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Full Length Research Paper

Numerical investigation on reinforcement requirement for piles embedded in clay

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In this study the necessity of reinforcement in concrete pile (bored or driven) is assessed. The soil was assumed to be unsaturated and homogeneous clayey soil. Throughout the study, a finite element computer program was developed and the pile was modeled as a beam-on-elastic foundation. The soil is represented by discrete spring. The stiffness of each spring is considered to be linearly variable with depth. The moment loading, lateral loading, pile length, pile diameter, in addition to the angle of internal friction; soil density and soil cohesion were taken as parameter to study their effect on the extent of reinforcement along the pile shaft. It is concluded that for piles embedded in clay, a length of reinforcement not less than one-half the pile length is needed.

Key words: Clay, reinforcement requirements, bored piles, driven piles, pile reinforcement.

INTRODUCTION

Since the reinforcement cost a lot, it is necessary to study the possibility of reducing this material to the minimum during pile construction. In the past, piles were fully reinforced. Nowadays, the designers prefer to minimize the length of reinforcing bars so that they may reduce the cost of piles. This minimization requires well separation for the cases where the piles need fully or partially reinforcement and the cases where the reinforcement can be completely eliminated. After making a survey on the codes and studying their recommendations in such field, it was found that all the codes give specifications and limitations for the percentage of bars that should be provided in the pile cross-sectional area. But the extension depth along the pile is left to the designer.

Objective of the study

The major objective of this research can be divided into two main categories:

1. Making a survey on the codes and their requirements on pile reinforcement.
2. Investigating whether the pile needs to be provided with reinforcement or not, and to which length the pile reinforcement is needed.

PILE REINFORCEMENT

The reinforcements are required in concrete piles to resist bending and tensile stresses, but may be used to carry a portion of the compression load. Its extension required at any section of the pile depends upon the loads and stresses applied to that section.

Reinforcement is required if the pile is subjected to bending moments. The bending moment and shearing force in a pile subject to lateral loading may be assessed using the method by Matlock and Reese (1960) as given in Figure 1. This method models the pile as an elastic beam embedded in a homogeneous or non-homogeneous soil. The structural capacity of along flexible pile is likely to govern the ultimate capacity of a laterally-loaded pile.

The pile reinforcement undergoes the needs and the requirements. Therefore, there is no specific limit where the pile should be reinforced. The needs are determined by one of the pile analysis theories, where field

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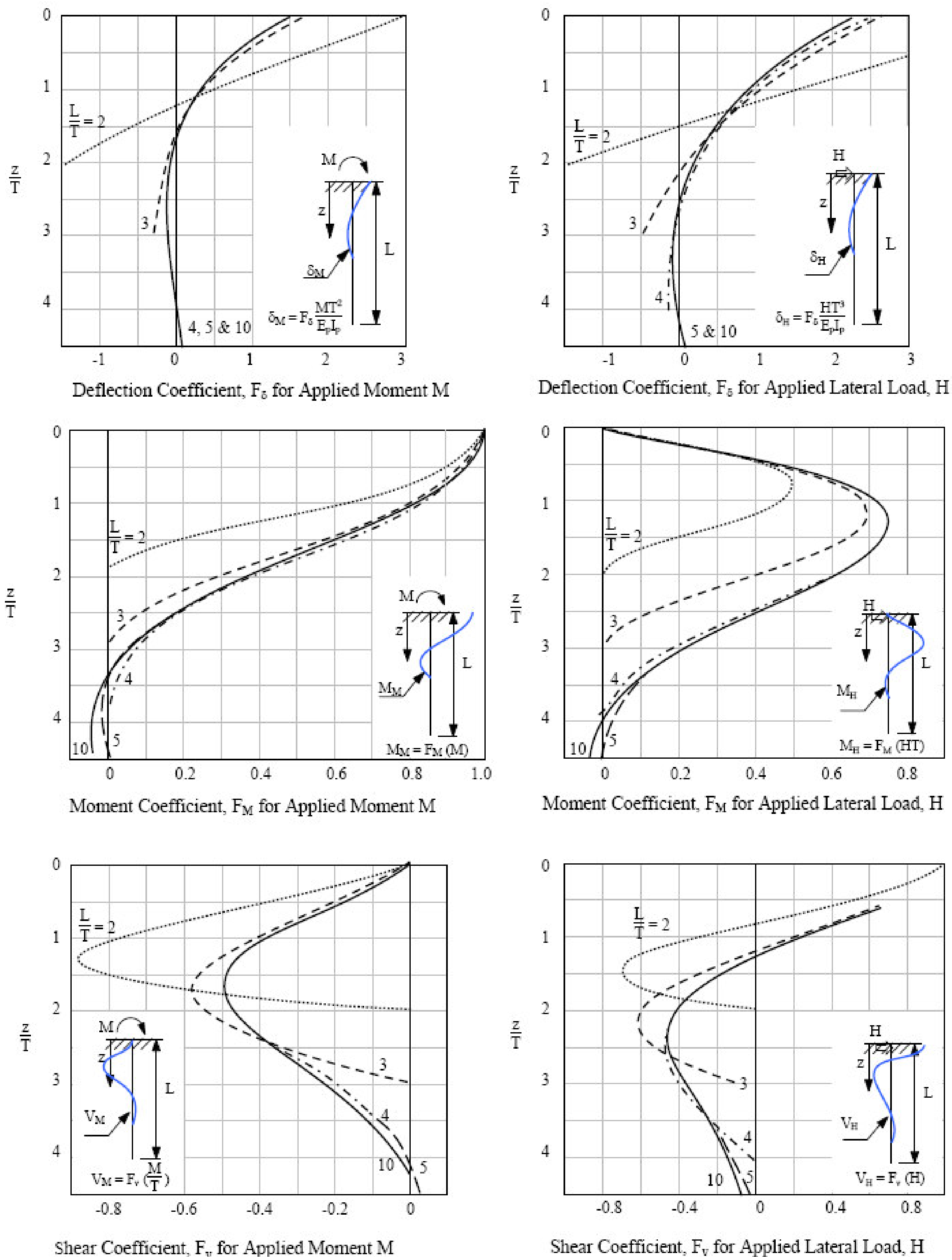

Figure 1. Influence coefficients for piles with applied lateral load and moment (flexible cap or hinged end conditions) (Matlock and Reese, 1960),

(1) $T = \sqrt[5]{\frac{E_P I_P}{n_h}}$ where E_P, I_P = bending stiffness of pile and n_h = constant of horizontal subgrade reaction.

