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# Modeling of Batter Pile Behavior under Lateral Soil Movement

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**Abstract.** Pile foundation is frequently used when structures are located on weak sublayers or are at risk from lateral loadings such as earthquakes. The design of pile foundations has recently become crucial to stop slope movement. To understand the behavior of pile foundations subjected to lateral soil movement, the three-dimensional Fast Lagrangian Analysis of Continua (FLAC3D) program was used to perform numerical simulations, which can reduce the cost of field testing. Vertical piles and batter piles were combined into 3 × 3 pile groups, and the response of batter piles to soil movement was analyzed. The outer batter piles led to an increased bending moment in the middle, vertical pile row. Increasing the pile spacing and the presence of battered piles reduced the pile group's displacement. The batter pile group's maximum bending moment was smaller than the vertical pile group's in sand soil, but 5–8 times higher in clay soil.

## 1. Introduction

Pile foundations are common used to reduce settlement and displacement. The main function of pile foundations is to transfer the load of a superstructure onto a hard layer through a soft upper layer. Batter piles are used to support horizontal loads, for example bridge piers, wharf piles, and retaining walls beneath the sloping areas, and they reduce displacement of piles and surrounding soil settlements, thus enhancing the stability of a superstructure. Numerous documented studies and models for the use of batter piles have been published [1-6].

Pile response is affected by soil–pile interaction, the space and arrangement of piles, and interaction with the pile cap. It is also influenced by liquefied surrounding soil, pile deformation, and kinematic response. Batter piles subject to lateral or seismic loadings have decreased pile cap displacement and are subject to axial forces up to eight times higher than vertical piles [1-4]. The presence of batter piles in a foundation can reduce the bending moment of a vertical pile and horizontal displacement under seismic loading. However, a batter pile was shown to cause non-negligible residual moments and higher rotation at the pile cap after seismic loadings [7]. Inclined batter piles were reported to have increased seismic resistance during numerical modeling using three-dimensional Fast Lagrangian Analysis of Continua (FLAC3D) [5]. Experimental and practical studies of batter pile foundations are still being conducted, but their interactions with superstructures and soft soil require further study to optimize their safe and economic design.

## 2. Material and method

The response of batter piles within a group of piles subjected to soil movement was studied. Specifically, finite difference analysis using FLAC3D was validated [6] and then employed to model the pile–soil interaction.

The numerical analysis assumed that soil was deposited under gravity (9.8 m/s$^2$) in an initial state with a high water table at ground level, to model a riverside or wharf scenario. The concrete pile was modeled as an elastic material following the Mohr–Coulomb failure criteria, and soil movement induced by liquefaction was replaced at a constant horizontal rate ($-1 \times 10^{-6}$ m/s) at the boundary. Pile responses in sand soil were considered and discussed.

Grid size and the boundary conditions used in the mesh are crucial control factors that determine the efficiency of the numerical calculations. For example, a smaller grid size and larger study area increases the precision of the modeling compared with a coarse mesh used with boundary conditions. To avoid boundary effects, a minimum horizontal distance to the boundary of 15–25 times the pile space is required [8,9]. A distance to the boundary 25 times the pile space was used in the present study (20 m vs 0.75 m). The boundary conditions used were roller for the surrounding soil, hinged for the base, and free at the soil surface with high water table (Figure 1). Single batter pile response under soil movement was modeled first and compared with two pile groups in a 3 × 3 scheme: one with nine vertical piles, and one with three vertical and six 20°-inclined batter piles (Figure 2).

