

Numerical Modeling of Laterally Loaded Piles

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Abstract: Design of laterally loaded piles due to soil movement relies on a number of theoretical and numerical approaches. However, the magnitude of soil movement is difficult to estimate with reasonable confidence and accuracy. Finite Element Analysis (FEA) offers an excellent alternative to study pile-soil interaction and pile's response under lateral loading due to soil movement. This research presents published analytical results and case history modeled in a 2D finite element environment in the case of single pile under a non-linear plain strain condition. Reasonable agreement has been achieved in comparing the single pile's response against published results of the pile near excavation and in sliding slope.

Key words: Excavation, finite element analysis, lateral load, piles, slope, soil movement

INTRODUCTION

Foundation piles are frequently required to carry inclined loads which are the resultant of the dead load of the structure and horizontal loads from wind, water pressure or earth pressure on the structure. There were also lateral loads which result from the effect of soil movements. These include piles in or near an embankment built on soft clay, bridge abutment piles, piles adjacent to an excavation and piles in unstable slope.

These piles are called passive piles. As these piles will experience additional stress and strain, failure to assess the effect in design will result in unacceptable pile movement or stress or both. Numerous numerical and empirical approaches are available in literature on the response of these piles.

Design of piles for lateral soil movement have to depend on a few factors, namely the soil movement mechanism, soil properties, pile head condition, superstructure loading and ground support by lower stable stratum.

For lateral soil movements in embankment, Tschebotarioff^[1] suggest that the pile will be subjected to a triangular distribution of earth pressure due to soil movements arising from the embankments loading. De Beers and Wallays^[2], assume soft clay is assumed to exert a uniform pressure on the pile. These are based on the concept of earth pressures.

Poulos and Davis^[3] provides a conservative value for the uniform lateral pressure based on the undrained shear strength of the clay layer. Springman and Bolton^[14] suggest

Stabilizing piles in slopes are also known as shear piles. Shear piles are reinforced concrete piles that pass through the unstable layer and are anchored at their lower end in stable soils or bedrock.

Design of the reinforcement steel is controlled by the maximum bending moment developed in the pile. The successful use of this method has been described by Sommer^[5], Ito and Matsui^[6], Reese *et al.*^[7] and Rollins and Rollins^[8]. Poulos^[9] suggested the design procedure for stabilizing piles.

Carrubba *et al.*^[10] present a full-scale reinforced concrete instrumental pile to study the response of piles used to stabilize a sliding slope. The concept of equivalent load introduced by Guo^[11,12] which allows a correlation between an equivalent load and the magnitude of soil movement. This concept is based on elastic-plastic solutions for either a free-head or fixed-head pile.

The impact of excavation on existing adjacent piles has been investigated by Poulos and Chen^[13] and design charts for supported and unsupported excavation are provided. A series of centrifuge model tests have been conducted to investigate the behavior of a single excavation-induced soil movement in dense sand is reported by Leung *et al.*^[14], piles in clay behind a stable wall by Ong^[15] and piles in clay behind a collapsed wall by Leung *et al.*^[16] that the pressure distribution is parabolic with a mean pressure and the empirical design charts are developed based on data from centrifugal tests on model piles.

Poulos and Chen^[13] analyzed an existing pile situated near an excavation. The excavation is analyzed

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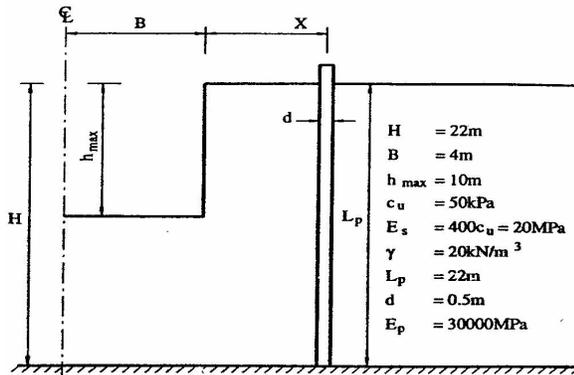


Fig. 1: Standard problem analyzed^[13]

in a two-dimensional plain strain condition. The parameters defining the problem are shown in Fig. 1. The two-stage analysis involves finite element method and the boundary element method.

