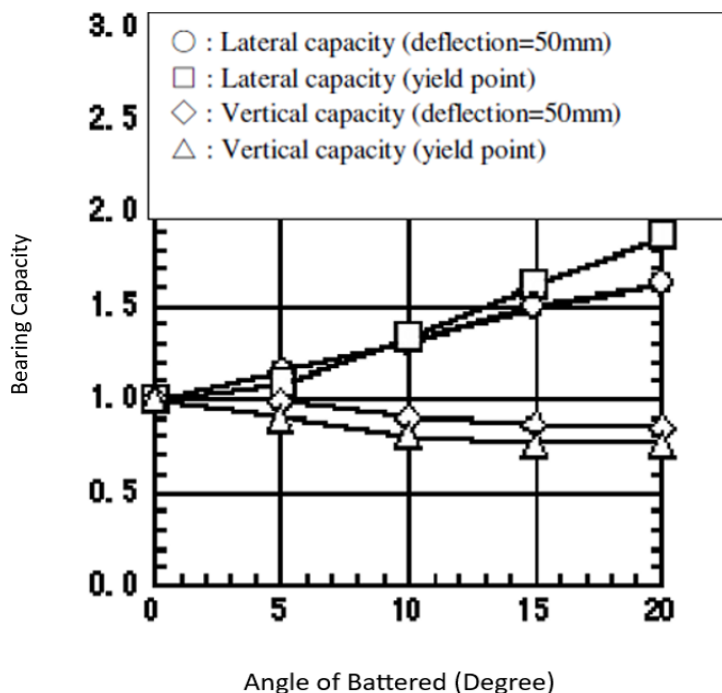


Figure 14. Inclination of batter pile versus bearing capacity ratio (**Komatsu et al., 2004**).

(**Deng et al., 2007**) observed the seismic performance of the raked pile group, designed as a foundation of a machine placed in a seismically active region. Furthermore, the dynamic interaction analysis results in this study revealed that raked piles transfer the seismic load to axial load, which required more attention when designing the pile connection. Also, less displacement was observed in the raked piles case than in the vertical ones.

(**Escoffier et al., 2008**) Investigate the impact of piles' inclination on the dynamic behavior of pile groups regarding the response of two pile group types (vertical and inclined) placed in sandy soil. Considering two conditions (floating and end-bearing) with a fixed connection to a rigid cap. Tests were conducted in two types of loading: repeatability cyclic loading, which was carried out on floating pile groups. Repeated impact loading was performed on the end-bearing groups pile. The response of the pile group was examined by evaluating parameters such as acceleration, moment, and axial loading. The results revealed that the battered pile foundation exhibited excellent lateral resistance with less moment than the vertical pile group.

Also considering Various angles of inclinations, (**Giannakou et al., 2010**) evaluate batter pile behavior through finite element modeling while assuming the soil is an elastic material. Results drawn from this study showed fewer horizontal displacements in the inclusions of batter piles corresponding to the vertical case. There was a higher value of bending moment in battered piles than in vertical ones. Further, more beneficial responses were reported with the inclusion of the batter piles group.

(Tazoh et al., 2010) The kinematic response of battered and vertical pile foundations constructed in sandy soil under seismic excitation was experimentally investigated. Acceleration, displacement, axial, and bending strain were considered in this study. Results indicate that axial and bending strain reach maximum magnitude at the pile head for both battered and vertical pile types. Also, Sufficient seismic performance by employed batter piles with various frequency ranges is shown in **Fig. 15**.

(Wang and Han, 2010) studied the battered angle and loading level effect on the seismic performance of micropile groups placed in liquefiable soil. A numerical approach with intensities of 0.1, 0.2, and 0.3 g has been adopted. Results highlight that the ultimate lateral displacement and bending moment along the pile depth decreased as the battered angle increased. However, relative lateral displacement increased.

The dynamic stiffness of single inclined piles and 2x2 and 3x3 pile groups with battered piles placed in homogenous half-space was investigated by (Padron et al., 2010). The study was carried out using numerical analysis, and results pointed out that the lateral performance of battered piles increases with the inclined angle, which has been attributed to axial and flexural stiffnesses. Also, this study represents insights into the dynamic performance of deep foundations with battered piles.

(Memari et al., 2011) They conducted behavior support wharves for battered piles subjected to seismic circumstances, including a structure fuse in the pile head, to enhance their behavior under earthquake conditions. Three patterns of piles were considered vertical piles and combined battered and vertical. Results indicate better seismic performance with the inclusion of batter piles and the presence of a fuse structure. Also, less lateral stiffness is observed in the case of pile foundations that do not consist of batter piles.