(2) Obtain coefficients Fσ, FM and Fv at appropriate depths desired and compute deflection, moment and shear respectively using the given formula.

observations and some theoretical consideration specify the requirements.

REINFORCEMENT REQUIREMENT

Precast concrete piles

The reinforcement should be provided in all precast concrete piles to take up the stresses caused in handling, pitching and driving and this greatly exceeds what is needed once the pile is in the ground (Saurin, 1949; Whitaker, 1976; Mohan, 1990).

IS 2911 (part I) 1964, recommended that the area of the main longitudinal reinforcement shall be not less than the following percentages of the cross-sectional area of the pile:

(a) 1.25% for piles with length less than 30 times the least width.
(b) 1.50% for piles with length between 30 to 40 times the least width.
(c) 2.00% for piles with length greater than 40 times the least width.

Where the lateral reinforcement shall be in the form of hoops or links and shall be not less than 5 mm in diameter. The volume of lateral reinforcement shall be not less than the following percentage of the gross volume of the pile:

(a) 0.20% in the body of the pile.
(b) 0.60% at each end of pile for a length of about 3 times the least width.

The transition between the closer spacing and the maximum shall be gradual over a length of 3 times the least width.

SABS 088 (1972), recommended that the cross-sectional area of longitudinal reinforcement should be at least 0.8% of the cross sectional area of the pile, and lateral ties should be at least 6 mm in diameter, closely spacing at both ends of the pile.

ACI 543R (1974), recommended that the longitudinal steel cross-sectional area be not less than 1.5% nor more than 8% of the cross-sectional area of the pile. At least six longitudinal bars should be used for rounds or octagonal piles and at least four bars for square piles. The lateral steel should not be less than 0.25 in. (6 mm) in diameter and spaced not more than 6 in. (15 cm) on centers except that the spacing should be closer at each end of the pile.

DIN 4026 (1975), recommended that the longitudinal reinforcement of the piles, at length not exceeding 10 m, shall be not less than 0.8% of the cross-section of the pile. For solid rectangular piles, at least 4 longitudinal bars of 14 mm diameter must be arranged in the corners; for round piles, at least 5 longitudinal bars of 14 mm diameter have to be placed and evenly spaced, without end hooks. The transverse reinforcement should be at least 5 mm in diameter. The axial spacing (pitch) of a helix should not exceed 12 cm and reduced to about 5 cm over a length of 1 m at top and bottom of the pile.

JIS A5310 (1987), recommended that the longitudinal reinforcement shall consist of 6 mm or more bars, with a steel ratio not less than 0.8% and it is desirable that they are arranged uniformly along the circumferences of the concentric circles in the respective cross sections of reinforced concrete pile. The minimum spacing should not be smaller than 0.75 times the maximum dimension of the coarse aggregate. The spiral bars should be arranged outside the longitudinal reinforcement. The additional bars should have a diameter not smaller than 3 mm, and a pitch not larger than 110 mm.

Many literatures recommended the same specifications for the reinforcement of precast concrete piles (Chellis, 1961; Rennie, 1986; Jha and Sinha, 1995).

Cast *in-situ* concrete piles

The extent of reinforcement in cast-*in-situ* concrete piles is governed by the loads involved and the design analysis. Some codes differentiate between the recommendations of reinforcement in both driven and bored cast-*in-situ* concrete piles (BS 8004 (1986), and DIN 4014 (part I), (1975), where others consider them as one unit under the main article, cast-*in-situ* concrete piles, (IS 2911 (part I) (1964), and ACI 543R (1974).

IS 2911 (part I) (1964), recommended that any reinforcement in cast-*in-situ* concrete piles should be made up into cages sufficiently well wired to withstand handling without damage. The bars should be so spaced as not to impede the placing of the concrete and the lateral ties or spiral should not be closer than 15 cm center to center. Reinforcement in the pile may reflect the manner of the transmission of the load by the pile to the soil, and need not normally exceed 0.8% of the cross-sectional area of the pile.

ACI 543R (1974), recommended that the reinforcement is used in cast-*in-situ* concrete piles for any unsupported section of the pile, uplift loads, or lateral loads when the analysis indicates. Unsupported sections (which extend through, air, water, or even through very fluid soil) should be designed to resist buckling under the imposed loads. Sufficient longitudinal and lateral steel should be used for the loads and stresses to be resisted.

For lateral loads, the pile should be designed and reinforced to take loads and stresses involved. In general, the amount of reinforcement required will be governed by the loads involved and the design analysis. Except for uplift loads, it is recommended that not less than four longitudinal bars be used. The extent of reinforcement below ground surface depends on the flexural and load distribution analysis.

DIN 4014 (part I) (1975), recommended that bored piles normally contain both longitudinal and transverse reinforcement extending over the entire length of the pile. The reinforcement shall be made in the form of a reinforcing cage and installed in the casing pipe in such a way that it cannot be displaced during the concreting or lifted with the casing when the latter is being extracted. A reinforcement extending over the full length of the pile may be dispensed with if the piles are vertical and are not less than 30 cm in diameter and not more than 7.5 m in length. Provided there is no likelihood of the piles being subjected to bending by either earth pressure, the lateral pressure of plastic soft soils, eccentric loading or any other cause.

