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Effect of Excavation-induced Movements on Adjacent Piles

Effets des mouvements causés par une excavation sur les pieux voisins

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ABSTRACT: This paper aims at investigating the effect of excavation-induced movements on the lateral deflections and bending moments of piles situated within the influence zone of a cantilever side-supported excavation. For this purpose, a series of non-linear finite element analyses were performed to assess the effects of excavation depth, distance of the pile from the side supported excavation, pile stiffness, and wall stiffness. Results indicate that distance of pile from side supported excavation and excavation depth have a significant effect on the lateral deformations and bending moment of the pile; while side support stiffness has a less markable effect. Charts for the preliminary evaluation of pile head lateral deflection and bending moments in piles were developed.

RÉSUMÉ : Cet article vise à examiner l'effet des mouvements induits par une excavation sur les déformations latérales et les moments de flexion des pieux placés dans la zone d'influence d’une excavation soutenu par un mur encastré. Dans ce but, une série d'analyses aux éléments finis non-linéaires a été réalisée pour évaluer les effets de la profondeur de l’excavation, de la distance du pieu à la paroi de l’excavation, du diamètre du pieu et de la rigidité du mur. Les résultats montrent que la distance de pieu à la paroi et la profondeur de l’excavation ont un effet significatif sur les déformations latérales et le moment de flexion du pieu; alors que la rigidité du mur a moins d'effet. Des diagrammes pour l'évaluation préliminaire du déplacement latéral de la tête du pieu et des moments de flexion dans le pieu ont été établis.

KEYWORDS: Finite element, pile, side-supported excavation.

1 INTRODUCTION.

Side-supported deep excavations are typically performed in urban densely populated cities for the construction of basements and cut and cover tunnels. Inspite of quality control applied during side support constrcution, some degree of side support lateral movement is unavoidable. This lateral movement is expected to generate lateral movements in soil, which in turn affect the perfomance of nearby pile foundations. Soil lateral movements will impose addtional lateral deflection and bending moment to the pile.

Several researches have used numerical modeling to evaluate the performance of pile adjacent to side supported excavations. Finno et al. (1991) and Goh et al. (2003) used lateral movements observed in the field to examine the behavior of a nearby pile. Finno et al. (1991) adopted a plane strain finite element code; while Goh et al. (2003) used a simple analytical model where the pile was discretized into discrete (linear elestic) beam elements with the soil-pile interaction modeled using a series of non-linear springs. Ong et al. (2006) and Leung et al (2006) used a numerical analysis similar to that adopted by Goh et al (2003) and obtained good agreement with results of centrifuge models of a single pile in clay and dense sand nearby a side-supported excavation. Although research exists for the use of three-dimensional finite element in analyzing the response of piles due to lateral soil movements and open excavations; there is limited research directed towards analyzing performance of pile under coupled wall-soil-pile interaction (Pan et al 2002, Miao et. al 2006, Kok et al. 2009).

This paper presents the results of numerical simulations performed using a 3D finite element approach to evaluate the behavior of a single pile nearby a cantilever side-supported excavation. Design variables considered in this study included pile stiffness, wall stiffness, distance of pile from side-support, and excavation depth. Relative contribution of the different design variables on the pile head lateral deflection and maximum bending moment was discussed.

1 FINITE ELEMENT ANALYSIS

1.1 *Finite element mesh*

Three-dimensional stress deformation analyses were performed using the finite element program ABAQUS (2010). The model consists of three parts; namely, soil, pile and wall of depth 10 m. Soil and piles in the model were discretized using solid tetrahdron elements that have nodes with 6 degrees of freedom. The wall was modelded as a planar shell that have both axial and bending stiffness. Main features and dimensions of the finite element model is shown in Figure 1.

