Investigation of rigid pile behaviour under lateral forces

Etude du comportement de pieux rigide sous pression latérale

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ABSTRACT: Regarding the vast usage of deep foundations for transferring loads of various types of structures, the behavior of rigid piles have been investigated by numerical methods. Soil has been considered as both linear and non-linear, and , by analysing various models, the condition of rigidity of piles, the distance of the centre of rotation of rigid piles from ground level and the distribution of shear forces and bending moments along the piles have been studied.

1 INTRODUCTION

Deep foundations are used for transferring heavy load structures, such as high rise buildings, bridges or where soft layer of soils exist near the ground surface. Regarding the geometric characteristics, loading and boundarly conditions, a group of piles are usually loaded by axial or lateral pressures. The later mainly occurs in the category of vertical and thick piles laying under lateral load. In the past, the analysis of piles under lateral pressures was often done by assuming a flexible beam on elastic foundation, whilst, depending upon the geometric charactristics of piles and soil mechanics behavior, in some cases the flexibility theory is not justified and the analysis had to be carried out by the assumption of rigidity. In the present paper, displacement of sections and distribution of internal forces were studied upon the range of application of rigidity assumptions.

2-METHOD OF ANALYSIS AND PROPOSED MODELS

For the purpose of realistic studies the analysis has been carried out in both linear and nonlinear cases. In the linear analysis, the elastic soil environment is displaced through a set of separate elastic springs nearby, so that the rigidity of springs is determined

proportional to the modulus of lateral soil reaction, such modulus changes have been considered for the preconsolidated cohesive soils relative to the depth which is constant. For granular soils a linear variation is considered. In the nonlinear analysis a computer program was prepared under the title "NALLP", in which, some nonlinear springs and the P-Y curve for pile through soil was used to represent the reaction of soil. Each curve indicates the soil behavior in a specified depth that the combination of such curves along with the pile shows the full soil behavior. With regards to the studies made on the P-Y curves and since these curves are resulted from the combination of theoretical analysis and laboratory experiments, their applications in the pile behavior analysis give nearly factual results.

Considering the applicability of the studies and to investigate the behavior further, various models of piles with six different lengths (6 to 14m) and 3 different diameters (1 to 2 m) have been examined.

Also to develope further investigations, two types of granular and cohesive soils, each in three states of loose, medium and dense (Table1) were selected.

Table 1. Characteristics of Cohesive soil

Type of soil	γ (KN/m^3)	$Cu\ (\frac{KN}{m^2})$	E(MPa)	ε	ν	$K_m\ \frac{MN}{m^3}$ for Φ=1,1.5, 2000
Soft	19	22.1	4.38	0.0107	0.48	3.6, 2.45, 1.86
Medium	19.7	42.3	9.78	0.0094	0.47	6.68, 4.41, 3.33
Hard	20.4	258	37.92	0.0094	0.44	36.3, 24.1, 17.6

Table2. Characteristics of granular soil

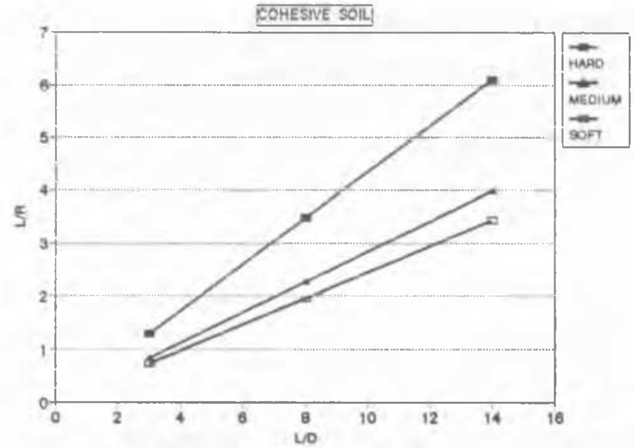
Type of soil	Φ	γ (KN/m^3)	k_h (MN/m^3)
Loose	29°	15.9	5.2
Medium	32°	18.25	16
Dense	38°	21	33.3

3 DISCUSSION OF RESULTS:

Following the linear and nonlinear analysis of different models in various types of soils; the following results were obtained:

3-1. Determination of the range of rigidity of piles:

A rigid pile under lateral forces is displaced so that the displacement line depends on the end conditions of pile and the type of adjacent soil. The effective factors in the pile behavior consists of: geometric characteristics (length and diameter), quality of the pile and the characteristics of the adjacent soil. Usually by increasing the diameter and the elastic modulus of the pile or by decreasing the length of the pile and the modulus of lateral reaction of soil, the pile behavior is inclined towards a rigid state. In this study, various models of piles with different diameters in various types of soils were investigated and their displacement curves were studied (Fig.1). If the relative stiffness coefficient of a pile for cohesive and non-cohesive soil is defined as: T and R, $R=\sqrt[4]{\frac{EI}{k}}$, $T=\sqrt[5]{\frac{EI}{n_h}}$ the condition of rigidity (equal slope through length) for various models will result only when the $\frac{L}{R}$ or $\frac{L}{T}$ becomes less than 1.75.



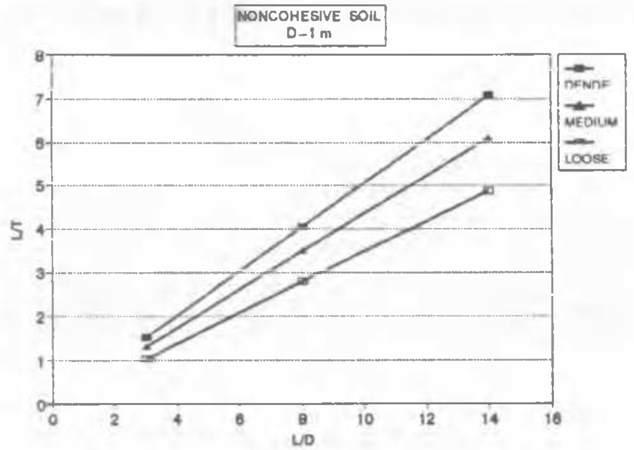
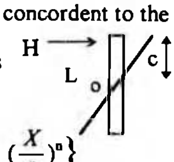


Fig. 1 Range of Rigidity for Piles in cohesive and noncohesive soils

3-2. Distance of rotating center of rigid piles from ground surface:

If a rigid pile is loaded by a lateral point load of "H", assuming the changes of modulus of reaction of soil concordent to the relation $K=K_{max}\left\{\frac{X}{L}\right\}^n$, the relation of changes of lateral reaction of soil may be defined as:



$$P=B\left\{(n+1)(n+2)(n+3)\left(\frac{X}{L}\right)^{n+1}-(n+1)(n+2)^2\left(\frac{X}{L}\right)^n\right\}$$

According to the definition, the center of rotation is a point where the reaction of soil is equal to zero. As a result, the following relation for the center of rotation, assuming p=0, is defined:

$$\frac{C}{L}=\frac{n+2}{n+3}$$

The magnitude of n is changed upon the quality of soil between zero, (the state of consolidated cohesive soils) and 1.5, (noncohesive soils). As it is observed, the distance of rotating center of pile to the ground surface in the noncohesive soils is more than the state of cohesive soils. Using the results of linear and nonlinear analysis of 22 models, a relation has been represented for such a distance as below:

$$\frac{C}{L}=0.9004-0.0186\frac{L}{D}.$$

With regard to the geometric characteristics of the piles, the ratio $\frac{C}{L}$ is changed between 0.756 to 0.856. In noncohesive soils the results of the linear and nonlinear analysis give a relation $\frac{C}{L}$ between 0.742 to 0.75

3-3. Distribution of shear force and bending moment along the rigid piles:

In figures 2 and 3 the distribution of shear force for the linear and nonlinear analysis of models with fixed and free ends have been described. The maximum shear force in both states is exerted at the head of pile. The distribution of shear force in the linear analysis state in cohesive soils as a result of fixed end conditions is nearly linear and decreases by increasing the depth (assuming soil reaction is constant). The amount of shear force from the nonlinear analysis for both free end and fixed end states is more than the linear analysis results. The deficiency is of much consideration, especially for the soft cohesive soils, due to nonlinear behavior of the pile.

Also, contrary to the linear analysis results, the distribution of shear force in the nonlinear analysis state is not independent from the type of soil, and the magnitude of this force in the case of soft cohesive state is more than the dense cohesive soil state.

In the state of non cohesive soils and within the limits of ordinary loads the distribution of shear force related to both linear and nonlinear states is similar to the second degree curve and is independent from the type of soil.