For the first stage, two-dimensional finite element program was used to simulate the plain-strain excavation without the presence of the pile. In the program, eight-noded isoparametric elements are used to model the soil as an elasto-plastic material. The excavation had been carried out from top to bottom in 10 steps, with each step involving the removal of a 1m thick layer. The computed lateral soil movements from a finite element analysis were then used as input into a boundary element program, PALLAS for pile response analysis.

Carrubba *et al.*^[10] presented a full-scale concrete instrumental pile test to study the response of piles used to stabilize a sliding slope. The pile was 1.2 m in diameter and 22 m in length. Pressure cells were installed along the pile shaft and an inclinometer was installed at the center of the pile. The pile was bored into the sliding slope, which had a sliding surface at a depth of 9.5 m from the ground surface. This sliding surface was assumed to have a transition layer of approximately 2 m as estimated from the measured bending moment and shear force profile.

The unconsolidated undrained strength C_u for both the sliding layer and the stable layer was 30 kPa. The field data collected over duration of 5 months showed that a plastic hinge was developed in the pile at the depth of 12.5 m measured from the ground surface.

Guo^[12] proposed a simplified approach for prediction pile response due to lateral soil movement. It is a closed form solution for a laterally loaded pile. The response of this pile due to soil movement can be resolved into two-portions in the sliding soil and the stable soil, respectively. The portion in the lower stable layer may be treated as an imaginary free-head pile

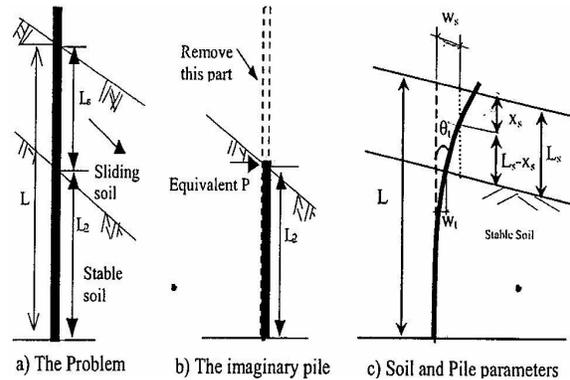


Fig. 2: Simplified analysis of pile due to soil movement^[12]

under an equivalent load P . (Fig. 2). The length of the imaginary pile is the difference between the pile length and the thickness of the upper sliding layer.

FINITE ELEMENT ANALYSIS

A two-dimensional finite element programme PLAXIS 2D has been used to model a single pile near an excavation^[13] and a single pile used to stabilize a sliding slope^[10] by using the concept of plain strain condition.

Plane strain as two-dimensional modeling: In PLAXIS 2D, selection of plane strain condition results in a two-dimensional finite element model with only two translational degrees of freedom per node. The 15-noded triangle provides a fourth order interpolation for displacements and the numerical integration involves twelve Gauss points.

Beam elements as single pile: Plates elements in the two-dimensional finite element model are composed of beams elements (line elements) with three degrees of freedom per node: two translational degree of freedoms (U_x, U_y) and one rotational degree of freedom (rotation in the x - y plane and about the out-of plane axis, ϕ_z).

When using a 15-noded soil elements, 5-noded beam elements are used. The beam elements are based on Mindlin's beam theory. Therefore, this allows for beam's deflection due to shearing as well as bending. Beam elements can become plastic if a prescribed maximum bending moment or maximum axial force is reached. Bending moment and axial forces are evaluated from the stresses at the stress points.

Mohr-Coulumb as soil's model: Mohr-Coulumb's model can be considered as a first order approximation

Table 1: Input parameters for clay and pile in Poulos and Chen^[13] analysis

Material	Model	Weight, γ (kN m ⁻³)	Young's Modulus, E (MPa)	Poisson's ratio, ν	C_u (kPa)
Clay	Mohr-Coulomb	20	20	0.35	50
Pile	Elastic	24	30000	0.15	-

For pile: Normal stiffness, $EA = 1.5 \times 10^7$ kN m⁻¹, Flexural rigidity, $EI = 3.125 \times 10^5$ kNm² m⁻¹

of real soil behavior. This elastic perfectly-plastic model requires 5 basic input parameters, namely a Young's Modulus, E, a Poisson's ratio, ν , a cohesion, c, a friction angle, ϕ and a dilatancy angle, ψ . This is a well-known and a basic soil model.