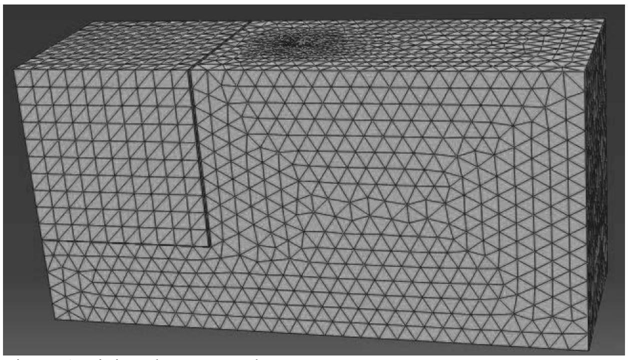


Figure 1. Finite Element Mesh

Interaction at the pile-soil and wall-soil interface was modeled using a master-slave surface contact formulation developed by Hibbitt et al. (1998) and built in ABAQUS. In this formulation, two contact surface pairs with specific interaction model were defined. At the pile-soil and wall-soil interface, a basic Coulomb frictional interaction model was assigned to define the interaction between the soil and wall surfaces. This model defines the maximum allowable frictional (shear) stress that can be transferred across the interface as the contact pressure between the contacting bodies multiplied by a friction coefficient. For the purpose of this study, a friction coefficient (μ) of 0.50 was assumed.

1.2 *Input parameters and model variables*

Input parameters considered in the analyses included soil mechanical properties (density, shear strength parameters, and elastic modulus) as well as pile and wall material properties. The soil considered for this study was medium dense sand modeled as an isotropic elasto-plastic material with a Mohr coulomb failure criterion as provided in Table 1. The pile and wall were modeled as isotropic linearly-elastic materials defined by moduli of elasticity, density, and passion's ratio shown in Table 2.

Model variables considered in assessing the effect of wall stiffness (E_{wall} I_{wall}), pile stiffness, excavation depth- to pile length ratio (H/L), and distance of pile from the wall (X) are summarized in Table 3. It should be noted that pile diameter (d) was considered as a representation of pile stiffness. Furthermore, wall stiffnesses shown in Table 3 correspond to different steel sheet pile section moduli defined by PU steel sheet pile walls.

1.3 *Modeling approach*

The finite element modeling was executed in three stages. The first stage involved the generation of the initial effective geostatic stress within the model. This was performed by applying a gravity load of 10 m/sec^2 on the entire model. At the end of this stage, the analysis output was checked to ensure triangular distribution of vertical stress (i.e., increasing with depth) accompanied by small vertical deformations. In the second stage, the pile and wall was introduced and contacts along pile-soil and wall-soil interface were activated. Finally, staged excavation was modeled by the removal of model elements in phases each of 1 m thick up to a total excavation depth of 5 m. Output fields monitored at the end of each excavation stage included lateral deflection and axial strain along pile shaft. Based on the axial strain along the pile shaft, the bending moment distribution along the pile was calculated using Eq (1).

$$M(z)=\varepsilon_b(z)\frac{E_{pile}\ I_{pile}}{r} \quad (1)$$

where $M(z)$ is the bending moment at any depth z from pile head; $\varepsilon_b(z)$ = bending strain at depth z from pile head = $(\varepsilon_1-\varepsilon_2)/2$; ε_1 ε_2= axial strains at outermost elements located on both sides of neutral axis; E_{pile} is the elastic modulus of pile; I_{pile} is the moment of inertia of the pile; and r is the radius of the pile

2 RESULTS AND DICUSSION

This section summarizes main findings obatined from the finite element analyses. For clarity and paper page limitaiton, only results related to d = 600 mm will be illustrated in figures presenetd in this section.

2.1 *Lateral deflection and bending moment distribution along pile*

Figures 2 and 3 show distributions of pile lateral deformation and bending moment for different excavation depths. As shown in Figure 2, pile lateral deflection increased with increase in excavation depth and decreased with increase in pile distance from the wall (X). Furthermore, change in the profile of lateral deflection was observed for pile of X = 2 m when H/L increased from 0.4 to 0.5 signifying that the pile underwent excessive lateral deformation due to wall deformation. The magnitude and shape of the lateral deflection at H/L = 0.5 depends on the pile stiffness (i.e., d).