In figures 4 and 5 the changes of bending moment along the pile out of the linear and nonlinear analysis have been shown in cohesive and noncohesive soils and for free and fixed end states.

In the state of the piles placed in the cohesive soil, the maximum bending moment, for the free end state, occurs at a distance 0.33L upto 0.4L from the ground surface. The fixed end pile causes significant bending moments at the top of the pile and the maximum negative moments of about 2.5 to 3 times the maximum positive bending moment.

In figure 6 the results of the linear and nonlinear analysis for the piles located in soft cohesive soils have been compared to each other. Upon these results the amount of bending moments obtained from nonlinear analysis are more than the moments of linear analysis.

In the case of the piles placed in noncohesive soil, the maximum positive bending moment is formed at an approximate depth of 0.42L and in the case of fixed end piles the maximum negative bending moment is 2 to 2.5 times more than the maximum positive bending moment.

3-4. Study of other factors on the behavior of rigid piles:

The effect of soil type.

The behavior of the pile under the lateral load may be defined by the load-displacement diagram. To do this, pile models have been analyzed in two cohesive and noncohesive types of soil, the results of which have been ploted in fig. 7. The ratio $\frac{L}{R}$, for three types of cohesive soft, medium and rigid soils being 0.73, 0.85 and 1.3 respectively and the ratio of $\frac{L}{T}$ for three types of noncohesive loose, medium and dense soils being 1.2, 1.5 and 1.74 respectively. Upon these results, the relation between load and displacement for the three types of cohesive soil upto about 20 tons, 30 tons, and 100 tons is linear respectively. For the non-cohesive soil the corresponding loads are 40, 50 and 70 tons respectively. It is implied that as the soil becoming softer, the load-displacement curve becomes non-linear sooner and the slope of the curve decreases. In similar conditions the behavior of the pile tends to a rigid state where the soil is looser and with increasing the $\frac{L}{R}$ and $\frac{L}{T}$, the pile will behave non-linear in a higher load.

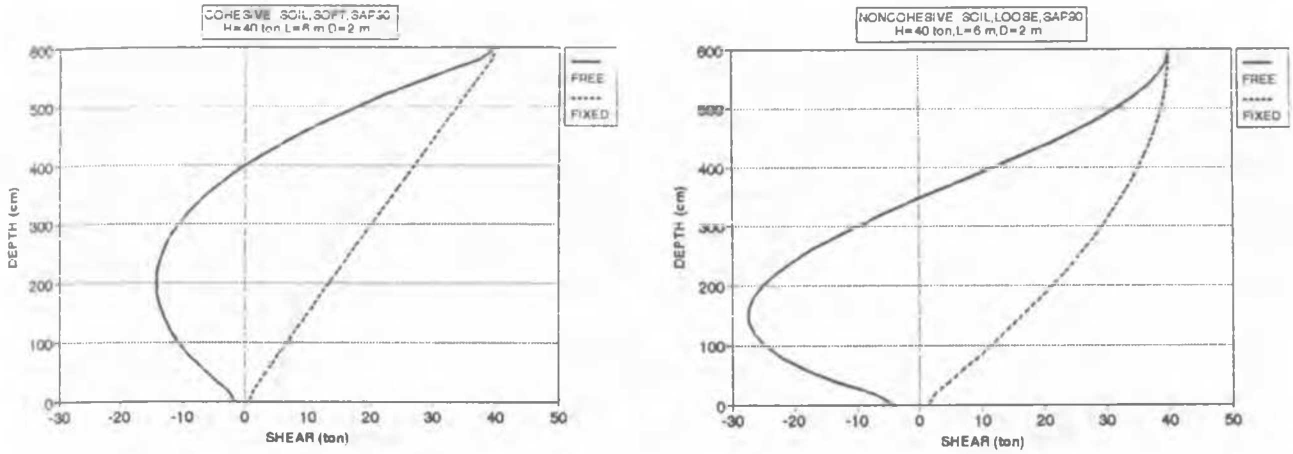


Fig. 2.1 Distribution of shear force along the pile (Linear analysis)

