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THREE-DIMENSIONAL NONLINEAR FINITE ELEMENT MODELING FOR LATERALLY LOADED VERTICAL PILES

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ABSTRACT

This paper presents a study for laterally loaded free head concrete piles using the finite element method (FEM). The finite element mesh is constituted from three-dimensional elements. The pile and soil boundary are defined cylindrically while lateral load is defined as single concentrated load from the top of the pile head. Various types of soil and pile properties are analysed and the load-deformation curves for different types of soils namely, sands and clays are evaluated.

Key Words : Piles, Lateral loads, Finite element method, Three-dimensional modeling

YATAY YÜKLÜ KAZIKLARIN SONLU ELEMANLAR YÖNTEMİ İLE ÜÇ BOYUTLU DOĞRUSAL OLMAYAN DAVRANIŞININ MODELLENMESİ

ÖZET

Yatay yüklü kazıkların deformasyon davranışını etkileyen en önemli etkenler zemin koşulları, yükleme durumu ve sınır koşullarıdır. Sonlu elemanlar yöntemleri bu etkilerin hepsinin göz önüne aldığı için çok önemli analiz araçlarıdır. Kazıkların yük-deformasyon davranışının doğruya en yakın modeli üç boyutlu tasarımlarla sağlanabilir. Bu çalışmada sözü geçen etkileri ve üç boyutlu davranışı dikkate alan analizler yapılmıştır. Nümerik analizlerde farklı çaplardaki dairesel şekilli betonarme kazık ve farklı elastik özelliklere sahip zeminler için deformasyon davranışı elde edilmiştir. Zemin özelliklerinin gerilme-deformasyon davranışı üzerindeki etkisi üzerinde durulmuştur.

Anahtar Kelimeler : Kazıklar, Yatay yük, Sonlu Elemanlar Yöntemi, Üç boyutlu modeller

1. INTRODUCTION

Pile foundations, which are commonly designed to resist compression and tension, are also designed to sustain lateral soil movements. Examples are, piles supporting bridge abutments adjacent to approach embankments, existing pile foundations adjacent to pile driving operations, excavations and pile foundations in moving slopes. The major concern for design of laterally loaded piles is much far from calculating the ultimate lateral capacity of the piles but the induced deformations and bending moments from the resulting soil movements (Chen et al., 1997; Hsiung et al., 1997). Hence, the most commonly used methods for analysing the laterally loaded piles are based on this phenomenon.

A large number of laboratory and field experiments have shown the fact that the lateral soil movement of piles varies from case to case (Chen, 1994). Although many extensive theoretical and empirical approaches and modifications of these approaches are developed for the design of laterally loaded piles, all these methods have some limitations or disadvantages (Prakash, 1989; Chen et al., 1997; Hsiung et al., 1997). Subgrade reaction theory, p-y curves, finite element methods are widely used in the analysis of laterally loaded piles. Based on these theories and methods a great number of analyses have been proposed by the researchers. Ito and Matsui (1975) studied the laterally loaded stabilizing pile problem with Mohr-Coulomb and visco-plastic flow theories. The behaviour of the soft soil between piles and the load induced from these piles due to the movement of the soil are investigated (Fig.1a). Theoretical equations are stated and effects of soil and pile parameters on the results are discussed. Baguelin et al. (1977) analysed the laterally loaded pile problem theoretically. Soil is assumed to be elasto-plastic and the pile is a rigid circle. Pile sections, disturbed soil section, undrained yield of the soil are taken into account. Byrne et al. (1984) studied the lateral displacement effect of the free field deformations due to excavations adjacent to piles or lateral deformations induced from an embankment construction.

Ashour and Norris (1998) presented a strain wedge theory, which takes the soil-pile interaction into account. The main concept is traditional one-dimensional beam on elastic foundation (Fig.1b). The theory is also capable to consider the effects like pile head condition, multiple soil layers.