The longitudinal reinforcement shall comprise not less than five reinforcing bars of 14 mm diameter, spaced at intervals of not more than 20 cm. The total of the cross-sections of the longitudinal reinforcement must not be less than 0.8% of pile cross-section. If any permanent casing is used, it shall not be reckoned as part of the reinforcement because of the risk that it may rust through. The transverse reinforcement shall be arranged in helical form with a bitch between 15 to 20 cm. It must have a diameter of not less than 5 mm, when the pile diameter is not more than 35 cm, or 6 mm with thicker piles.

BS 8004 (1986), and CP 2004 (1972), recommended that the reinforcement should normally be carried down for the full length for bored piles and into the enlarged base, if piles are required to resist tensile force. Where the tensile forces are small, the reinforcement need only be of the length necessary to transmit fully the tensile forces. Reinforcement should be provided for tensile forces, which are not expected to exist when the structure is completed.

For driven cast-*in-situ* concrete piles, it was recommended that the reinforcement may be provided over the whole of their length, over part of their length, or merely provided with short splice bars at the top for bending into the pile cap. The extent of the reinforcement will depend on whether the pile is used to resist tensile or bending forces, on the type of foundation, and on the possibility on horizontal or vertical movements due to the installation of other piles nearby or to moisture changes in the soil.

Derrington (1966), stated that if piles of 3 ft (0.9 m) diameter and over do not generally require reinforcement unless passing through a considerable depth of very soft ground. Only nominal reinforcement is required at the pile head for connection to pile cap or column. In 2 ft (0.6 m) and 2.5 ft (0.75 m) diameter piles it may be considered desirable to reinforce the upper part of the pile shaft if this passes through weak ground. Large diameter piles may be reinforced to resist bending moment resulting from horizontal forces, these forces being balanced by the passive resistance of ground against the pile.

Fleming et al. (1985), recommended that for bored piles loaded in compression alone, it is only necessary to reinforce the shaft to a depth of 2 m greater than the depth of temporary casing, to prevent any tendency for concrete lifting when pulling the casing. Piles subjected to tension or lateral forces and eccentric loading (possibly being out of position or out of plumb) require suitable reinforcement to cope with these forces. Nominal reinforcement for piles in compression only would comprise about four 12 mm diameter bars for a 400 mm diameter pile to five 16 mm diameter bars for a 550 mm diameter pile. A special cage of 5 mm steel, or hoops of flat steel, are employed as lateral ties. Bars should not be so densely packed that concrete aggregate cannot pass freely between them and hoop reinforcement is not recommended at closer than 100 mm centers. Provided the cage can be oriented, maximum steel need only be placed over that part of the pile subjected to maximum stress, and a reduced density can be used in the plane of the natural axial. For driven cast-*in-situ* concrete piles, Fleming et al. in 1985 recommended that widely spaced reinforcement bars being necessary to allow the low workability mix to penetrate to the interior of the pile. If the pile is to resist compressive forces only, the reinforcement may be restricted to the upper section.

Bowles (1988), stated that, for bored piles, the reinforcing bars may be required only in the upper region for moments that are carried by the shaft, because these moments dissipate with depth are hence the shaft load is primarily axial at about L/2. At this depth, temperature changes are not great; therefore, longitudinal and spiral reinforcements are not required.

Tomlinson and Woodward (2008), stated that reinforcement is not needed in bored piles unless uplift loads are to be carried (uplift may occur due to the swelling and shrinkage of clays). Reinforcement may also be needed in the upper part of the shaft to withstand bending moments caused by any eccentricity in the application of the load, or by bending moments transmitted from the ground beams.

DESIGN ASPECTS

Laterally loaded piles are analyzed by means of two main categories, one using Winkler modulus of subgrade reaction concept as the soil model, and the other using and elastic continuum as soil model. Each one has its advantages and disadvantages.

Matlock and Reese (1960), formulated and solved the differential equation for the deflection of the pile using a beam-on-elastic foundation approach. The soil strength is characterized using coefficient of subgrade reaction. They obtained a series of non-dimensional curves so that a user could enter the appropriate curve with the given lateral load and estimate the ground-line deflection and maximum bending moment in the pile shaft.

Broms (1965), presented methods for the calculation of lateral deflections at working load based on the concept of a coefficient of subgrade reaction. It has been assumed that the coefficient of subgrade reaction increases linearly with depth in case of cohesionless soil, and that it is constant with depth for cohesive soils.

Poulos (1971), analyzed the behavior of piles that were subjected to lateral load and moment using the continuum theory. It was found that the major factors influencing the pile behavior are the length to diameter ration, $\frac{L}{D}$, and the pile flexibility ratio, K_R, which is defined as

$$K_R = \frac{(EI)_P}{E_S \times L^4} \quad (1)$$

Where K_R is the pile flexibility ratio, E is the modulus of elasticity of the pile, I is the moment of inertia of the pile, E_S is the modulus of elasticity of soil, and L is the length of pile embedded in clay.

Randolph (1981) studied the response of flexible pile to lateral loading using finite-element method and treated the soil as an elastic continuum with a linearly varying soil modulus. It was found that the maximum bending moment induced in a free-headed pile subjected to lateral force, H, can be estimated as:

$$M_{\max} = \frac{0.1}{\rho_c} \times H \times l_c \quad (2)$$

Where $M_{\max}$ is the maximum bending moment induced, H is the lateral force, ρ_c is the factor giving relative homogeneity of soil and l_c is the critical length of the pile.