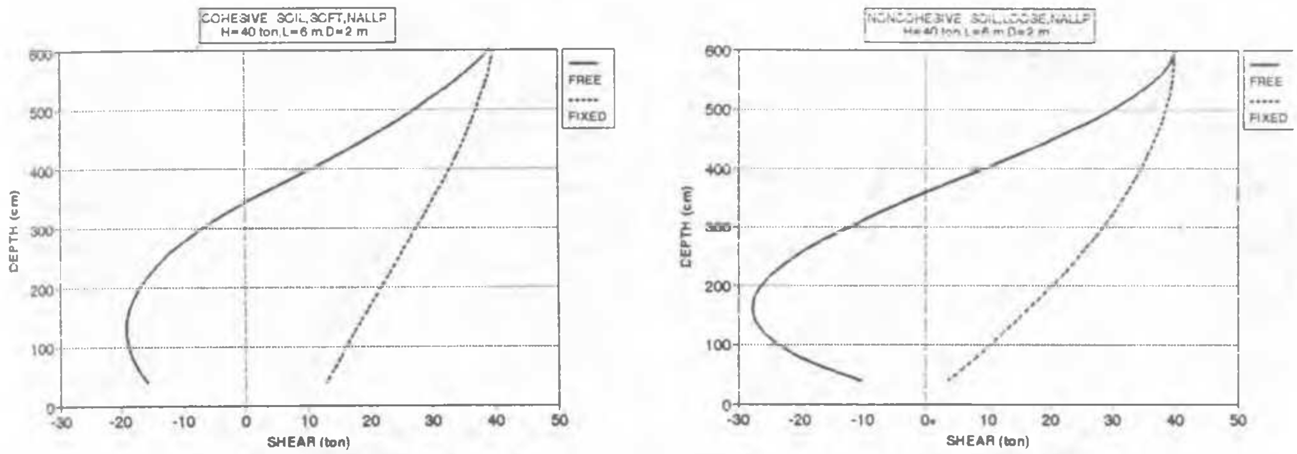


Fig. 2.2. Distribution of shear force along the pile (Non linear analysis)

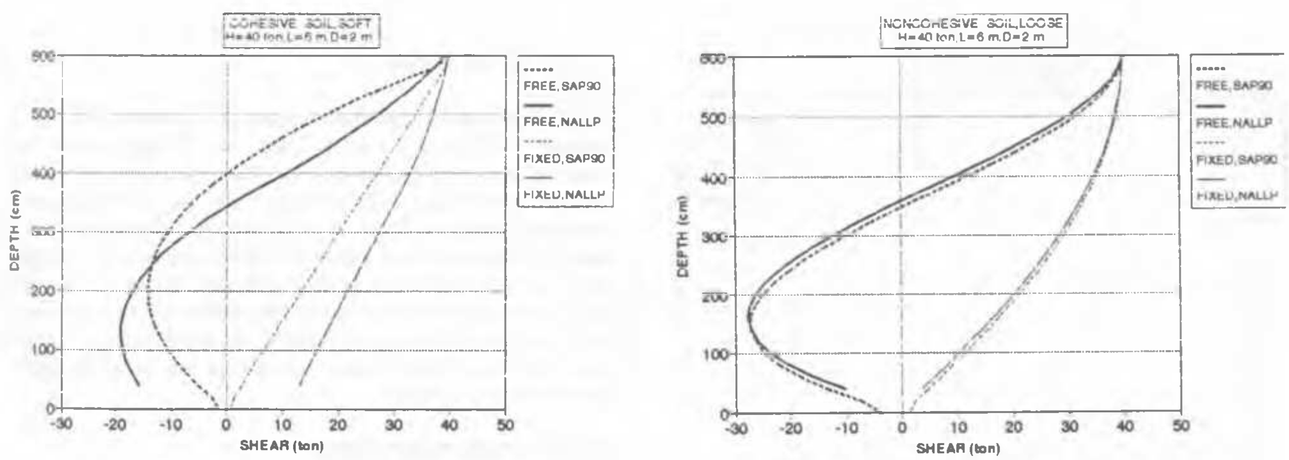


Fig. 3. Comparison of distribution ofshear forces along the pile
(Linear and non linear analysis)