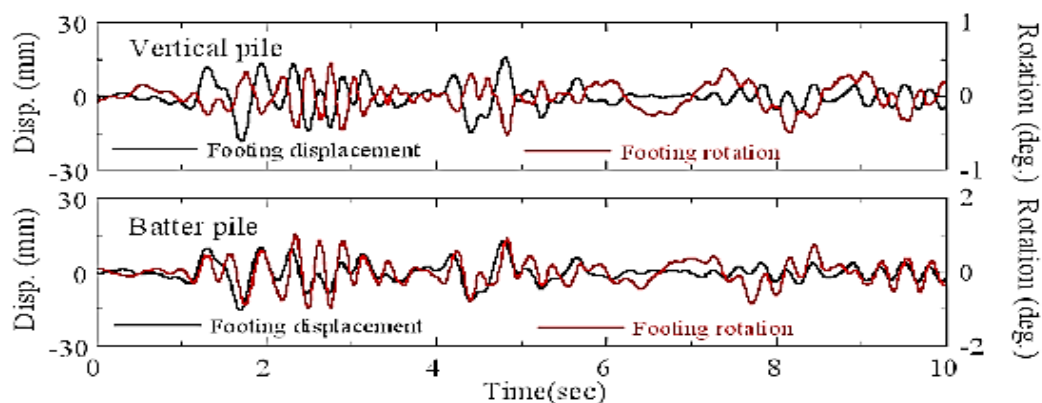


Figure 15. Comparisons between vertical and batter piles (Tazoh et al., 2010).

Experimental and numerical investigations were employed by (Li et al., 2012) to demonstrate the response of inclined piles subjected to earthquake actions; the practical part was done using centrifuge modeling with two configurations: vertical and inclined with a 15° pile group. In comparison, Numerical simulations were performed with a 3D ABAQUS, which provides experimental data on the responses of inclined pile foundations. The results point out that, under certain circumstances, inclined pile foundations exhibit better behavior than vertical pile foundations. Furthermore, this study reported the importance of observing the interaction response and effects of the inclination angle.

(Escoffier, 2012) studied the inclined pile under seismic action through two test groups of dynamic centrifuges, which were sinusoidal and seismic tests, that were carried out to indicate the battered pile's effects considering factors such as response frequencies, bending



moment profiles, axial loads, and the kinematic performance of group pile. The objectives of the first pile group were to evaluate the frequency induced between the footing and soil, while the other test was to observe the effect of the inclination of the group pile on the frequency behavior. Results highlight that the frequency range of amplification of the group pile is affected by the inclined pile, and less horizontal acceleration of the cap was reported. **(Ghazavi et al., 2013)** Investigate the batter pile groups' performance under an inclined load. Through an analytical approach, different parameters such as the geometry of piles and spacing, soil properties, angle of batter, and frequencies are considered. The results revealed that the interaction decreases at a given inclination angle as the spacing between piles and the departure angle increases. Also, as the inclined angle increases, the interaction decreases. **(Wang and Orense, 2014)** conducted the response of raked piles embedded in liquefying soil using nonlinear finite element analysis. Results showed that negative raked piles perform better than vertical piles, while a lower moment was observed in the case of positive raked piles. **(Medina et al., 2014)** The impact of battered angles of pile footing on the dynamic response was observed. This provided a kinematic interaction factor for various group Configurations embedded in the homogenous ground. Results indicate that the battered piles exhibit a great capacity to dissipate the energy of the lateral input motion. **(Jiren et al., 2015)** investigating the seismic damage of vertical and raked piles in wharf structures using a numerical modeling approach. The batter piles perform better under seismic conditions when the peak ground acceleration (PGA) equals 350 Gal. Results were indicated. Also, the ultimate displacement in the case of vertical piles was much higher compared with raked piles. **(Li et al., 2015)** conducts the frequency effect and superstructure center of gravity on the behavior of batter pile through experimental sinusoidal excitation tests. The soil-structure interaction has been considered. Results indicate beneficial performance regarding Pile cap displacements, Pile cap rotations, and total overturning moment. **(Subramanian and Boominathan, 2016)** presented a batter piles group model (2×1) embedded in soft clayey soil to examine the lateral response of batter piles exposed to different magnitudes of sinusoidal lateral loads and batter angles. It also discusses the bending and displacement response of batter and vertical pile foundation groups, as well as the angle of battered effect on peak responses. The results highlight that Batter piles behave as vertical piles, which exhibit a substantial reduction in frequency value. At the same time, the amplitude of dynamic displacement increases as the excitation force increases. Batter piles also provide more lateral stiffness than vertical piles, as observed by increased natural frequency and decreased peak displacement at significant magnitudes of lateral loads. Batter pile performance, which was placed in soft soil, was observed by **(Tomisawa and Isobe, 2016)** through centrifuge model tests subjected to various earthquake loading. Results reported sufficient seismic behavior when battered piles were included. Also, there is a reduction in pile heads' lateral displacement under various earthquake loading levels. In addition, better seismic resistance of batter piles when exposed to lateral loading has been conducted. **(Li et al., 2016)** conducted the behavior of inclined pile foundations with seismic loading conditions through a dynamic centrifuge test program to analyze several seismic responses such as (Displacement, rotation, shear force, overturning moment, etc.) The tests have been conducted using sandy soil with a relative density of 80%. Which was embedded in the Equivalent Shear Beam (ESB) box, and complimentary shear stresses provided by vertical shear rods were attached. The results indicate that battered piles could enhance the