Sogge (1981), used the method of beam-on-elastic foundation to simulate a laterally loaded pile. This method gives comparable results to a solution, which idealizes the soil as an elastic continuum. A laterally loaded pile can be handled using the finite element method by modeling the pile structure with beam elements and using bars to represent the uniaxial soil resistance. The 17 bar and 16 beam elements provided an adequate division of piles of any length in order that the solution corresponds exactly to the closed form differential equation for a constant coefficient of subgrade reaction.

Pyke and Beikae (1984) presented a new analytical solution for the resistance of a horizontal slice through a pile to lateral loading. The solution assumes that a pile is surrounded by an infinite elastic medium, but it allows for the tendency of this medium to separate from the back of the pile.

Sogge (1984) applied the finite element formulation to the vertical beam-on-elastic foundation idealization of a laterally loaded pile system. He analyzed a problem consisting of a laterally loaded pile in a non-homogeneous soil using a computer program that characterizes the soil strength by a relation between soil pressure and displacement, which is represented by the coefficient of subgrade reaction. It was demonstrated that the soil strength must be described accurately in the upper third of the pile since the coefficient of subgrade reaction values below this depth have little influence on pile behavior. It was also stated that the springs need only to be placed on one side of the pile since a net resistance value, passive minus active type, of resistance is used.

Davies and Budhu (1986) compared between the deflection and maximum bending moment obtained from both elastic continuum approach and Winkler model (using p - y idealization) with those obtained from a series of field tests, conducted by Reese et al. (1975) on laterally loaded pipe piles embedded in heavily over-consolidated clay. The load deflection prediction of both models is very encouraging for large diameter pile. In the other hand, for maximum bending moment, the Winkler model gives closer and more accurate results than those of elastic continuum. In general, Davies and Budhu stated that the load-deflection and bending moment for the two theories are in a good agreement with the results of full-scale tests on laterally loaded piles.

Verruijt and Kooijman (1989) presented a numerical model for a laterally loaded pile in a horizontally layered elastic continuum, and obtained a quasi-three-dimensional analysis. They combined the finite-element and finite-difference methods with a relatively simple and compacted method of analysis. A comparison between their solution and the solutions obtained by Poulos (1971) and the sub grade theory showed a good agreement for intermediate and large values of flexibility ratio. In general, the values of sub grade theory are somewhat larger than those obtained by Poulos; the agreement is good over the entire range of flexibility factors.

THEORETICAL APPROACHES FOR DETERMINATION OF K_h

Many theoretical approaches were used to determine the values and variations of horizontal subgrade reactions, K_h. However, some of these studies are given.

Palmer and Thompson (1948) suggested the following expression for the variation of K_h with depth:

$$K_h = \left(\frac{Z}{L}\right)^n K_L \quad (3)$$

Where K_h is the horizontal modulus of subgrade reaction, Z is any depth along the pile, L is the pile embedded length, K_L is the value of K_h at the pile base ($Z = L$) and n is an empirical index equal to or greater than zero.

The most common assumptions are that (n = 0) for clay where the modulus is constant with depth and (n = 1) for granular soils where the modulus increases linearly with depth. For the case (n = 1), it is convenient to express the variation of K_h as:

$$K_h = \frac{Z}{B} n_h \quad (4)$$

where B is the diameter or width of the pile, and n_h is an empirical value ranging from (271.5-542.9) kN/m^3 for soft normally consolidated clay.

Glick (1948), proposed the following equation to find K_h :

$$K_h = \frac{22.4 E_S (1-\nu_S)}{(1+\nu_S)(3-4\nu_S)\left[2\ln\left(2L/B\right)-0.443\right]} \quad (5)$$

Where E_S is the soil modulus of elasticity, and ν_S is the soil Poisson's ratio.

Alizadeh and Davisson (1970), analyzed the results of the field tests on laterally loaded piles by means of the theoretical expression presented by Matlock and Reese (1960). This expression is based on the triangular distribution of horizontal subgrade modulus, K_h , with depth, in which:

$$K_h = n_h Z \quad (6)$$

For design purposes, n_h should be selected compatible with the anticipated deflections.

Sogge (1981), proposed the following simple relationship to obtain a range of n_h values for shallow piles is:

$$K_h = (2 \text{ to } 30)\frac{Z}{B} \text{ in kcf} \qquad (\text{kcf} = 159 \text{ kN/m}^3) \quad (7)$$

Bowles (1996), gave the most general form for either horizontal or vertical modulus of subgrade reaction, which is:

$$K_S = A_S + B_S Z^n \quad (8)$$

Where A_S is a constant for either horizontal or vertical members, B_S is a coefficient for depth, and n is an exponent to give K_S the best.

At the ground surface, As is zero for horizontal K_s, but at any small depth As will be greater than zero. For footing and mats, A_s > 0 and B_s ≈ 0. This means that K_s is considered constant because the depth of influen-ced zone is small compared to piles.

THE COMPUTER PROGRAM

If the pile is not designed for buckling, then the main causes of tensile stresses in a pile section are the lateral loads and/or bending moments, that is, the reinforcement should be provided for all sections subjected to tensile stress. For this reason, a computer program (PLRN) is modified from that given in Bowles (1988), to check the depth through which the reinforcement will only be required to cover the tension zone of the pile. PLRN program is coded in Fortran-77 language and based on Winkler foundation model where the pile is treated as beam element and the uniaxial soil resistance is represented by independent springs.