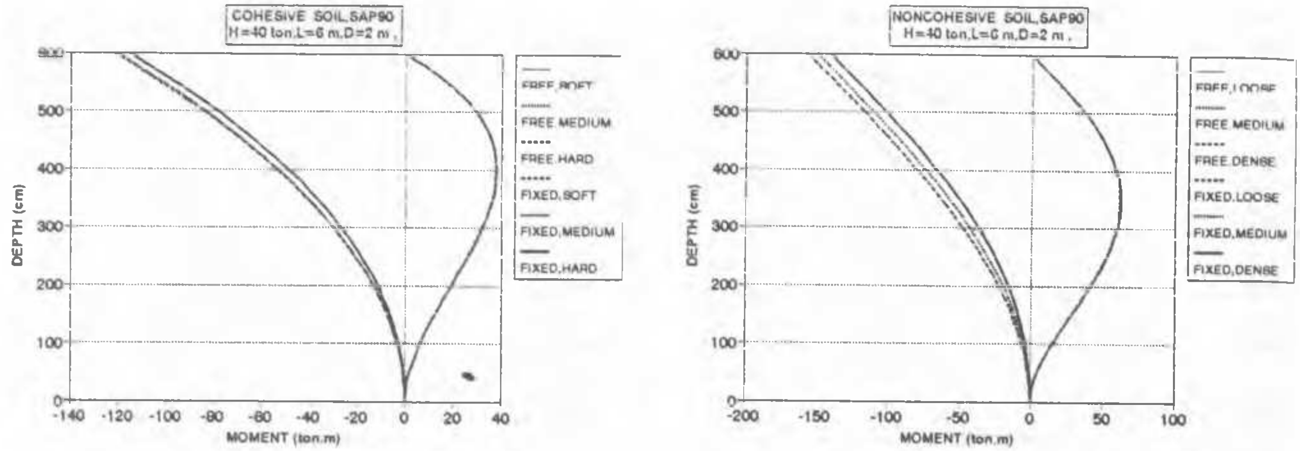


Fig. 4. Distribution of bending moment along the pile (Linear analysis)

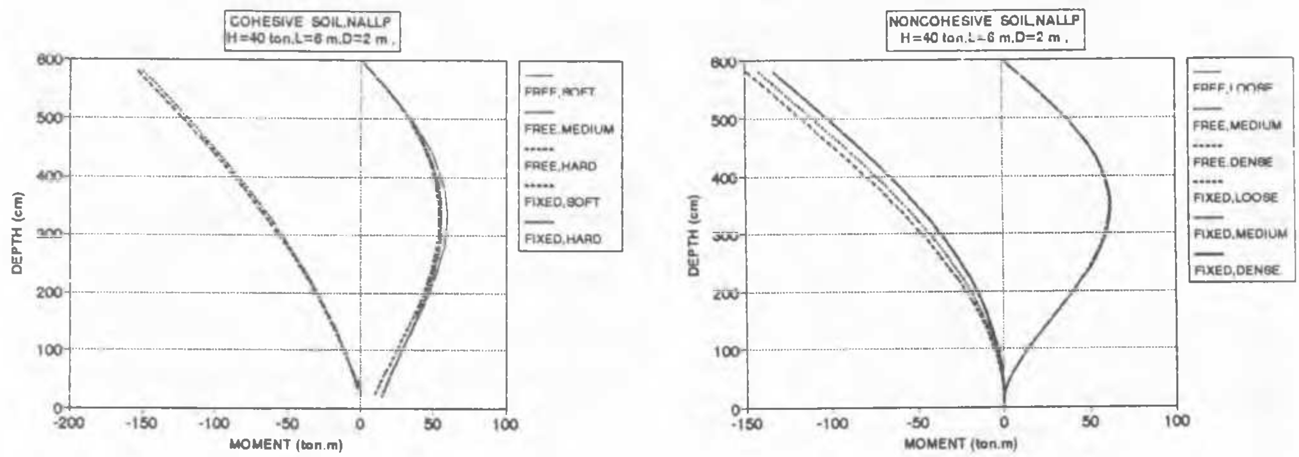


Fig. 5. Distribution of bending moment along the pile (Non linear analysis)

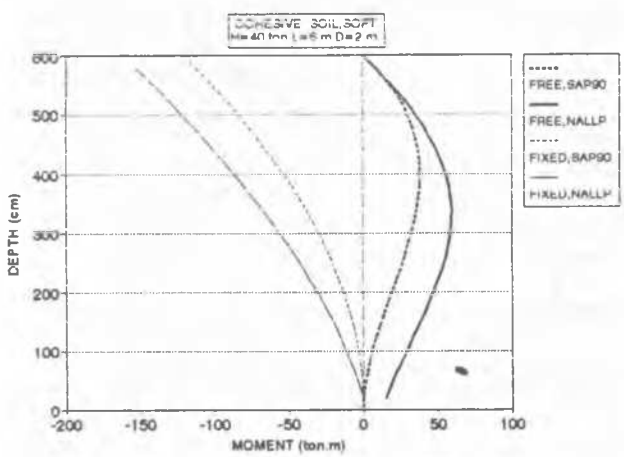


Fig. 6. Comparison of disribution of bending moments along the plie (Linear and non linear analysis)

The effect of pile length.

