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# Three dimensional modeling of laterally loaded pile groups resting in sand

**Amr Farouk Elhakim [a,*], Mohamed Abd Allah El Khouly [a], Ramy Awad [b]**

[a] *Public Works Department, Faculty of Engineering, Cairo University, Egypt*
[b] *Civil Engineering Department, Queen's University, Canada*

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**Abstract** Many structures often carry lateral loads due to earth pressure, wind, earthquakes, wave action and ship impact. The accurate predictions of the load–displacement response of the pile group as well as the straining actions are needed for a safe and economic design. Most research focused on the behavior of laterally loaded single piles though piles are most frequently used in groups. Soil is modeled as an elastic-perfectly plastic model using the Mohr–Coulomb constitutive model. The three-dimensional Plaxis model is validated using load–displacement results from centrifuge tests of laterally loaded piles embedded in sand. This study utilizes three dimensional finite element modeling to better understand the main parameters that affect the response of laterally loaded pile groups ($2 \times 2$ and $3 \times 3$ pile configurations) including sand relative density, pile spacing ($s$ = 2.5 D, 5 D and 8 D) and pile location within the group. The fixity of the pile head affects its load–displacement under lateral loading. Typically, the pile head may be unrestrained (free) head as the pile head is allowed to rotate, or restrained (fixed) head condition where no pile head rotation is permitted. The analyses were performed for both free and fixed head conditions.


## Introduction

Pile foundations are often necessary to support structures when soil conditions are not favorable, so the pile foundations are required to carry the superimposed load and transfer it to a higher resistant stratum through its bearing and shaft resistance. Piles may also be subjected to lateral loading on abutments and piers which may be caused by earth pressure, ship mooring and berthing forces and wave action. Also lateral loads may occur as a result of wind and unpredicted events such as earthquakes, slope failure and lateral ground spreading induced by liquefaction.

Full scale load tests are the best means for investigating the behavior of laterally loaded piles, they are expensive and time consuming. Other experimental models for determining the movement of the pile under lateral load include 1 g models [1,2], and centrifuge tests [3,4]. However such methods are only

* Corresponding author.
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suitable for research purposes because it is impossible to replicate the exact site conditions.

In this study, three dimensional finite element analyses are used to better understand the response of laterally loaded pile groups embedded in sand as outlined in this paper.

## Numerical model

The three-dimensional finite element program Plaxis 3D Foundation was adopted in the numerical analysis of this study. Soil is modeled using quadratic 15-node wedge elements. Piles are modeled using beams which are structural objects used to model slender structures in the ground with a significant flexure rigidity (bending) and a normal stiffness. A three-dimensional mesh is automatically generated taking into account the soil stratigraphy and structure levels as defined by the user. Fig. 1 shows a typical mesh generated by Plaxis 3D Foundation.

Soil is modeled as an elastic-perfectly plastic model using the Mohr–Coulomb constitutive model built in PLAXIS. In general stress state, the model's stress–strain behaves linearly in the elastic range, with two defining parameters from Hooke's law (Young's modulus, $E$ and Poisson's ratio, $\nu$). Failure criteria are defined by the angle of shearing resistance ($\phi$) and cohesion ($c$).

## Model validation

The three-dimensional Plaxis model is validated using load–displacement results from centrifuge tests of laterally loaded piles embedded in sand [5]. The validation is used to confirm the ability of Plaxis 3D Foundation finite element software to predict the load–displacement relationships for pile groups with various configurations ($3 \times 3 \rightarrow 3 \times 7$).

The centrifuge test is performed on solid square bars having a width of 9.525 mm and an overall length of 304.8 mm (L/B = 32). Each pile is equipped with strain gauges to determine the load distribution within the pile group. The centrifuge test is performed at acceleration equal to 45 g. The equivalent prototype pile width and length are 0.429 and 13.7 m, respectively. The spacing between the piles is three times the pile width. Table 1 summarizes the sand properties used in the centrifuge test and the numerical model [3,5]. Figs. 2 and 3 show the load versus displacement curves of individual piles in laterally loaded pile groups ($3 \times 3$, $3 \times 4$, $3 \times 5$, $3 \times 6$ and $3 \times 7$) embedded in both sand 1 and sand 2, respectively. The predicted curves (shown as lines) are also found in good agreement with the measured ones (represented by dots). An average error of 10% and a maximum error of 12% are obtained in load component of load–displacement relationship at maximum applied load when the predicted results are compared with the measured ones for all configurations.

**Table 1** Summary of test sand properties.

| Properties | Sand 1 | Sand 2 |
|---|---|---|
| $G_s$ | 2.645 | 2.645 |
| $\gamma$ (kN/m$^3$) | 14.5 | 14.05 |
| $D_r$% | 55 | 36 |
| $\varphi°$ | 37 | 35 |
| $E_{soil}$ (MPa) | 40–45 | 25–35 |

## Parametric study

A parametric study is performed to evaluate the effect of sand relative density (angle of shearing resistance and soil modulus), spacing between piles and row location on the behavior of laterally loaded piles in groups embedded in sand. The effect of the investigated parameters on the load–displacement response of the loaded piles and the load distribution within pile groups with fixed head conditions are investigated.

The study investigates the behavior of 15 m long, 0.8 m diameter flexible circular piles. The modulus of elasticity of the pile is taken as 20 GPa which is typical to concrete with $f_{cu}$ = 25 MPa. Pile rigidity can be evaluated following the criteria presented in the Egyptian code of practice [6] where piles are considered rigid when $L/t < 2$ and are considered flexible when $L/t > 4$ where $L$ is the pile length and $t$ is the elastic length calculated according to Eq. (1).

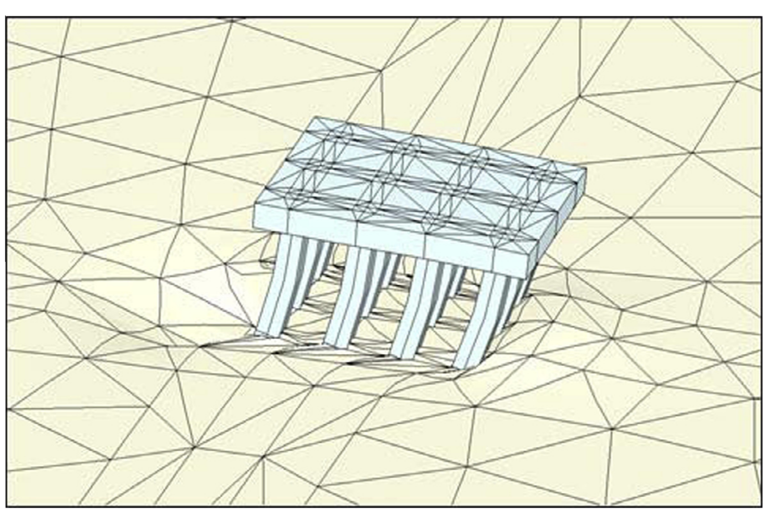

**Fig. 1** Representative mesh for a pile group subjected to lateral loading generated using Plaxis 3D Foundation.