Case 1: FE Analysis of a Single Pile near an Excavation: A finite element programme PLAXIS 2D Version 8 has been used to model Poulos and Chen^[13] single pile situated near an excavation (Table 1). As excavation proceeds, the surrounding soils will move towards the excavation and this will induce bending moments and deflections in the pile. The soil is assumed to be uniform clay layer and to be in undrained condition during excavation. The excavation is assumed to be sufficiently long that a two-dimensional plain strain analysis is applicable.

The depth of excavation may be expressed by:

$$N_c = \frac{\gamma h}{c_u}$$

The main purpose of this 2D analysis is to predict the maximum deflection and maximum bending moment. Since these maximum values is predicted in the direction of the lateral load due to soil movement, thus the single pile can be modeled by using plate elements which consists of beam elements with two translation degrees of freedom and a rotation degrees of freedom.

Figure 3 shows a typical generation of the single pile in a plane strain condition. Figure 4 shows the deformed mesh for the single case of $N_c = 4.0$ and $x = 3$ m. N_c and x are dimensionless depth of excavation and horizontal distance to excavation respectively (Fig. 1).

Case 2: FE Analysis of a Single Pile used to Stabilize Sliding Slope: The purpose of this case is to study the response of the pile used to stabilize a sliding slope^[10]. The pile was about 1.2 m in diameter and 22 m in length. To evaluate the total lateral force acting on the single pile from the movement of the unstable sliding

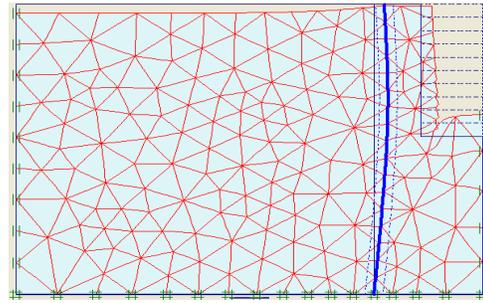


Fig. 3: Generation of 2D mesh for the single pile in plane strain condition

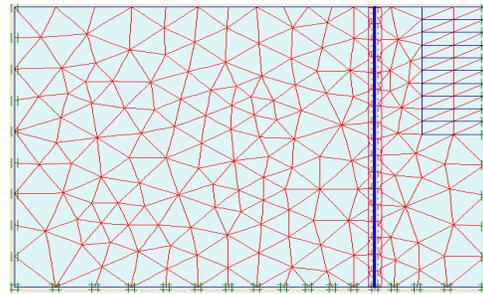


Fig. 4: Deformed mesh for the single pile, $N_c = 4.0$, $x = 3$ m

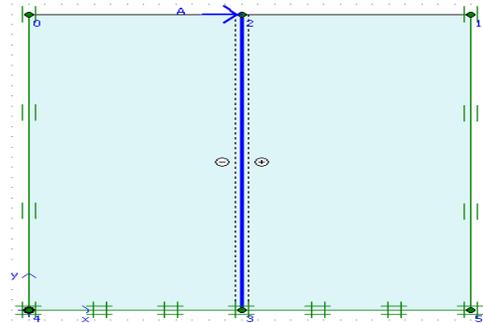


Fig. 5: A typical 2D model for the single pile in plane strain condition

layer, Guo and Ghee^[17] presented an equivalent load P of 862.49 kN applied at the depth of 7.5 m (rather than 9.5 m) which is just above the surface of the transition layer.

In PLAXIS 2D, only the depth from 7.5 to 22 m, where the load P is applied to the pile is modeled. Like before, the single pile is modeled by using plate elements and the input parameters are as shown in Table 2.

Figure 5 and 6 show the pile in the plane strain analysis.