Figure 8 shows the load-displacement curves for the piles with a diameter of 2m, and 6,8,10,12,and 14m length within two cohesive and non-cohesive soils. These plots which are the results of non-linear analysis, show that the pile displacement within the allowable load limit, is inversly proportional to its length. In the case of noncohesive soils the displacement of rigid pile is inversly proportional to the second power of the pile length. It is therefore, concluded that the behaviour of the pile in non cohesive soils is more affected by the length than in cohesive soils, and in a limited range, increase in length is resulted in decrease in displecement.

The effect of pile head condition.

To investigate the effects of head pile conditions on the amount of lateral displacement of pile in different soils, various models of piles with fixed and free ends and different lateral loads have been analyzed, a sample of which has been represented in figure 9. Upon these results, the effect of degree of fixing of head pile depends on the load exerted, and comes into a nonlinear state by

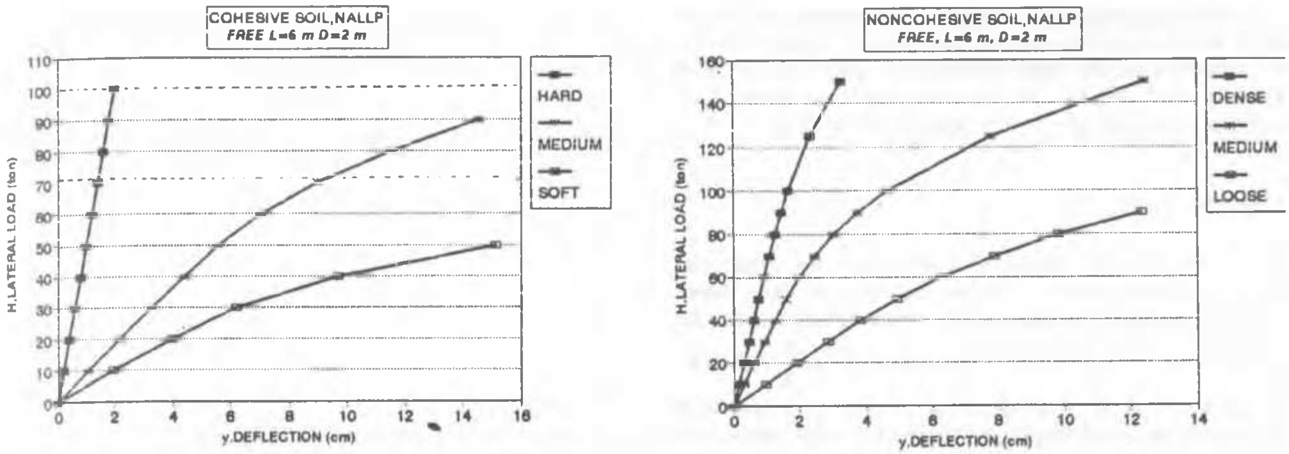


Fig.7. Load-displacement diagram of curves for piles (Non linear analysis)