response, which is influenced by the rise of the center of gravity of the superstructures and the input signal intensity of the base shaking.

(Vu et al., 2016) reported the performance of pile-raft and group piles with and without inclined piles using a laboratory test on a pile foundation model placed in sandy soil with relative density (80%), close-end piles model with 255mm length and 20mm diameter, **Fig. 16**. Represents the foundation model used in this study, Results indicate that the foundation's settlement reduced with inclusion inclined piles as shown in **Fig. 17**. Moreover, inclined pile group provides more significant value of axial force and moments corresponding to those vertical pile groups.

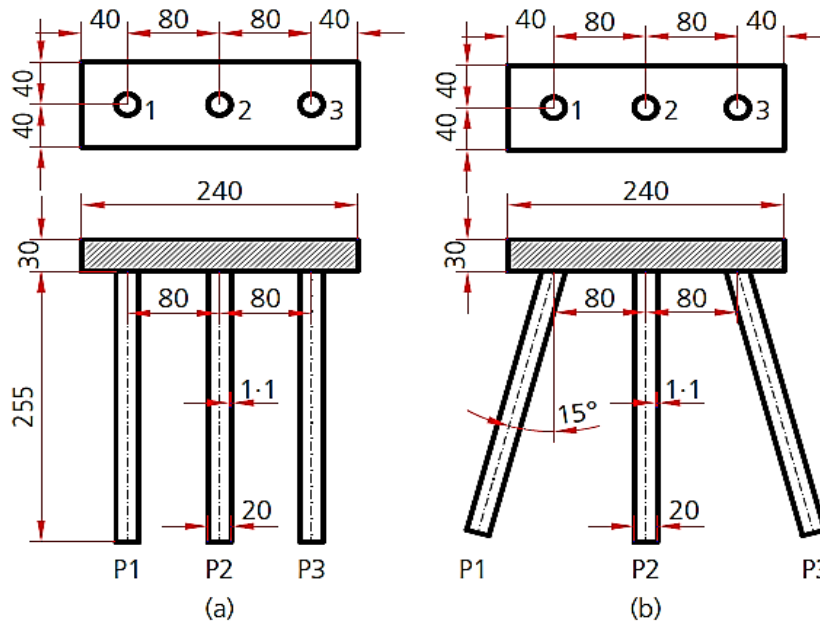


Figure 16. Foundation models: (a) vertical piles and (b) batter and vertical piles, values are in mm (Vu et al., 2016).

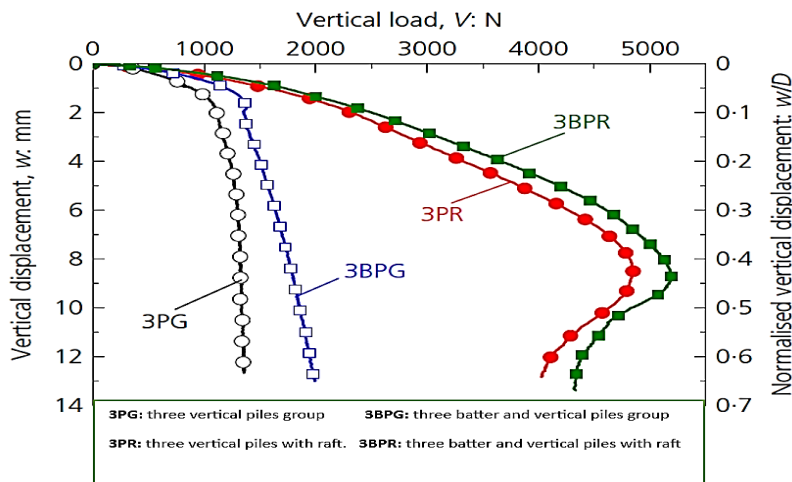


Figure 17. Load–settlement curves of the foundation models (Vu et al., 2016).

Considering the soil-pile interaction and geometric damping, (Dezi et al., 2016) investigated the seismic performance of the pile group foundation with batter piles placed in laterally layered deposits; a numerical modeling approach, the beam was used to model

piles, and the frequency domain was the control of the problem in this study. A good constitutive practical model was revealed, which may be employed to demonstrate the performance of vertical pile foundations with batter piles.