PROBLEM DESCRIPTION AND MODELING

The basic parameters that are used in this study are as follows:

For pile

$M = 0.1 \times B \times Q_a$ (*kN.m*)

$H = 0.1 \times Q_a$ (*kN*)

$Q_a = 100$ *kN*

$L = 25.0\,m$

$B = 1.0\,m$ (for bored piles)

$B = 0.5\,m$ (for driven piles)

For Soil

$\gamma = 15$ *kN/m*^{3}

$\phi = 5^\circ$

$c_u = 80$ *kN/m*^{2}

Bored piles are usually constructed with larger diameters compared to driven piles. Therefore, for a constant depth, the depth ratio in bored piles will be smaller than that in driven piles. This paper does not deal with the effect of construction of the pile on its behavior, but when the pile is loaded laterally, its behavior will depend on whether it has large diameter (bored) or small (driven).

ANALYSES AND DISCUSSION

The effect of different parameters on the stress distribution and, hence, on the extend of reinforcement below the ground surface are presented in this section.

Effect of pile type

Figure 2 presents a relationship between the minimum bending stress (tension or compression) within the pile sections under the general working load and the depth ratio for both bored and driven piles embedded in clay.

The pile will no longer be subjected to tensile stress and, therefore, it will act as a compression member. The variation in the stress distribution along the pile shaft is due to the change in the distribution of bending moment along the shaft. The tensile stresses in bored piles are smaller than in driven piles because the diameters and hence, the moments of inertia of the pile section are greater which lead to decrease in the stresses.

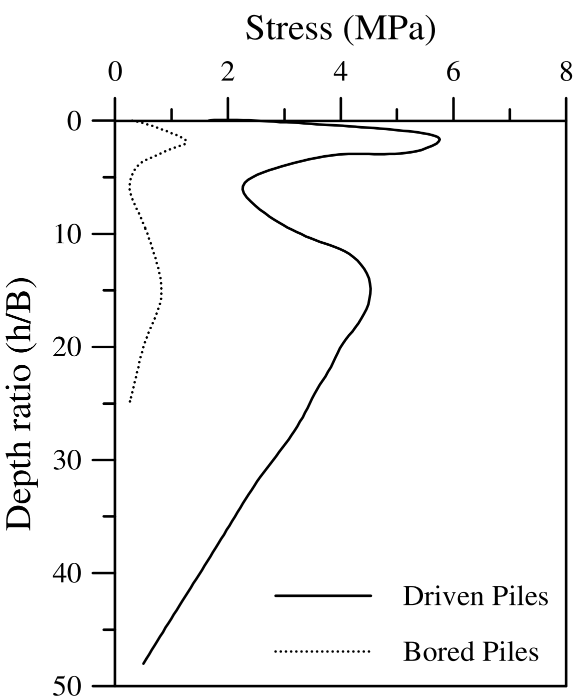

Figure 2. Stress distribution for driven and bored pile embedded in clay.

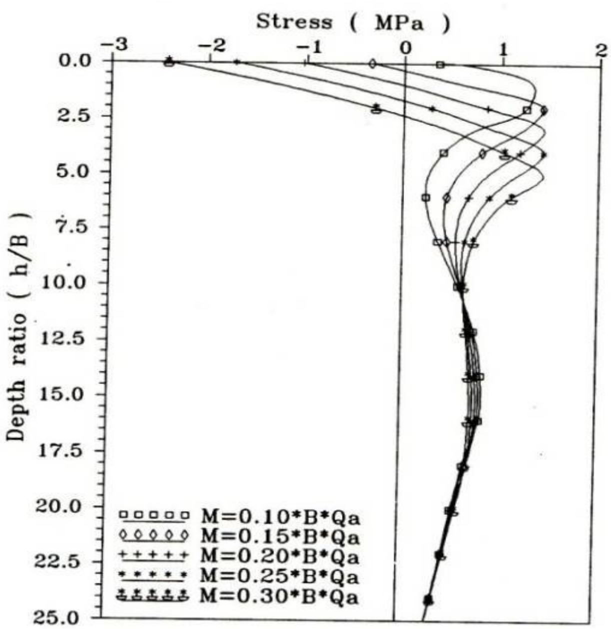

Figure 3. Effect of moment loading on the stress distribution along the shaft of bored pile.

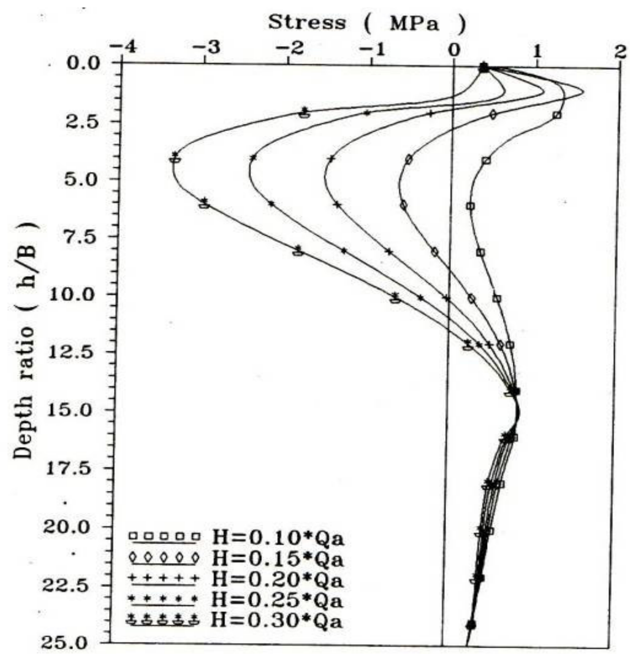

Figure 4. Effect of lateral loading on the stress distribution along the shaft of bored pile.

Bored piles

Effect of moment loading

Figure 3 shows the effect of moment loading on the stress distribution along the shaft of bored piles embedded in clay. The tensile stress will appear only in the top of the pile shaft, due to the applied moment up to a certain depth after which stresses will be changed to compression. The tensile stresses will reach a maximum with the maximum applied bending moment. At a depth ratio of about 2.5, stresses will be zero and then stresses will be changed to compression with depth. Therefore, the pile is expected to need reinforcement only to this depth.