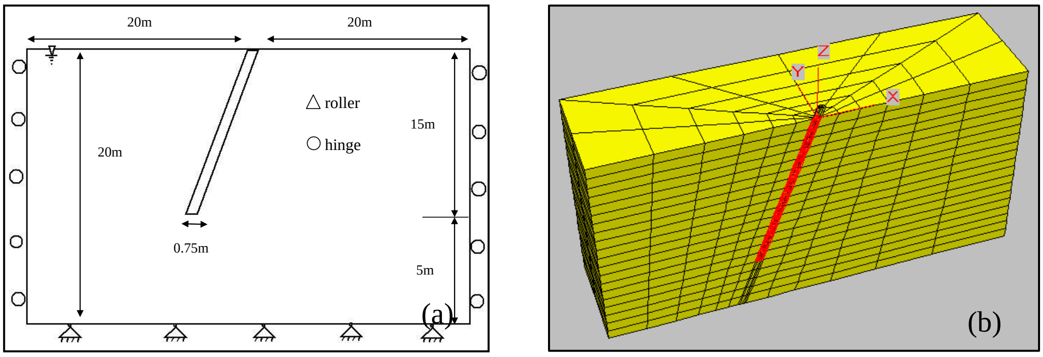


**Figure 1.** Numerical scheme for (a) boundary conditions and size used, and (b) the design mesh for a single batter pile.

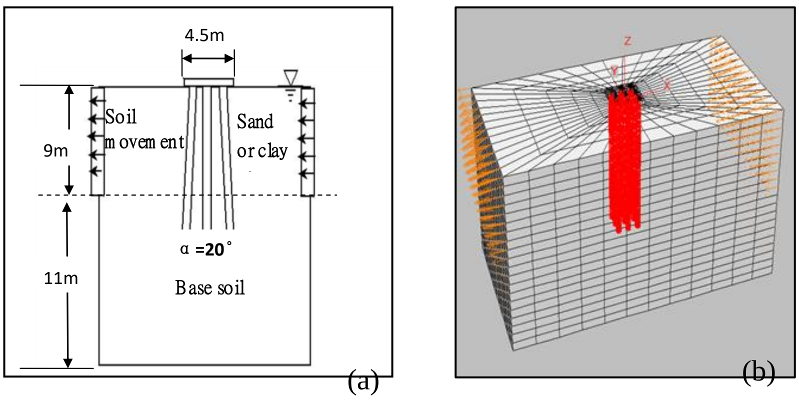


**Figure 2.** Modeling of the batter pile group subjected to soil movement (a) soil profile, and (b) designed 3D mesh.

Several elasticity and strength parameters were required for the numerical analysis, namely bulk modulus, shear modulus, internal friction angle, dilation angle, and cohesion strength (Table 1).

An interface element was used to model slippage at the soil–pile interface. This element was single sided with zero thickness, and had normal stiffness $K_n$ and shear stiffness $K_s$ to transfer loadings from soil to the pile shaft. The parameters are suggested be ten times larger than the stiffness of the surrounding soil [10], as described by

$$K_n = K_s = 10 \times \max\left[\frac{(K+\frac{4}{3}G)}{\Delta Z_{min}}\right] \tag{1}$$

where K is the bulk modulus, G is the elastic modulus, and $\Delta Z_{min}$ is the minimum mesh size in the interface element. Parameters for friction angle, cohesion strength, and tension strength are also required to model slip movement and tension failure in the plastic state. The friction angle between the pile shaft and soil has a large effect on the bearing capacity of the frictional pile and has been previously estimated as 0.6–0.7 times the soil internal friction angle [11,12]. Table 2 presents a list of the parameters used for the interface element.

**Table 1.** Material parameters used during numerical analysis.

| Material/ parameter | Bulk modulus (MPa) | Shear modulus (MPa) | Cohesion (kPa) | Friction angle (°) | Dilation angle (°) | Density (kg/m$^3$) |
|---|---|---|---|---|---|---|
| Sand | 15 | 10 | 0 | 30 | 0 | 2000 |
| Base soil | 50 | 30 | 0 | 40 | 0 | 2000 |
| Concrete pile | 27800 | 20800 | -- | -- | -- | 2500 |

**Table 2.** Parameters for the interface element used during numerical analysis.

| Parameters/ Soil types | $\Delta Z_{min}$ (m) | $K_n$ (MPa/m) | $K_s$ (MPa/m) | Cohesion (kPa) | Friction angle (°) |
|---|---|---|---|---|---|
| Sand | 0.25 | 1100 | 1100 | 0 | 21 |
| Base soil | 0.25 | 1100 | 1100 | 0 | 28 |

The pile shaft moment was calculated using the shear forces along the pile section. These shear forces were measured at the mesh nodes in a horizontal direction using the FISH language (the language of FLAC3D) and modified to the normal direction of the pile shaft. The top of the pile, which was connected to the pile cap, was free to rotate but could have been fixed to model a real field situation. Pile space is the distance between the centers of two adjacent piles; thus, piles in a given group were coded in a numerical sequence, as portrayed in Figure 3.