Elastic continuum approaches are also being used for single pile analysis. Poulos and Davis (1980) used boundary element method and based on a point load solution of Mindlin (1936). Boundary integral approach by Banerjee and Davies (1978) utilizes a solution for point loads acting at the interface of two layer elastic half space.

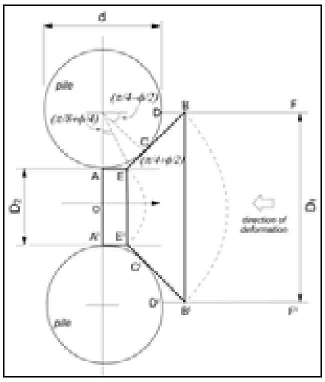
The subgrade reaction method considers a pile as a beam on an elastic foundation and the soil as a series of elastic and closely spaced independent springs. This method is known as being relative simple and also considers the factors like soil nonlinearity, variation of subgrade reaction with depth and layered soil properties. However, the modulus of subgrade reaction is not a unique soil property.

The p-y curve approach proposed by Reese (1984) considers the soil nonlinearity and is based on limited pile-load tests in medium sands. This method uses some semiemprical coefficients developed from test data. p-y curve approach dismisses the change in pile property such as pile bending stiffness, pile cross-sectional shape, pile head fixity, pile head embedment below ground surface. However, besides its disadvantages the p-y curve approach is the most commonly used method determining the behaviour of laterally loaded single piles. There are numerous modified p-y curve methods proposed by various researchers.

Broms (1964) used Winkler theory in which pile and soil are modelled by a beam and series of elastic spring respectively. Spring constant is the subgrade reaction coefficient. For a *cohesive* soil, the ultimate lateral resistance is assumed to increase from the soil surface down to a depth equivalent to three pile diameters and then remain constant. Broms (1964) suggested a soil resistance distribution beginning from the depth of 1.5 times pile diameter below the soil surface and assigns a constant value of $9c_u$. According to this assumption pile movements will be sufficient to generate this value of reaction in the critical zones, which are found by the failure mechanism. Possible deformation modes for free head piles are shown for short and long piles in Figure 2. Lateral capacity for short (rigid) piles primarily depends on soil resistance, while for long piles primarily depend on the yield moment on pile itself. For a *cohesionless* soil the distribution of passive pressure along the front of the pile is equal to three times the Rankine passive pressure. This assumption is based on limited empirical evidence from comparisons between predicted and observed ultimate loads (Broms, 1964). Figure 2a and 2b show the deformation modes for free head short and long piles, respectively. Some of the symbols refer to figure are as shown below:

Stewart (1992) conducted a review about these methods and grouped these design methods as: empirical methods, pressure-based methods, displacement methods and finite element analysis. Empirical and pressure based methods are capable of practical calculations of maximum bending moment and pile cap deflections. However displacement based and finite element analysis can define soil stratigraphy and loading conditions more accurately. Since any kind of geometry and material property can be assigned to each element in FEM, this method is useful to solve complex boundary conditions or complicated soil layers (Hsiung et al., 1997).

In this study the finite-element software LUSAS is used to determine the load-deformation behaviour of laterally loaded free head single piles in different types of soils, namely: for sands and clays. Ozkan et al. (2002) also conducted an investigation on the behaviour of laterally loaded group piles.



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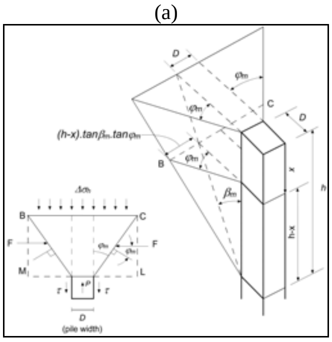

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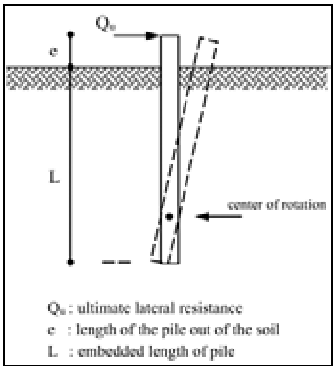
Figure 1. (a) Plastic deformation state of soil between piles (Ito and Matsui, 1975) (b) Strain wedge mechanism of soil (Ashour and Norris, 1998)