(Subramanian and Boominathan, 2017) conducted a numerical investigation on a pile group of (2 × 1) installed in clayey soil using ABAQUS. The dynamic analysis examined different pile configurations: all piles were vertical, one pile was vertical, and the other was batter, and both piles were batter with the angle of inclination equal to 20°, as shown in Fig. 18. Considering two cases as the soil stiffness increases linear and nonlinear variation with depth Fig. 19. results indicate that displacement of battered piles was less than vertical piles, as shown in Fig. 20. Also, there is a half reduction in the maximum displacement of battered piles compared to vertical ones. The natural frequency increases when batter piles are embedded, which enhances the overall stiffness.

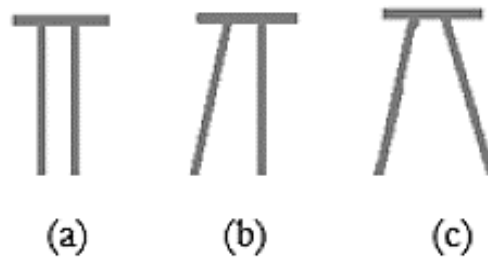


Figure 18. Pile group patterns; (a) B0B0, (b) B20B0, and (c) B20B20 (Subramanian and Boominathan, 2017)

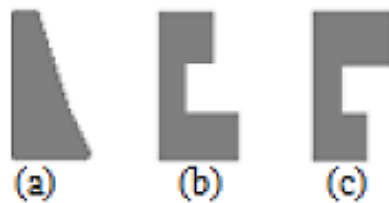


Figure 19. Soil profiles: (a) linearly, (b) profile variation I, and (c) profile variation II (Subramanian and Boominathan, 2017)

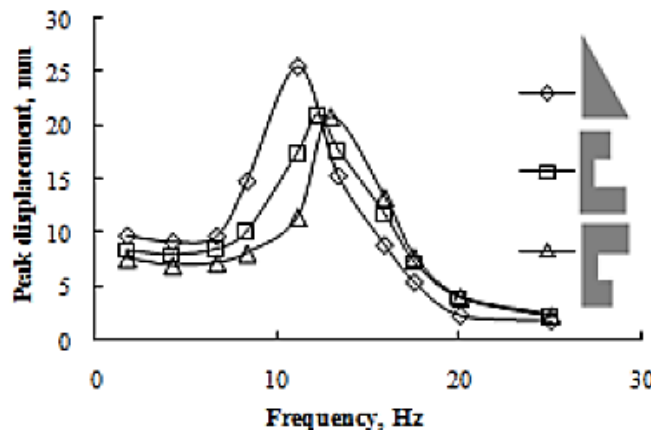


Figure 20. Frequency displacement response of symmetrical batter pile (Subramanian and Boominathan, 2017)

(Sarkar et al., 2017) Three dimensions of dynamic analysis have been evaluated to examine the seismic performance of vertical and raked group piles (2×2), and the ratio of spacing to diameter of 2, 4, and 6 was adopted. The tests were carried out considering two cases. The first was by uniform soil modulus with pile depth. The other was a nonlinear soil modulus along the depth, as illustrated in Fig. 21. Results point out that the raked pile stiffness groups exceeded the stiffness of vertical piles with excitation frequencies range and soil modulus, which was examined throughout this study. Also, the raked piles group performs better than the vertical one for the same (s/d ratio) with all values of soil modulus.

(Wang and Orense, 2017) The battered pile's impedance embedded in liquefaction soil and subjected to seismic excitation was examined using a numerical test to evaluate the impact of battered angle and soil liquefaction on seismic performance. Results revealed that the battered angle plays a prominent role in decreasing lateral displacement.

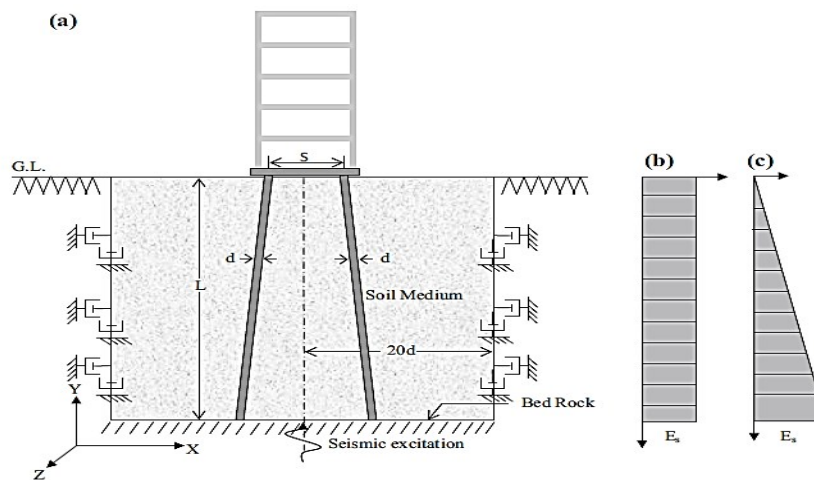


Figure 21. (a) soil pile system, (b) constant soil profile, and (c) nonconstant soil profile (Sarkar et al., 2017).