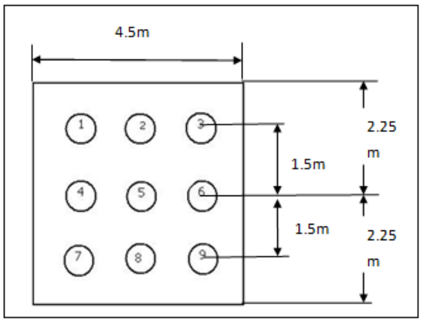


**Figure 3.** Code numbers of 3 × 3 pile group (top view).

## 3. Results and analysis

A 3 × 3 pile group arranged with two rows of three inclined batter piles and one middle row of three vertical piles was modeled (Figure 3), and the results were compared with a 3 × 3 pile group containing nine vertical piles. The moment distribution along the pile shaft subjected to soil movement in two times (2d) and four times (4d) the pile diameter space is illustrated in Figs 4 and 5, respectively. The maximum moment of the pile shaft occurred at a depth of 6 m for the vertical piles and at 12 m for the 20° inclined piles. The 2d space of the vertical piles' maximum moment due to sand soil movement was approximately two times larger than that for the inclined batter piles (Figure 4); in this scenario, pile #2 in the batter pile group was subjected to the largest moment. When the pile space increased to 4d, the middle row piles #2 and #5 had larger moments in the batter pile group. This demonstrates that the presence of surrounding batter piles did not protect the vertical middle pile during sand soil movement. The pile displacement curve illustrates that the affected area was less covered, and that the beneficial grouping effect tends to diminish as pile space is increased (Figure 5).
Moreover, the batter piles were less displaced by the sand soil movement than were the vertical piles when the pile space was increased (Figure 6). Pile displacement decreased from 33% for the 2d batter pile space to 80% for the 4d batter pile space. Finally, the presence of the batter piles reduced the displacement of pile #5 in the pile group, whereas the pile moment caused by sand soil movement was not reduced.

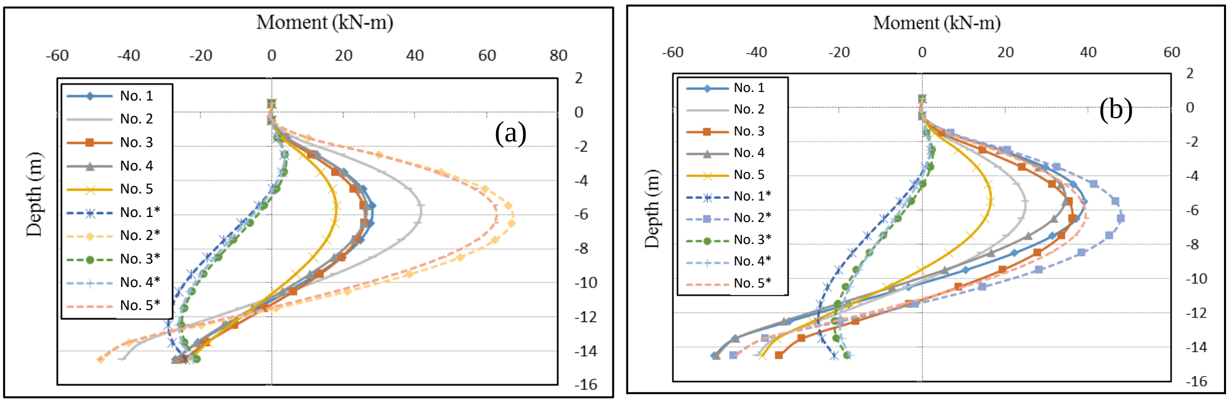


**Figure 4.** Pile shaft moment distribution in two 3 × 3 pile groups (a) in the 2d pile space (b) in the 4d pile space that were subjected to sand soil movement (*batter pile).