Effect of lateral loading

Figure 4 presents the effect of lateral loading on the stress distribution along the bored pile in clay. The tensile stress will decrease as the applied lateral load increases and, therefore, the depth of zero tensile stress will increase too. In general, the maximum tensile stress will be approximately at depth ratio between 4 to 6 for a lateral load of 30 to 10% of the applied load, respectively. The zero tensile stress takes place at about at depth ratio of about 11.5 for a lateral load of 30% of the applied load. The effect of applied moment vanishes at a depth ratio of about 10 while this depth is about 15 for lateral load.

Effect of pile length

Figure 5 shows the effect of bored pile length on the stress distribution. It is obvious that if the pile increases in

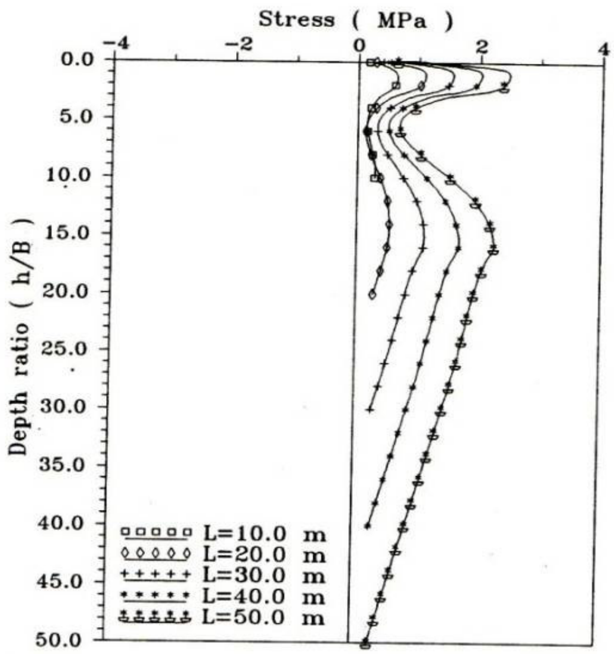

Figure 5. Effect of pile length on the stress distribution along the shaft of bored pile.

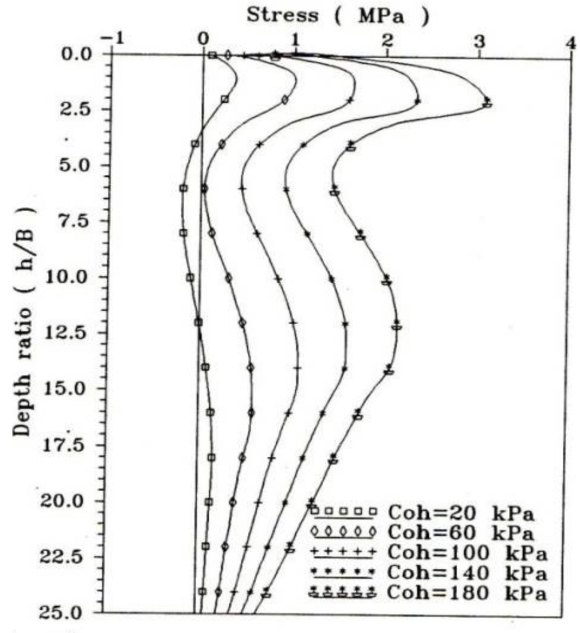

Figure 7. Effect of soil cohesion on the stress distribution along the shaft of bored pile.

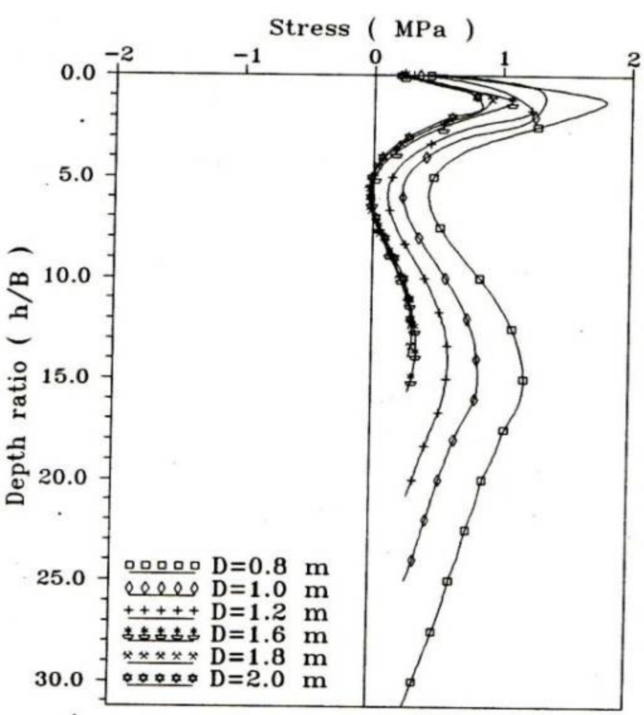

Figure 6. Effect of diameter on the stress distribution along the shaft of bored pile.

length, the compression stresses will increase and, therefore, the pile will not be subjected to any tensile stress.

Effect of pile diameter

Figure 6 shows the effect of pile diameter on the stress distribution along the pile shaft. The minimum stress will decrease in value as the pile increases in diameter and the maximum tensile stress was obtained at diameters of 1.8 and 2.0 m with a depth ratio of about 6. This may be related to the high moment applied at the pile top. Zero stresses for these two diameters will be at depth ratio of approximately 7. When the pile diameter increases, the moment of inertia of its section will increase which causes reduction in stresses.