Table 2: Input parameters for clay and pile in Carrubba et al. ^[10] analysis

Material	Model	Weight, γ (kN/m ³)	Young's Modulus E (MPa)	Poisson's ratio, ν	C_u (kPa)
Clay	Mohr-Coulomb	20	15	0.35	30
Pile	Elastic	24	20000	0.15	-

For pile: Normal stiffness, $EA = 2.4 \times 10^7$ kN m⁻¹, Flexural rigidity, $EI = 2.88 \times 10^6$ kNm²

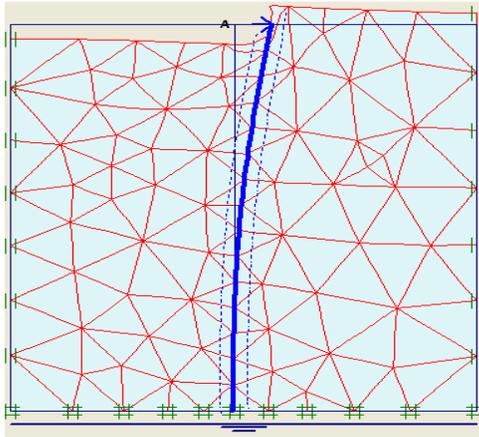


Fig. 6: Deformed mesh of the pile under lateral load

RESULTS AND DISCUSSION

Case 1: FE Analysis of a Single Pile Near an Excavation: Figure 3 above shows the 2D mesh for the single pile near an excavation. The distance of the pile from the face of the excavation is 3 m and soil removal is done in 1m depth layers for each step up to 10 m. Figure 4 shows the deformed mesh of the soil and pile. In the excavation trench, soil heaving is observed due to the release of overburden pressure. Soil behind the single pile seemed depressed due to the movement of the soil in the direction of the excavation. It is obvious that the pile bends in the direction of the excavation and the maximum bending occurs in the middle portion of the pile. In this case, the soil seemed to 'squeeze' the pile as it tries to move pass the pile. Maximum moment profile is shown in Fig. 7.

Figure 8 shows that in both cases of $N_c = 2$ and $N_c = 4$, FE analysis underestimates the moment in the single pile. In Fig. 9, FE analysis of $N_c = 2$ agrees well with the deflection profile from the published data but underestimates significantly the deflection for the case of $N_c = 4$.

Figure 10 compares the maximum bending moment for all cases in the single pile for the FE analysis and the published results. FE analysis of $N_c = 2.4$ and $N_c = 3.2$ tends to overestimates the

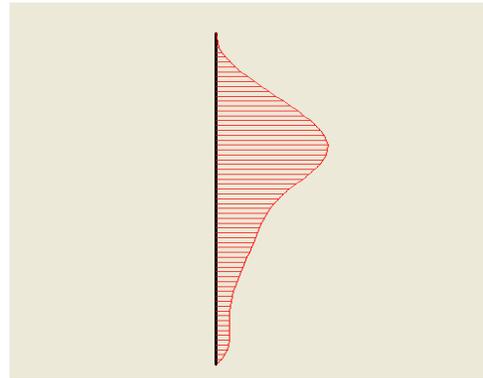


Fig. 7: Maximum moment diagram for the single pile, $N_c = 4.0$, $x = 3m$

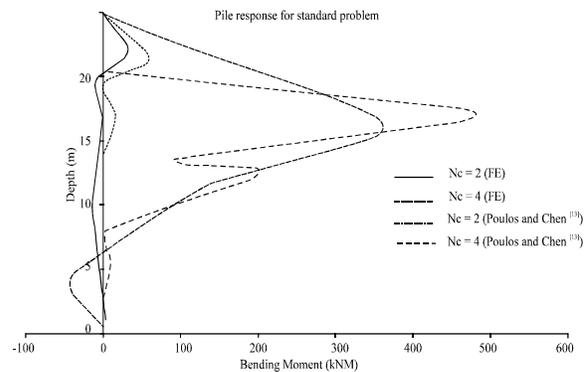


Fig. 8: Comparison of FE and published results for bending moment profile, $x = 1 m$

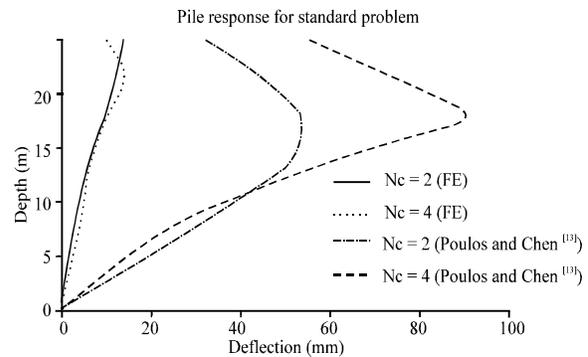


Fig. 9: Comparison of FE and published results for deflection profile, $x=1m$

maximum bending moment about 18% at $x = 1 m$ and for $N_c = 4.0$, FE analysis underestimates the value about 25% at $x = 1 m$ but starts to overestimates the maximum moment starting from $x = 4 m$ before becoming constant.