Bending moment distributions along pile length for different X and H/L are illustrated in Figure 3. From Figure 3, it is observed that, for H/L ≤ 0.4, bending moment had a one sided parabolic distribution; however, for H/L = 0.5, bending moment distribution showed degree of moment direction reversal. This is attributed to significant change in lateral deformation profile (Figure 2). The degree and magnitide of moment direction reversal decreased with increase in X as shown in Figure 3. Furthermore, it was observed that the degree of moment reversal increases with increase in pile stiffness.

Table 1. Input parameters of soil

Parameter	Value
Cohesion (c, kPa)	5
Angle of friction (ϕ, degree)	35
Poisson's ratio	0.35
Density (ρ, kg/m^3)	1800
Elastic modulus (E, kPa)	50000

Table 2. Input parameters of pile and wall

Component	Density (ρ, kg/m^3)	Elastic modulus (E, MPa)	Poisson's ratio
Pile	2500	25	0.15
Wall	7800	200	0.30

Table 3. Modeling variables

Variable	Value
Pile diameter (d)	300, 600, 1000 mm
Pile distance from the wall (X)	2, 4, 8 m
Wall stiffness (E_{wall} I_{wall})	1.45x10^5, 6.10x10^4, 2.32x10^4 kN.m^2
Excavation depth-to-pile length ratio (H/L)	0.1, 0.2, 0.3, 0.4, 0.5

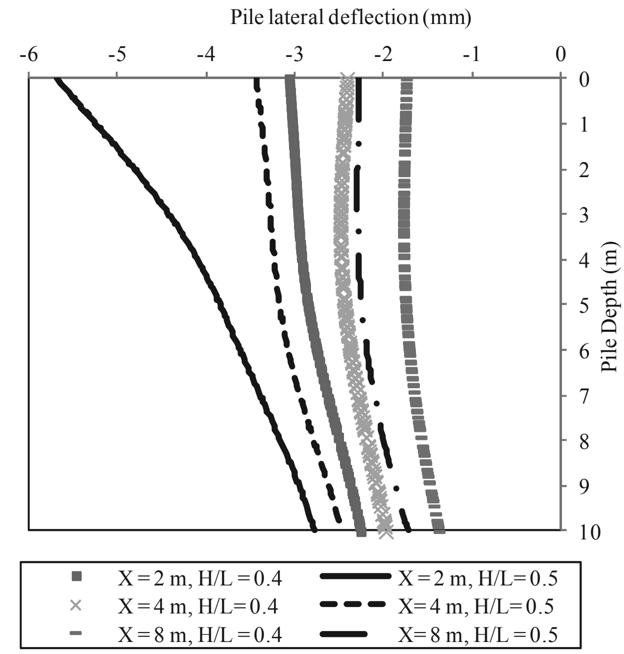
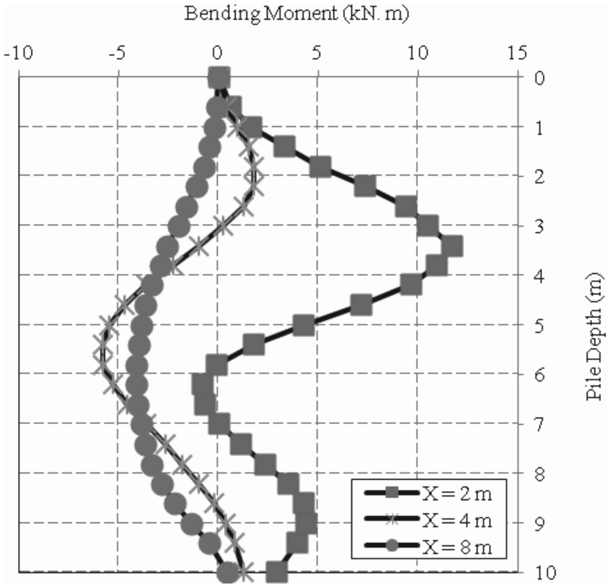
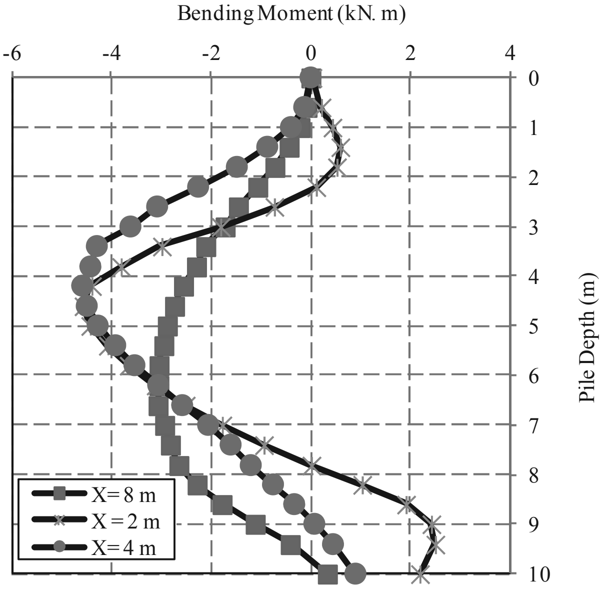