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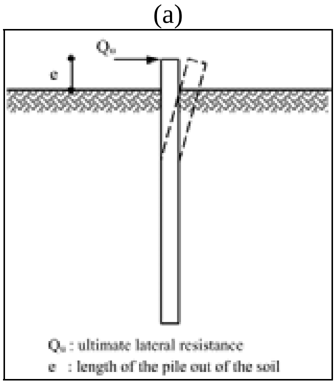

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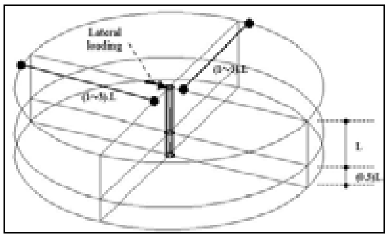
Figure 2. Deformation modes for short and long piles (a) short pile deformation (b) long pile deformation (Broms, 1964)

2. MESH, GEOMETRY AND MATERIAL PROPERTIES OF FİNİTE ELEMENT MODEL AND LOADING CONDITIONS

2. 1. Constituting the Mesh

The model, which is used to analyse pile head deformation on laterally loaded piles, is formed by three-dimensional elements. At Figure 3a the mesh is outlined with geometrical details while Figure 3b shows the detailed finite element mesh. The view of the mesh on the X-Z plane is exposed in Figure 3c. As seen from the figure cylindrical pile is surrounded with soil medium with cylindrical boundary conditions.

Elements constituting the mesh are 3D isoparametric solid continuum elements. The pile shape is generated from PN15 (pentahedral, 15 nodes) while soil shape from the HX20 (hexahedral, 20 nodes) elements. Both elements are higher order models capable of modelling curved boundaries so are suitable to form the cylindrical shape of pile and boundary surfaces.



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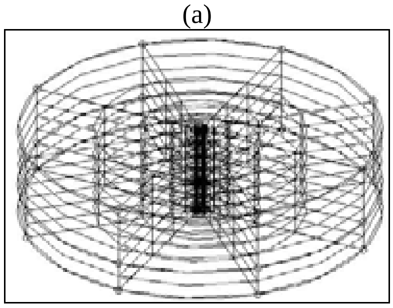

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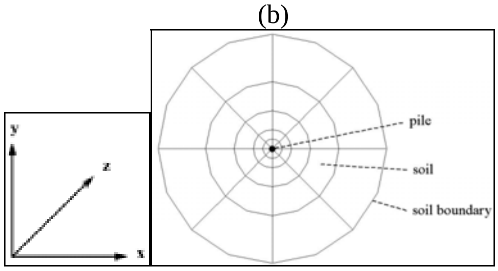

(c)

Figure 3. Details of the mesh (a) outlined (b) finite element mesh details (c) XZ plane view

2. 2. Geometrical Properties

Geometrical properties of the constituted mesh are outlined in Figure 3a. Using the pile length (L) as a reference the mesh is formed for a height of 1.5xL in the vertical direction. Because no vertical loads applied to the pile along the vertical axis the distance from the pile tip to the mesh boundary is limited to 0.5xL. Along the horizontal direction mesh radius is chosen as 1 to 3 times of the pile length. Horizontal dimensions are selected to meet the requirement for a horizontal boundary. The required condition is the approximation to zero lateral stress values at the boundary.

As shown from the Figure 3b and 3c for an accurate analysis the mesh is discretisized into smaller elements, while the outer element sizes are much larger. The ratio of the horizontal and vertical sides of the elements is chosen to be unity especially for the elements near the pile. The total number of elements forming the mesh is chosen to reach an accurate analysis and time saving is also considered. To take the pile-soil interaction into account a 100 mm.'s of interface area is defined along the pile-soil contact surface.