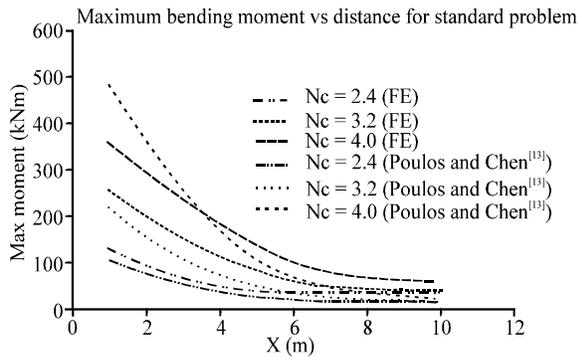


Fig. 10: Comparison of FE results and published results for $N_c = 2.4, 3.2$ and 4.0 versus x

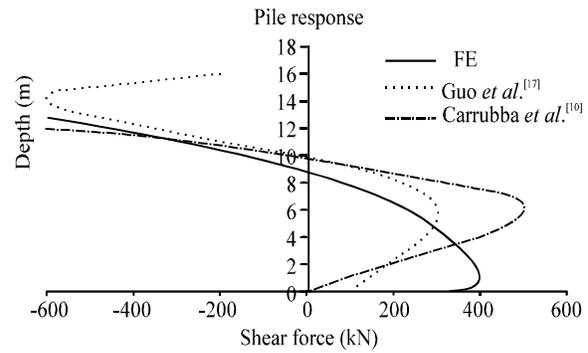


Fig. 13: Comparison of FE and published results for shear force profile

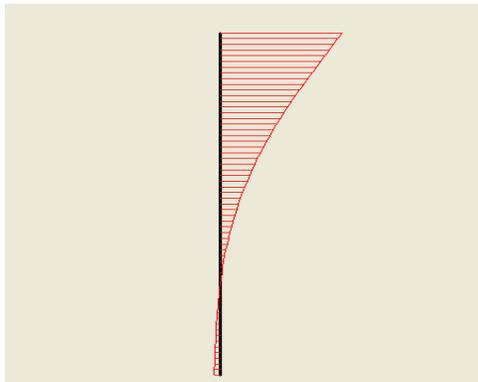


Fig. 11: Deflection profile for the pile

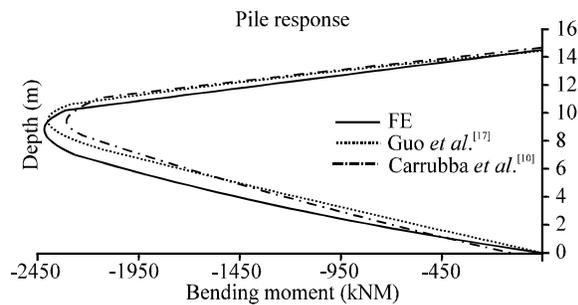


Fig. 12: Comparison of FE and published results for bending moment profile

Case 2: FE Analysis of a Single Pile used to Stabilize Sliding Slope: For this case, Fig. 5 shows the modeling in FE analysis in plain strain condition with an applied lateral load at the pile at depth 7.5 m. Figure 6 shows the deformed mesh after the analysis.

Figure 11 shows the deflection profile. There is some uplift of soil in front of the pile observed due to the lateral deflection at the top of the pile.

From Fig. 12 good agreement can be seen from the maximum bending moment although FE analysis tends to slightly overestimate the moment. As for the shear profile (Fig. 13), satisfactory trend is observed from the comparison. The maximum deflection at depth 7.5 m was analyzed about 53.27 mm. Guo and Ghee^[17] reported a calculated value of 49.4 mm. No measured deflection value is reported.

CONCLUSION

Finite-element analysis offers an excellent alternative to model single-pile under lateral loading to study the pile-soil interaction. Since in a two-dimensional environment, the single pile is modeled as an infinitely long wall, the shear flows of soil around the pile tend to be neglected, hence underestimating the maximum moment acting along the pile. Following this, further research is essential in a three-dimensional environment for single pile to identify the contribution of increased moment due to the discussed shear flow around the pile.

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