Figure 2 Lateral defelction distribution along pile (d = 600 mm, E_{wall} I_{wall} = 6.10 x10^4 kN.m^2)



(a) for H/L= 0.5



(b) for H/L = 0.4

Figure 3 Bending moment distribution along pile shaft (d = 600 mm, $E_{wall} I_{wall} = 6.10 \times 10^4$ kN.m^2)

2.2 *Effect of wall-stiffness*

Variation of pile head lateral deflection and maximum bending moment with wall stiffness are shown in Figures 4 and 5; respectively. From these figures, it is apparent that wall stiffness has an insignificant effect on both pile head deflection and maximum bending moment for H/L $\leq$ 0.30. Specifically, the percent decrease in pile head deflection ranged from 1.7% to 5.2% with increase in wall stiffness; while the percent decrease in maximum bending moment ranged from 1.5% to 7.8% with increase in wall stiffness. For H/L greater than 0.3, the wall stiffness seem to have a more markable effect with percent decrease in pile head deflection ranging from 12.5% to 20% and percent decrease in maximum bending moment ranging between 25% and 62% with increase in wall stiffness. It should be noted that Figure 4 show reversal in bending moment sign (from negative to positive) indicating reversal in the location of maximum moment due to excessive deflection underwent by the pile as H/L approaches 0.5.

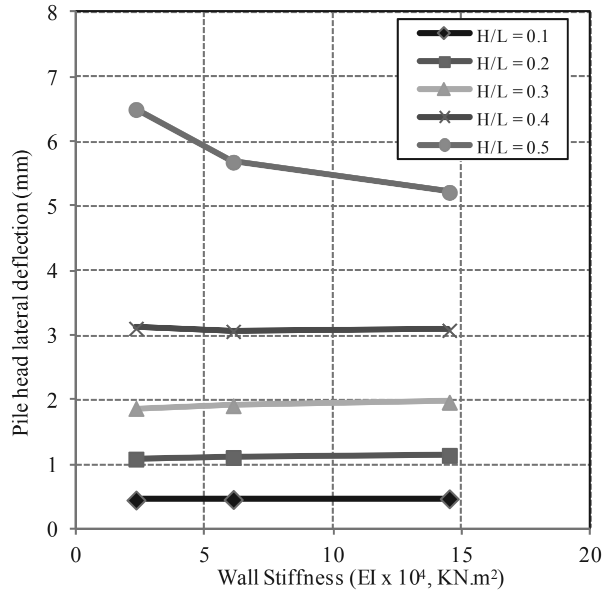


Figure 4. Effect of wall stiffness on pile head lateral deflection (d=600 mm)