The pile geometry (diameter, length), which is used through out the analysis, is given in Table 1. Pile diameters are 250 and 400 mm.'s for sands and 600, 800, 1000 mm.'s for clays while pile lengths are 4, 6, 8 m.'s for both soils however 12 m. of pile length is also analysed for stiff clays.

Table 1. The Dimensions of the Piles used Through the Analysis According to the Soil Type

Pile diameter	Soil Type			
	Sand		Clay	
d=250 mm.	L= 4-6-8m.	L= 4-6-8m.	-	-
d=400 mm.	L= 4-6-8m.	L= 4-6-8m.	-	-
d=600 mm.	-	-	L= 4-6-8-12m.	L= 4-6-8m.
d=800 mm.	-	-	L= 4-6-8-12m.	L= 4-6-8m.
d=1000 mm.	-	-	L= 4-6-8-12m.	L= 4-6-8m.

2. 3. Material Properties and Loading Conditions

Through the analysis Drucker-Prager continuum plasticity model is used to model soil continuum while isotropic linear elastic material property is used to model piles.

Drucker-Prager yield surface criterion is suitable for materials which exhibit volumetric plastic straining like soil, rock and concrete. The criterion is an approximation to the Mohr-Coulomb criterion and is a modification of Von Misses criterion. The soil properties are defined with Young modulus, Poisson ratio, mass density, cohesion, friction angle, the slope of both cohesion and friction angle against the effective plastic strain (Lusas 12.1 User Guide). For isotropic linear elastic model two material properties are utilised which are Young modulus and Poisson ratio.

The values of the representative parameters defining the soil and pile properties are given in Table 2 according to soil type. The parameters are the values of Spundwand Handbuch (1986) and Poulos and Davis (1980). Poisson ratios corresponding to these soil types are the proposed values of Poulos and Davis (1980).

In order to model the geological history of the soil continuum body loads are initially applied to the system. Then as seen from Figure 3a the pile is loaded with a lateral concentrated load from the top of the pile. Load is applied incrementally using the Newton-Raphson iteration procedure.

Table 2. The Representative Parameters of Soil and Pile Used Through the Analysis

Material Name		Young modulus (MN/m^2)	Poisson ratio	Cohesion (kN/m^2)	Friction angle (^{0})
Soil	Sand, dense	150-250	0.3	-	35
	Sand, loose	20-50	0.4	-	25
	Clay, medium	5-10	0.3	25	15
	Clay, soft	1-2.5	0.4	10	5
Pile	Concrete	21000	0.15	-	-

3. ANALYSIS RESULTS

The results of the finite element model analysis on laterally loaded single pile are given as the form of load-deformation curves. The obtained curves are like typical load-deformation curves constituted from two lines. The initial line implies the soil is in an elastic condition and the second line implies the soil attains yielding condition. The deformation curves implies that both the amount of deformation and ultimate lateral capacity have the major concerns for the design of laterally loaded piles in clay type soils. For sands however the amount of deformation has little effect than clays. After a specific value, the effect of pile length on ultimate lateral resistance of laterally loaded piles decreases with increasing pile length. In Figure 4 the load-deformation curves of medium clays for pile lengths 4, 6, 8 and 12 m.'s are shown. It is apparent from the figure that as the pile length increases to 12 m. the load-deformation curves are gradually tending to get closer each other. This behaviour is common for clay type soils analysed through this study.

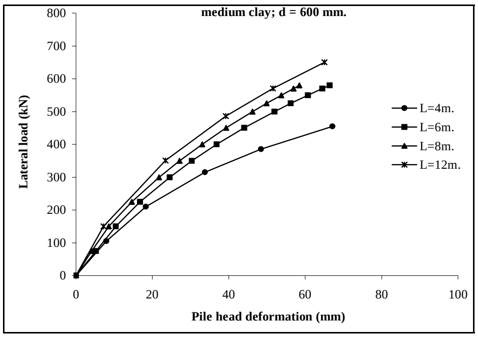

Figure 4. Load-deformation curves according to pile length of d=600 mm. for medium clays

The deformation behaviour of the short and long piles obtained from the analysis results are given in Figure 5. The obtained behaviours are similar to those Broms (1964) offered in Figure 2. Free-head short piles are expected to rotate around a centre of rotation as seen in Figure 5a. As seen in Figure 5b due to very high passive soil resistance occurred along the lower parts of the long piles translation or rotation cannot occur like short piles.