(Johnson et al., 2017) investigates various parameters' impact on the behavior of the T-Wall constructed on inclined piles by using numerical analysis. Fig. 22 illustrates the cross-section of the T-Wall founded on inclined piles. The result was compared with the centrifuge model test, which recorded a reasonable agreement. Connection types of piles, angle of inclination, and stiffness were considered in this study; a high moment value was noticed in the fixed connection compared to the pinned one, which is shown clearly in Fig. 23. Also, a linear trend was observed in the relation between inclined angle and bending moment as shown in Fig. 24.

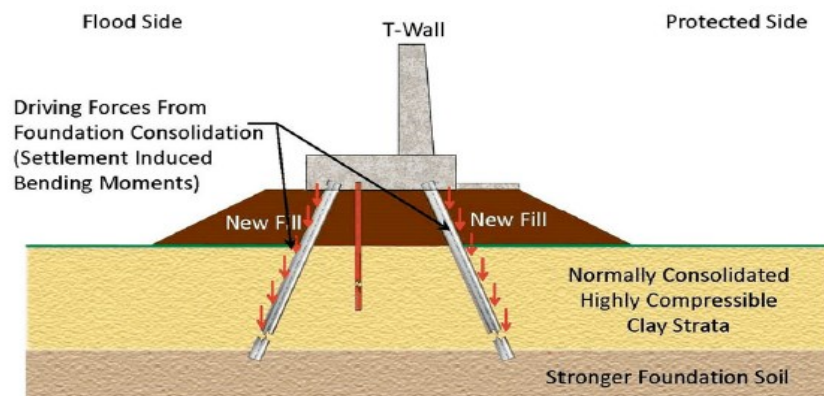


Figure 22. The t-wall is supported with inclined piles (Johnson et al., 2017).

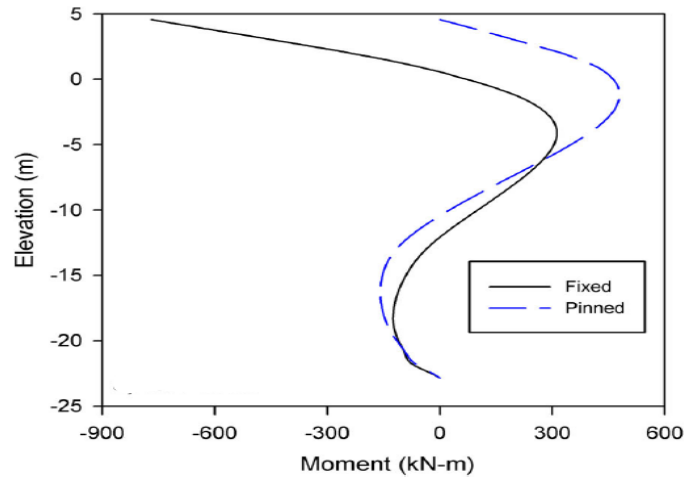


Figure 23. Bending moments for pinned versus fixed connection (Johnson et al., 2017).

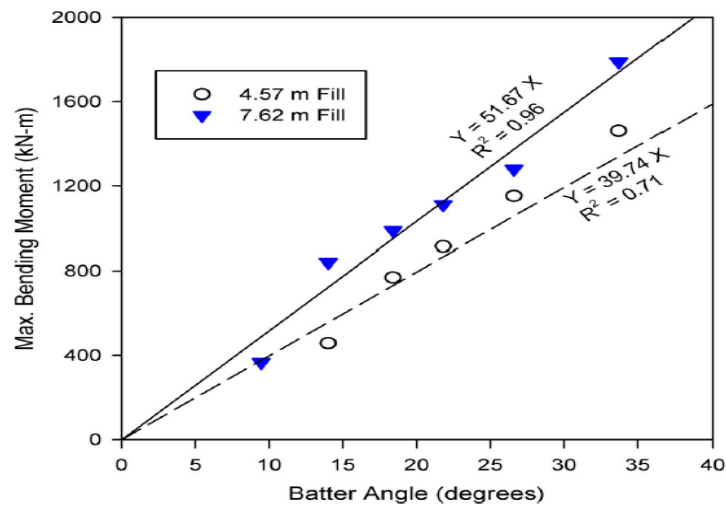


Figure 24. Bending moments versus batter angles (4.57m, 7.62m) fill (Johnson et al., 2017).