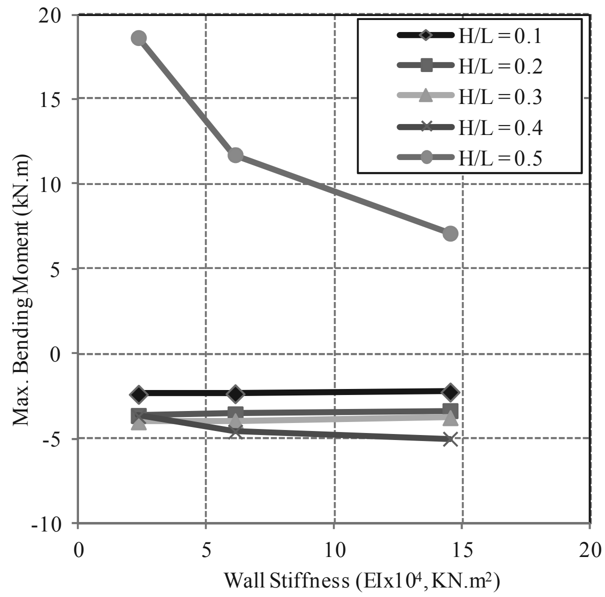


Figure 5. Effect of wall stiffness on maximum the bending moment (d= 600 mm)

2.3 *Effect of excavation depth and pile distance from the wall*

The effect of excavation depth (expressed as H/L) and distance of pile from wall (X) on the lateral deformation and maximum bending moment of pile due to excavation induced movements are illustrated in a combined plot shown in Figure 6. With respect to the pile lateral deflection, it is observed that H/L has a significant effect on lateral deflection. The maximum increase in pile head lateral deflection ranged between 6% and 11.3% as H/L increases to 0.5. It can be further inferred from Figure 6 that the pile head deflection is highly sensitive to X for H/L > 0.30. In particular, the percentage decrease in pile head lateral deformation was observed to range between 14% and 60% with increase in X for H/L > 0.30.

On the other hand, it is apparent from figure 6 that H/L has a small effect on the maximum bending moment in the pile with percent increase in bending moment varying from 0.5% to 6% with increase in H/L. On the other hand, X had a significant effect on pile maximum bending quantified by an observed decrease ranging between 10% and 60% with increase in X. Positive moment observed in Figure 6 indicates reversal in maximum moment location as described in section 2.1.

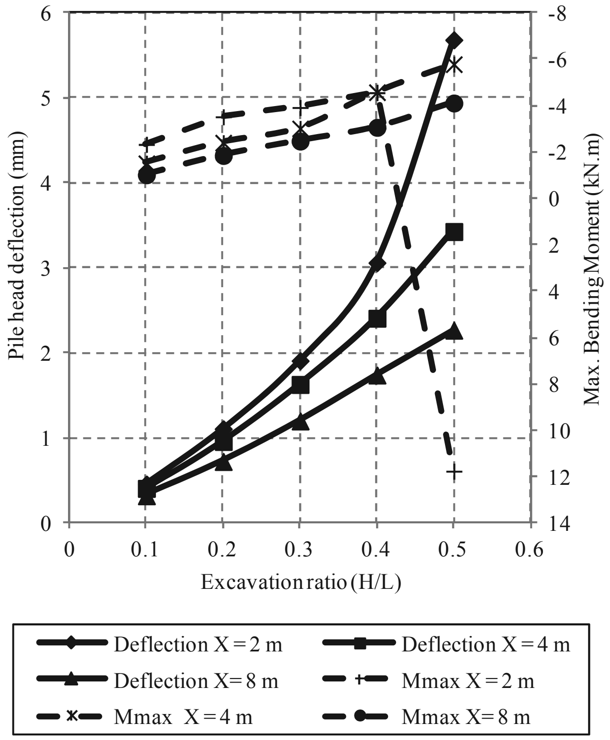


Figure 6. Variation of pile head lateral deflection and maximum bending moment with excavation ratio d = 600 mm ($E_{wall}I_{wall}$ = 6.10 x10^4 kN.m^2)