Effect of soil cohesion

Figure 7 shows the effect of soil cohesion on the stress distribution along the pile shaft. The cohesion has a significant effect on the stress curves. Compression stresses will increase as the soil cohesion increases due to the increase in soil stiffness. For soft soil, with low cohesion, the pile will be subjected to a tensile stress at a depth ratio of about 6 and at a depth ratio of 12, stresses will be zero then after this depth ratio, stresses change to compression.

Driven piles

Effect of moment loading

Figure 8 shows the effect of moment loading on the

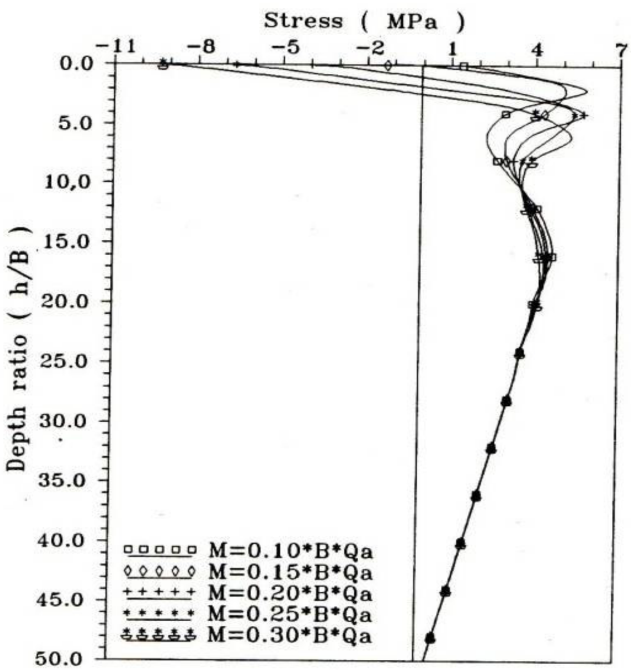

Figure 8. Effect of moment loading on the stress distribution along the shaft of driven pile.

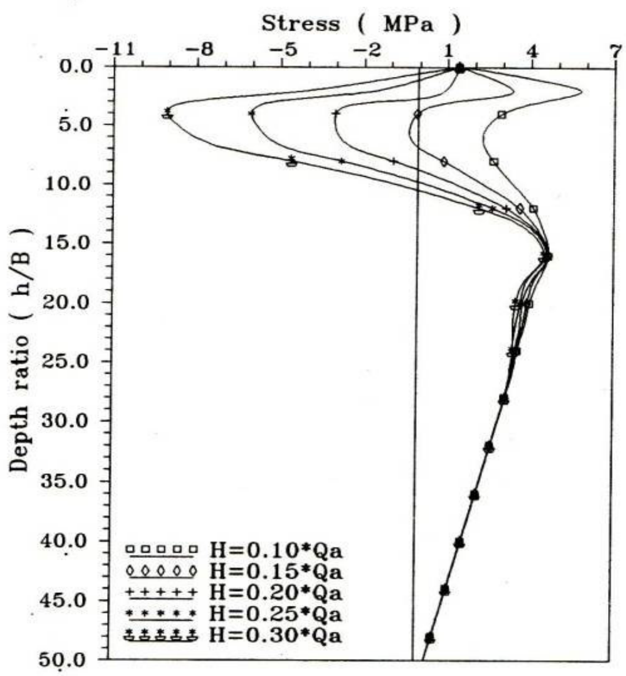

Figure 9. Effect of lateral loading on the stress distribution along the shaft of driven pile.

stress distribution along the shaft of driven piles embedded in clay. The applied moment has no effect on the stress distribution below a certain depth and the performance is somehow similar to that of bored piles, but with greater tensile stresses up to less depth. The zero stress will be at a depth ratio of about 2 associated with the maximum moment loading from 30% of the applied load.

Effect of lateral loading

Figure 9 represents the effect of lateral loading on the stress distribution along the driven pile in clay. Similar to that of bored pile, the stress will decrease as the applied lateral load increases and the maximum tensile stresses will occur at a depth ratio between 4 to 6. The maximum depth of zero tensile stress will correspond to the maximum applied lateral and it will be at depth ratio of about 10.

Effect of pile length

Figure 10 shows the effect of driven pile length on the stress distribution. Similar to the performance of bored pile, the increase in pile stress, as the length increases, may be related to the increase in pile capacity and decrease in resulting moment.

Effect of pile diameter

Figure 11 shows the effect of pile diameter on the stress distribution along the pile shaft. As the pile increases in diameter, the resulting moment will decrease and, hence, the stress distribution will increase.

Effect of soil cohesion

Figure 12 shows the effect of soil cohesion on the stress distribution along the pile shaft. The stress increases with the increase in soil cohesion, which is similar to that of bored pile. The intersection between stresses at the pile tip can be related to the increase in soil cohesion, which decreases the pile capacity, decreases the adhesion factor.

It is obvious, from the results that the pile diameter and the soil cohesion have a significant effect on the stress distribution along the pile shaft and, subsequently, on the extent of reinforcement below the ground surface, this is similar to that stated by Derrington (1966). From the above, it is seen that; the depth of the necessary reinforcing bars in case of bored piles embedded in clay is more or less equal to that recommended by Bowles (1988), and this will be reduced for other cases.