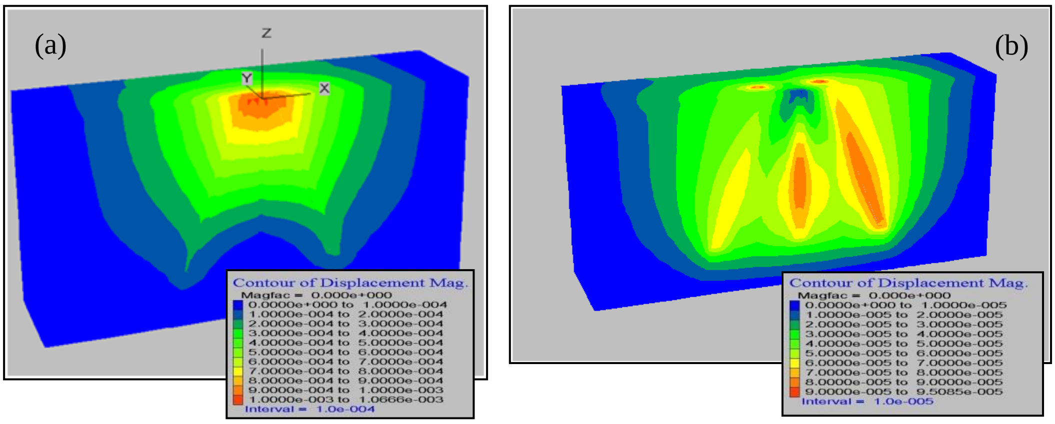


**Figure 5.** Pile–soil displacement contour in (a) the 2d pile space, and (b) the 4d pile space, for the batter pile group subjected to sand soil movement (unit: mm).

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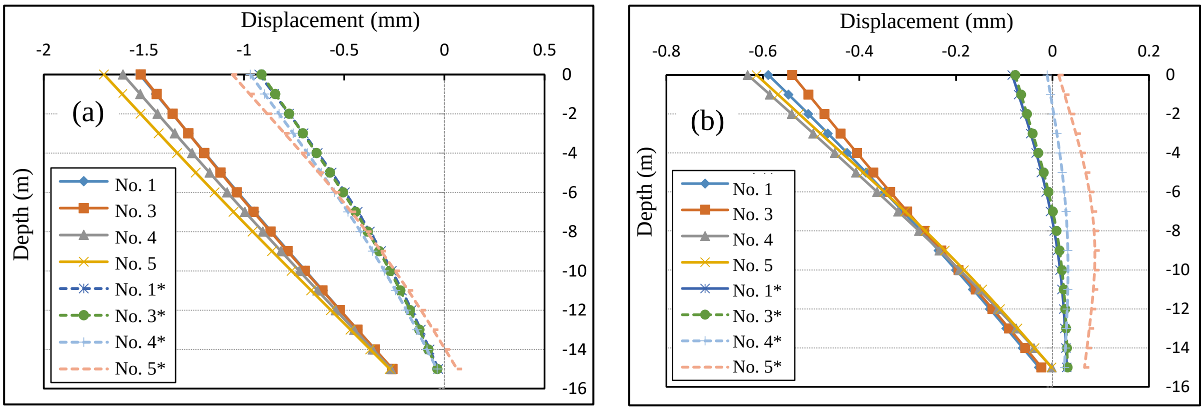


**Figure 6.** Lateral pile displacement in (a) the 2d pile space, and (b) the 4d pile space of the pile group subjected to sand soil movement (*batter pile).

## 4. Conclusions

The response of batter pile groups under lateral soil movement was modeled using finite difference analysis. Pile shaft moment, lateral displacement, and group effects were evaluated by adjusting the pile space and introduction pile inclination. The comprehensive batter pile design and analysis results are as follows:

1. The maximum moment of vertical piles in a 2d pile space subjected to sand soil movement was approximately two times that for inclined batter piles. Additionally, the pile shaft moment for the batter piles was 5–8 times larger than that in the vertical pile group subjected to clay soil movement.
2. The batter piles were less displaced than the vertical piles when subjected to sand soil movement. The presence of batter piles reduced the displacement of the middle pile in a pile group.
3. The design of batter piles in a pile group reduced the displacement of the pile group under soil movement, and their displacement decreased when the pile space was increased from 2d to 4d. Additionally, a soil arch formed in the first row of batter piles to halt soil movement through the pile group.

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