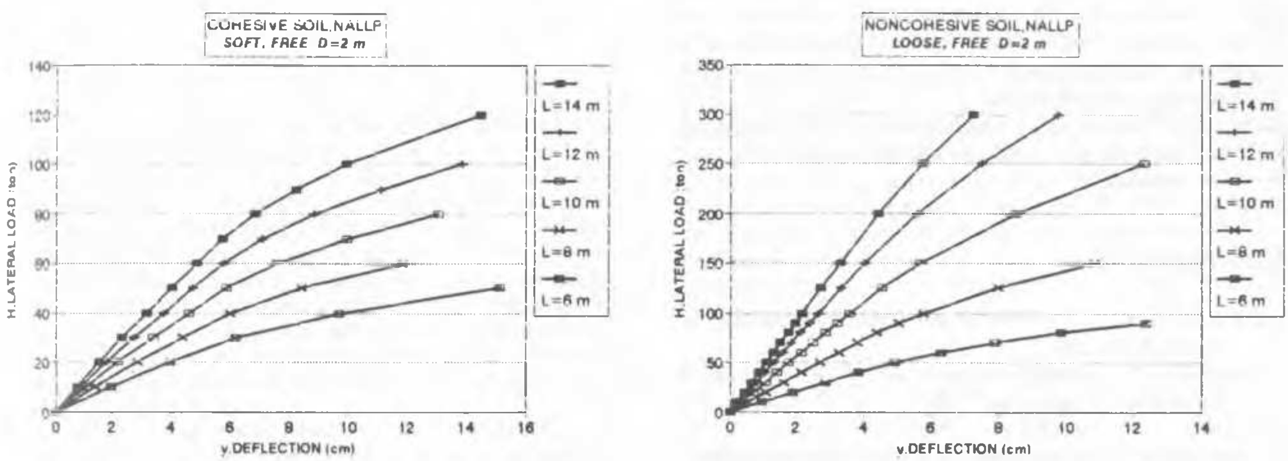


Fig. 8. The effect of pile length (Non linear analysis)

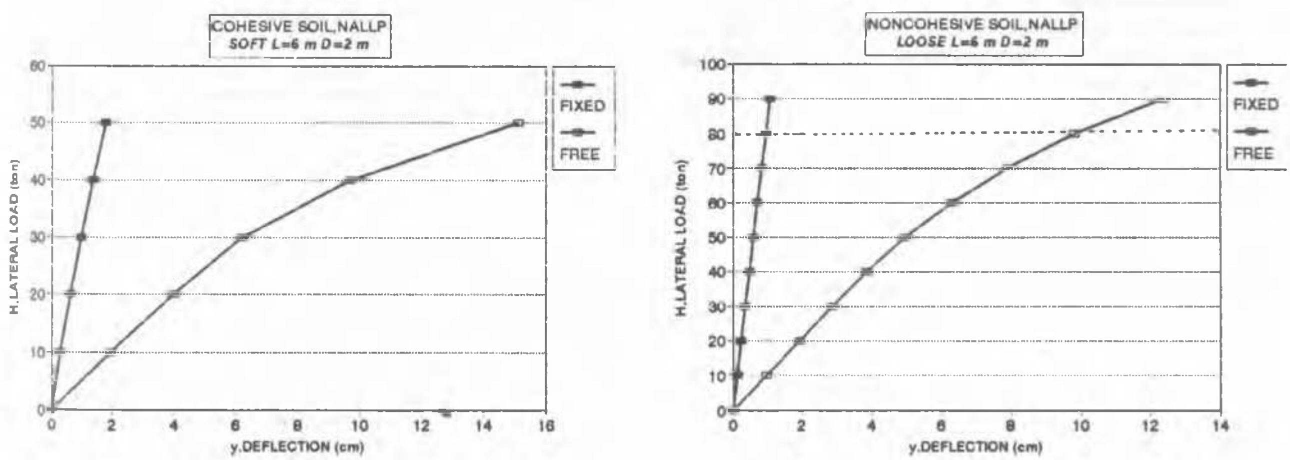


Fig. 9. The effect of pile head condition (Non linear Analysis)

increasing the magnitude of loading of surrounding soil and the effect of fixing conditions of the head pile will be more reative to the reduction of the lateral displacement. Also, the effect of fixing of head pile to the reduction of lateral displacement and the behavior of rigid piles is more than the flexible piles.

4. CONCLUSION:

In the present paper, the behavior of laterally loaded rigid piles have been investigated in the linear and nonlinear states. Based upon the analysis of various models, the condition of rigidity for these models will be less than 1.75 at a limit of $\frac{L}{R}$ or $\frac{L}{T}$. Secondly, the location of the rotating center of rigid piles have been investigated and with regard to the relations stated, the ratio of $\frac{C}{L}$ for different soils are attained between 0.74 to 0.86. In the state of internal forces of rigid piles the results of nonlinear analysis firstly represent some magnitudes more than the linear analysis, and secondly the amount of shear at the head pile is always maximum. In the state of fixed end piles, the amount of negative bending moment at the head pile is between 2 to 3 times the maximum positive moments.

Finally, the effect of type of soils, length of piles, the support conditions of head piles, and the load-displacement diagrams have been presented.

5-REFRENSES

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