(Bharathi and Dubey, 2018) studied the vertical and batter under-reamed piles behavior with dynamic loading conditions, carried on single bored piles model with pile cap. Various experiments were conducted on reinforced concrete model piles under lateral vibrations induced by the machine. The lateral displacement and frequency values were measured. The results revealed that the direction of the load substantially affects the response of under-reamed battered pile foundations in controlling both the ultimate lateral displacement and resonant frequency. The pile foundation frequency decreased as the loading level increased, which was attributed to the mobilization of the soil mass adjacent to the pile participating in the vibration. Also, the study observed that shear strain and peak lateral displacement increased as the loading level increased.

(Li et al., 2018) investigates battered pile performance in sandy soil subjected to cyclic and monotonic loads and compares this with the vertical pile's behavior. Finite element analysis has been adopted, considering macro elements to ensure they are sufficient to create the nonlinear behavior of parameters such as force and displacement. Results indicate that the macro element can reproduce piled system behavior with the same accuracy level as

nonlinear modeling and with less computational cost, which is essential in design procedures and practical applications.

The performance of vertical and battered piles groups placed in silty soil was investigated by **(Bharathi et al., 2019)**. The experimental work was conducted through four tests, two vertical and two battered pile groups, with different configurations. In contrast, the battered angle for all batter piles was 20° to the vertical, as illustrated in **Fig. 25**. Oscillator-motor assembly for inducing dynamic force, supported on the rigid pile cap, the test was performed under various exciting load levels with different load directions. The observed dynamic performance was by evaluating both displacement and frequency. The results present a substantial reduction in the ultimate displacement and the resonant frequency of the inclined piles group compared to the vertical pile group.

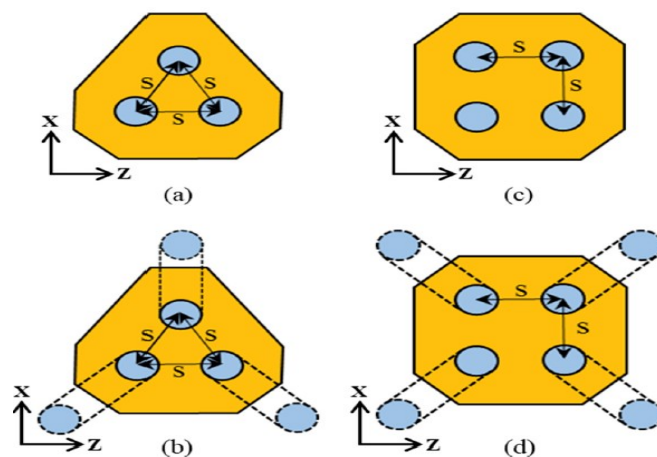


Figure 25. Pile group plan (a) three vertical piles, (b) three inclined piles, (c) four vertical piles, and (d) four battered piles **(Bharathi et al., 2019)**

(Ralli et al., 2019) investigates the frequency–amplitude performance of inclined piles under machine-generated vertical vibration; three soil models were used in this study: linear model, which assumes no slippage between the soil and pile; nonlinear model 1, which models the soil as a continuum approach, and nonlinear model 2 this model supposes the boundary as parabolic trend function. Also, with different boundary zones of inclined pile systems, results indicate that with increasing loading levels, the damping and stiffness of inclined piles decreased. It also revealed that nonlinear model 1 efficiently accurately captures single inclined piles' damping and stiffness satisfactorily.

(Saeid, 2019) studied the seismic performance of various states and configurations of micro piles. Three states of thickness and soil were modeled, while four states of arrangements were modeled. Moreover, the impact of batter micro-piles on the displacement of the structure was examined. Finite element ABAQUS software was employed in this study. Results find that the relative displacement of the structure is reduced with increased pile diameter irrespective of soil condition. Also, the relative displacement and the bearing piles' behavior improved by including batter piles with an angle of batter 60° .