2.4 *Effect of pile stiffness*

The effect of pile stiffness (expressed as pile diameter) on the pile head lateral deformation and maximum bending moment is illustrated in Figure 7. From Figure 7, it is observed that pile stiffness has an minimal effect on pile head deflection up to H/L equal to 0.4 (percent difference ranging between 2% and 10%); however, for H/L equal to 0.5, the contribution of pile stiffness is heightened due to excessive pile deflection (percent difference varying from 13% to 21%). In contrast, pile stiffness showed a significant influence on maximum bending moment with maximum influence apparent at H/L = 0.5.

3 CONCLUSIONS

Main conclusions that can be deduced from this study can be summarized in the folllowing points:

- Distribution of lateral pile deflection along pile depth show similar trends with pile head deflcetion in the range of 3 mm for H/L=0.4. For H/L=0.5, wall undergoes rotation causing excessive lateral deflection in pile and transformation in the pile deflection profile.
- Profiles of bending moment distribution along pile length show single sided parabolic distrition; however, when excessive deformation occurs (i.e., at H/L=0.5) reversal in bending moment distribution was observed. The degree of bending moment reversal is highly dependent on distance of pile from supported excavation (X) and pile stiffness (d).
- Wall stiffness (E_{wall} I_{wall}) has minimal effect on pile head deflection and maximum bending moment for H/L $\leq$ 0.30. However, for H/L > 0.30, the wall stiffness effect was more pronounced.
- H/L has a pronounced effect on pile head lateral deformation that is further highlighted for X equal to 2 m.
- H/L and X have a insignificant effect on the maximum bending moment in the pile with percent increase in bending moment varying from 0.5% to 6% with increase in H/L.
- Pile stiffness has an insignificant effect on pile head deflection up to H/L equal to 0.4; however, for H/L equal to 0.5, the contribution of pile stiffness is heightened due to excessive wall and pile deflection.
- Pile stiffness showed a significant influence on maximum bending moment with maximum impact apparent at H/L = 0.5.

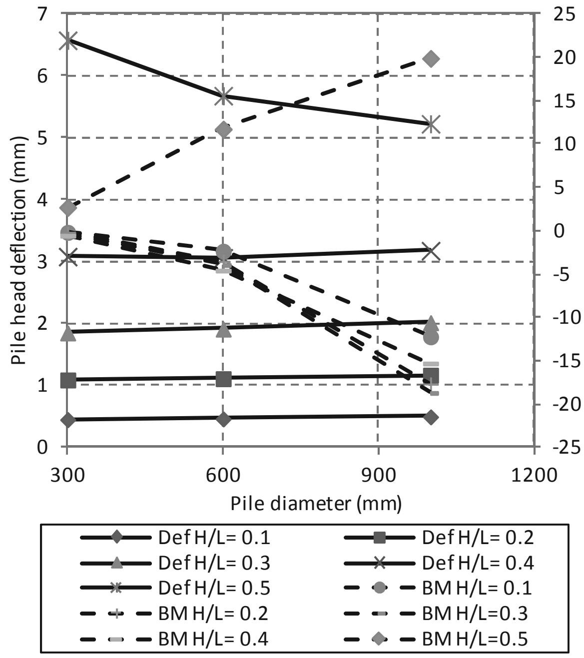


Figure 7 relationship between pile diameter and pile head deflection and maximum bending moment (X = 2 m, $E_{wall}I_{wall}$ = 6.10 x10^4 kN.m^2).

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