Conclusions

A beam -on- elastic foundation model was used to

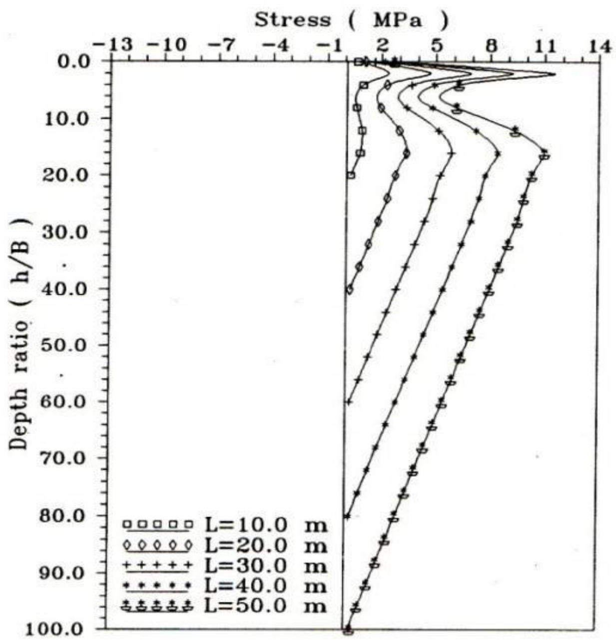

Figure 10. Effect of pile length on the stress distribution along the shaft of driven pile.

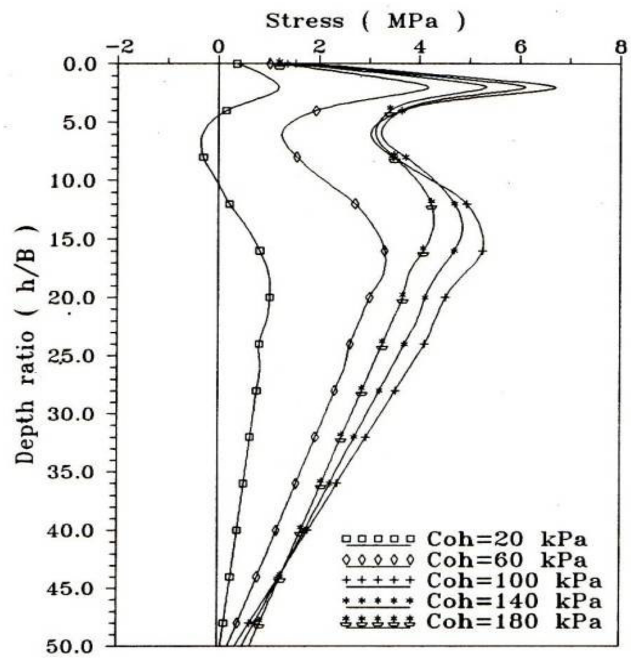

Figure 12. Effect of soil cohesion on the stress distribution along the shaft of driven pile.

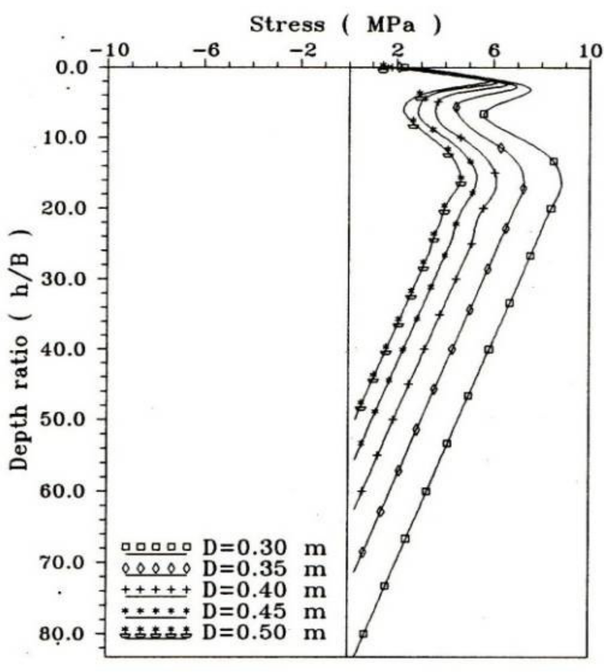

Figure 11. Effect of diameter on the stress distribution along the shaft of driven pile.

analyze a loaded pile in order to investigate the need and necessity for reinforcement. This model is performed using the finite element method as a numerical tool for the analysis. The pile is discretized into a number of elements while the soil is represented by a number of springs. The stiffness of these springs is considered to be variable with depth. Based on the results obtained, the following conclusions can be drawn:

(a) Concrete piles are of two types, precast and cast-*in-situ*. The first one must be fully reinforced to resist the stresses caused in handling, pitching, transporting, and driving. Whereas cast-*in-situ* concrete piles are divided into bored and driven. Generally, bored piles need greater depths for the reinforcement than driven piles.
(b) For cast-*in-situ* bored or driven piles, the codes did not recommend a specific depth for the reinforcing bars that should be provided to resist the tensile stresses. This issue is left to the designer.
(c) The reinforcement required for bored piles placed in clay depends mainly on the strength of the soil. For stiff clay, the length of the reinforcement may be reduced to the top quarter only to provide anchorage with the pile cap. While in soft soil, this length may be exceeded to cover more than one-half of the pile length. In case of driven piles, the required reinforcement may be extended to only 25% of its length in all types of clay.
(d) For bored piles in soft clay, the pile will not be subjected to tensile stresses below a depth ratio of 12, accordingly reinforcement is not needed below this depth.
(e) For bored piles, the depth of zero moment in soft clay is greater than that of medium or stiff. This depth will be less than one-half the pile length.
(f) The depth of zero tensile stress in clay generally occurs at one - half the pile length, except for 2.0 m

diameter pile embedded in clay in which it occurs at 56% of the pile length.
(g) Driven piles in clay need a depth of reinforcement to be extended to 10 diameters to resist the tensile stresses, while it does not need any reinforcement at a depth of 19 diameters because the zero moment will start at that depth.
(h) For driven piles in clay, the depth of zero tensile stress is not less than 0.2 times the pile length.
(i) The depth of zero moment for driven piles embedded in clay will generally not exceed one-third the pile length except for very soft soil in which it may exceed three-quarters the pile length.

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