(Azizkandi et al., 2020a) Observed the performance of batter pile groups exposed to sinusoidal excitation in the experimental work using a shaking table, the (2×2) pile foundations groups with various inclination angles. A better response was indicated with battered pile groups than vertical ones in terms of displacement of pile caps. Furthermore, batter piles experience considerable lateral stiffness, while the pile cap bending moment has

reached its maximum value in the batter piles group case. Also (Azizkandi et al., 2020b) evaluate pile configuration and angle of inclination influence on lateral acceleration and bending moment of pile foundation placed in cohesionless deposits exposed to explosion loads. Experimental work was conducted on a (2 × 2) pile foundation with various battered and vertical pile configurations. Results indicate that the lateral displacement of battered piles was in the opposite direction, corresponding to that of vertical piles. Group piles provide ultimate lateral stiffness and minimum acceleration with the angle of batter 15°. However, battered piles exhibit ultimate bending moment compared to other group models. (Yun and Han, 2020) examined the performance of battered piles that support structure, considering inclined and horizontal ground with pile inclinations of (1:3 and 1:5) through centrifuge modeling, moment and acceleration were employed, as well as displacement and axial force. Results showed that with employed battered piles, the ultimate moment was reduced by about 88% compared with vertical ones. Moreover, battered piles exhibit a more sufficient response in the sloped ground than in the flattened ground condition. (Zhang et al., 2020) The response of battered piles placed symmetrically in soil susceptible to liquefaction was examined, and the impact of overlying non-liquefiable layers on battered pile foundation behavior was observed. Experimental work was carried out through three dynamic centrifuge model tests. Results highlight that the magnitude of the moment in the front pile case is greater than that of the rear pile, attributed to liquefaction, which generates lateral deformation, in addition to the ultimate moment occurring at the middle length of the pile. Also, there is a noticeable reduction in settlement and liquefaction potential by including a non-liquefiable sand layer. (Li and Zhang, 2020) studied the dynamic performance of vertical and inclined pile foundations in the liquefiable cohesionless ground by using a centrifuge modeling test. They evaluated the impact of bending moment and pile type on the dynamic response. Results indicate that the battered piles cap does not present significant amplification in displacement and horizontal displacement. Moreover, the excitation intensity affects the moment envelopes of the vertical and inclined piles. (Rajeswari and Rajib, 2021) demonstrate dynamic analysis of battered piles group considering various angles of batter constructed in liquefiable sandy soil, regarding the performance of two periods with fixed and pinned connections between pile and cap for end bearing and floating types; Fig. 26 illustrates the schematic of piles group.

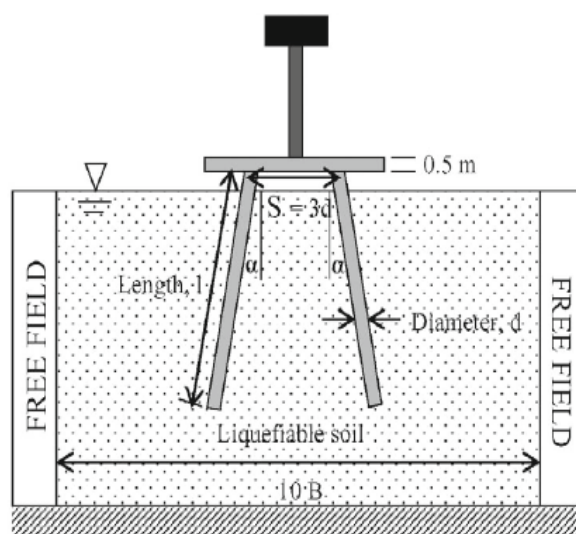


Figure 26. The schematic of the piles group (Rajeswari and Rajib, 2021).



Three earthquake motions with various controlling frequencies were conducted. Results point out that inclined pile foundation groups constructed in soil with liquefaction potential exhibit a beneficial performance response for both pinned and fixed connections in case of extended periods. In short-term circumstances, beneficial performance is only in fixed head connection. The response of pile foundation as pile raft and pile group exposed to an axial load and lateral cyclic loading carried out by a numerical three-dimensional finite element approach. Results have been compared with the experimental work reported by authors, so a reduction in displacement and inclination of the battered pile raft was observed in this study as well as Pile rafts exhibit less inclinations due to cyclic lateral loading than the pile group with battered piled, which, reduces the inclination significantly **(Vu et al., 2021)**.

(Yan et al., 2021) Investigate the performance of wharf structures founded on inclined piles under cyclic lateral loading with different amplitudes. Parameters such as soil and pore pressure, bending moment, and displacement were observed. Results indicate that the displacement remains decreasing over time, which denotes the remolding and softening of soil around the piles. Also, the pore pressure was positive and small over time.

(Mondal and Disfani, 2022) They studied the behavior of vertical and battered minipiles placed in dense cohesionless soil under cyclic horizontal loading. Results regarding strain, stiffness, bending moment, and hysteresis loops are provided. At a 25° inclination angle, the batter piles exhibit a sufficient response compared to a vertical and 45° inclination angle.

Through a finite element analysis approach **(Wang and Orense, 2023)** conducted the batter piles behavior subjected to lateral spreading generated from ground liquefaction. The soil deposits, batter angle, ground slope, and input signal amplitude have been considered. Batter piles provide sufficient response compared with vertical ones in terms of cap performance, and soil deformation also exhibits less moment at the head of the pile. The optimum angles of the batter were ranging from 0° to 15°.