Analysis results for various soil and pile properties are summarized in two graphics for better understanding. In Figure 6a the whole curves for lateral load-pile head deformation are given for clays while the similar curves are given in Figure 6b for sands. The curves given in both figures are ordered according to pile diameters. It is obvious from Figure 6a that the piles in medium clays deformed much less than the piles in soft clays for a given lateral load. The deformation amount is about 150 mm for much of the curves between the values of 400-600 kN/m^2 for lateral load. An increase in pile diameter has very little effect on decreasing the pile head deformation for soft clays. The piles in dense sand have the capability to resist lateral loads much better than in loose sands. The effect of pile diameter on lateral resistance is also seen for d=250 mm. and d=400 mm. piles in medium and loose sands. In medium sands the soil resistance is roughly twice of the loose sands. The deformation values of the sands are much less than the clays. Especially the deformation values of the dense sands are not much than 20 mm.'s for dense sands. For a specific pile diameter the load-deformation curves are very close to each other for increasing pile lengths. It is seen from the figure that for sands the effective pile length on ultimate lateral resistance of laterally loaded piles has very little influence than that for clays.

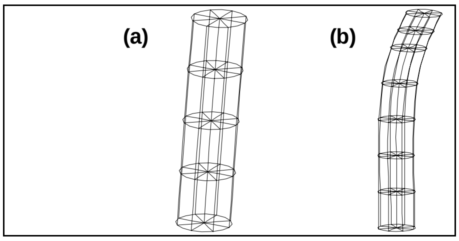

Figure 5. Pile deformation shapes from FEM (a) L=4 m. short piles (b) L =12 m long piles

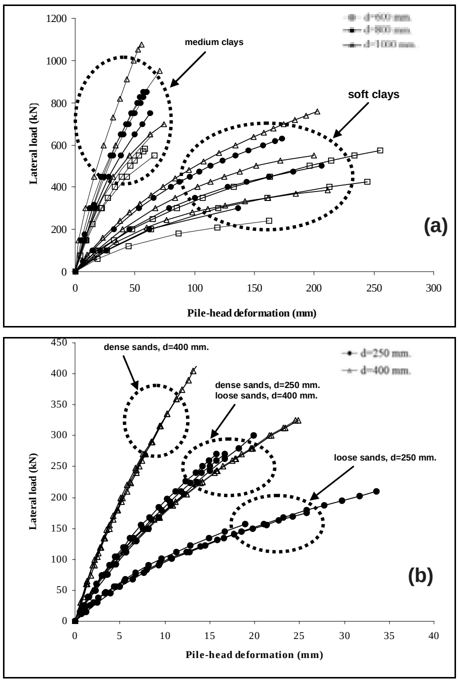

Figure 6. The pile head deformation (a) clays (b) sands

4. CONCLUSIONS

The major concerns of the design for the laterally loaded piles are the induced deformations and bending moments. In this study finite element method is used to predict lateral deformations on a single pile. Various pile geometry and soil properties are used defining the pile and soil characteristics. The study in this paper leads the following conclusions.

- Free-head short piles are expected to rotate around a centre of rotation point while such deformations cannot occur for long piles due to high soil pressures occurred along the lower parts of the pile.
- The effect of pile length on ultimate lateral resistance decreases as the pile length increases.
- Soil type has the dominant role on predicting the deformation characteristics of the laterally loaded piles. For clays, the deformation values have a significant role while ultimate resistance is much important for sands through out design of the piles

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