4. FACTORS INFLUENCING THE PERFORMANCE OF BATTER PILES

Based on numerous previous observations, batter pile installation can improve the foundation's response by providing sufficient lateral stiffness and capacity, minimizing the bending moment generated in pile foundations, and reducing the horizontal displacement under different loading conditions. According to previous studies, several factors have obvious roles in the batter Pile performance:

- The spacing, arrangement, and slenderness ratio of piles.
- The interaction between soil-pile, the soil-liquefaction potential, pile deformation, and kinematic response.
- Pile type (floating or end bearing) and surface roughness of pile.
- Pile head connection type (fixed, pinned).
- The magnitude and the types (negative or positive) of the angles of the batter.
- The frequency and amplitude of input loading.
- The superstructure's center of gravity.
- Stratifications of deposits laterally or vertically layered.
- The condition of the ground surface (sloped or flattened) and the relative density of soil in which the battered pile was placed.



5. CONCLUSIONS

The above literature review reported that batter piles' behavior is a critical aspect that deserves further research. It was also observed that the approach adopted to design batter piles coincides with some features of vertical piles, so more investigation is needed to provide a particular design procedure for batter pile foundations. A comparative study on the response of batter piles has been conducted. This can guide engineers and designers in selecting the appropriate arrangement of batter piles to enhance seismic performance and reduce foundation settlement. The conclusions are revealed below.

- The importance of batter piles in limiting deflections from lateral loads and improving the overall stability of wharf structures. The inclusion of battered piles reduces the settlement and dynamic moments.
- The negative batter pile performs better than the vertical and positive batter pile under lateral load circumstances.
- The lateral bearing capacity and stiffness of battered piles increased as the inclination angle increased. They reached the ultimate value with an angle of inclination equal to 20°.
- Negative raked piles performed better in liquefaction ground under seismic loading than vertical piles.
- By inclusion of battered piles, the natural frequency increases and decreases the lateral displacement of the pile head under lateral loads.
- Beneficial performance is achieved when batter pile groups are constructed in soil with liquefiable potential compared with the vertical pile group.
- The ultimate pullout capacity of batter piles placed in medium or dense sand increased, corresponding to the batter angle.
- The most common failure of batter piles occurs at the connection zone with the pile cap or deck.

From past observations, it has been noticed that an adequate design with a suitable pile head connection exhibits sufficient performance under various circumstances. Also, the failure mechanism of batter piles still has not been well recognized and needs more investigation. Further research is required to employ batter piles in piled embankments and slopes and determine their performance when placed in liquefiable soil and laterally spreading ground.

NOMENCLATURE

| Symbol | Description | Symbol | Description |
|--------|-------------------|----------|---------------------------------|
| D | Pile diameter, m. | α | Angle of inclination, deg. |
| L | Pile length, m. | β | Batter angle, deg. |
| S | Pile spacing, m. | θ | the angled of the shearing zone |

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Credit Authorship Contribution Statement

All the authors have read and approved the manuscript. Adel Hani Writing –the original draft of the manuscript. Bushra Suhale, reviewed and edited the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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استجابة الركائز المائلة المعرضة للتحميل الاستاتيكي و الزلزالي : مراجعة

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الخلاصة

الركائز المائلة لديها اداء كفوء عند استخدامها في الاساسات التي تتطلب مقاومة جانبية عالية ، ممكن ان تنجم هذه الاحمال الجانبية عن الرياح الشديدة او امواج المياه او ضغوط التربة او الانفجارات الضخمة او الزلازل. يجب ان تركز البحوث التجريبية والنظرية في هذا الاتجاه لغرض معرفة تصرف هذا النوع من الاسس تحت تاثير مختلف حالات التحميل, تستعرض الدراسة الحالية الدراسات التي اجريت على اداء اساسات الركائز المائلة وتحاول فهم وتغطية مختلف الجوانب المتعلقة بهذا الموضوع, بعد اجراء المراجعة تشير النتائج الى ان الركائز المائلة السالبة تبدي صلابة جانبية كفوءة مقارنةً مع الركائز المائلة الموجبة والركائز العمودية , أيضاً ان قابلية التحمل الجانبية تحسنت بوجود الركائز المائلة, بالإضافة الى ذلك الركائز المائلة ابدت استجابة افضل من الركائز العمودية في الترب القابلة للتسييل تحت تاثير الاحمال الزلزالية.الدراسة الحالية ايضاً بينت ان قابلية السحب للركائز المائلة ازدادت مع زيادة زاوية الميل.

الكلمات المفتاحية: الركائز المائلة، التحميل الزلزالي، التحميل الاستاتيكي.