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Time-dependent lateral response of pile embedded in elasto-plastic soil

J. M. ABBAS[1], Z. H. CHIK[1], M. R. TAHA[1], Q. S. M. SHAFIQU[2]

1. Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi 43600, Selangor, Malaysia;
2. Department of Civil Engineering, Nahrain University, AI-Jadrea 10072, Baghdad, Iraq

Abstract: A two-dimensional (2D) finite element analysis was carried out to assess the time-dependent behavior of single vertical pile embedded in elasto-plastic soil. The finite element analyses were carried out using the linear elastic model for the structure of the pile, while the Mohr-Coulomb model was used for representing the soil behavior surrounding the pile. The study includes cohesionless and cohesive soil to assess the lateral response of pile in the two types of soil. The whole geotechnical model is suitable for problem of piles to determine the design quantities such as lateral deformation, lateral soil stress and its variation with time. The model is verified based on the results of published cases and there is good comparison between the results of published case and the present simulation model. It is found that, the pile in cohesionless soil has more resistance in the rapid loading and less one in the long term loading. On the other hand, the pile in cohesive soil shows opposite behavior.

Key words: single pile; consolidation effect; lateral response; soil pressure; 2D finite element method

1 Introduction

Pile foundations are usually used to support lateral loading as well as axial loading. One source of lateral load results from the super structure itself, for example, pile support offshore structure, transmission tower and bridge piers in addition to abutment of pile foundation which is usually designed to support lateral loadings in these types of loading applying for long time. On the other hand, the lateral load maybe results from the nature, for example, earth quick, wind pressure, and soil movement.

Time-dependent behavior of vertical piles has received little attention by the researchers in the geotechnical engineering fields. This is mainly due to the complexity of the problem and the difficulties when solving the problem analytically or experimentally. In addition, the comparison of the lateral response of piles embedded in cohesionless and cohesive soil is little in case of time-dependent performance.

TAIEBAT and CARTER [1] indicated that the equations of a non-linear consolidating soil are complex. In order to solve problems of any complexity it is usually necessary to resort to a numerical approach such as the finite element method. An efficient formulation was developed based on semi-analytical finite element method and applied to the laterally loaded pile problem which was also studied by CARTER and BOOKER [2]. For cases where the load is applied rapidly and then maintained, the lateral displacement at the end of consolidation is greater than the displacement predicted by assuming fully drained conditions.

For lateral loading at pile, there are three methods of analyses which can be categorized into [3]: (1) beam on elastic foundation method-subgrade reaction; (2) elastic continuum method and (3) the finite element method. Because the finite element method is a sufficient procedure to solve such a problem, many finite element investigations available to obtain the response of laterally loaded piles, the finite element method has been proposed and implemented to perform a numerical analysis of the soil-pile system and was developed previously by POULOS and DAVIS [3], MUQTADIR and DESAI [4], TROCHANIS et al [5], YANG and JEREMIC [6], KARTHIGEYAN et al [7−8] and ZHAO et al [9].

Based on the previous studies, there is little knowledge on the finite element technique of time-dependent behavior of laterally loaded and compared the results assessment when the piles are embedded in two types soils. Also TAIEBAT and CARTER [1] reported that there were no solutions for laterally loaded pile foundations in consolidating elasto-plastic soil. Therefore, this work presents a numerical simulation based on the 2D finite element approach to assess time-

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Corresponding author: J. M. ABBAS, PhD; Tel: +60−1−76384641; E-mail: jasimalshamary@yahoo.com

dependent effect on the lateral behavior of pile in elasto-plastic soil, and undertakes the influence of soil type, pile slenderness ratio and load intensity on the lateral response of pile.

2 Numerical simulation and constitutive models

2.1 Finite element based numerical model

To assess all numerical analysis the finite element program, which has the feature of modeling two-dimensional (plane strain and axisymmetric) geotechnical problems such as consolidation is used. It is primarily based on the programs presented by SMITH and GRIFFITHS [10] for the analysis of one and two-dimensional solid by finite element method which is modified to achieved the purpose of this work which mainly includes the consolidation effect on the lateral pile response subjected to lateral loads. The program includes the transient formulation of BIOT's equation [11] and Mohr-Coulomb model, and allows one to assign linear elastic behavior to any part of the problem geometry.

The program is supported by a pre-processor to develop 2D meshes consisting of rectangular type prismatic elements, eight-node quadrilateral elements. The program has the ability to plot the original mesh, as illustrated in Fig.1, in which D is the pile diameter, and H is the horizontal (lateral) load. Description of all of the program features is beyond the scope of this work, and a brief summary of the consolidation theory relevant to this study is given in next sections.

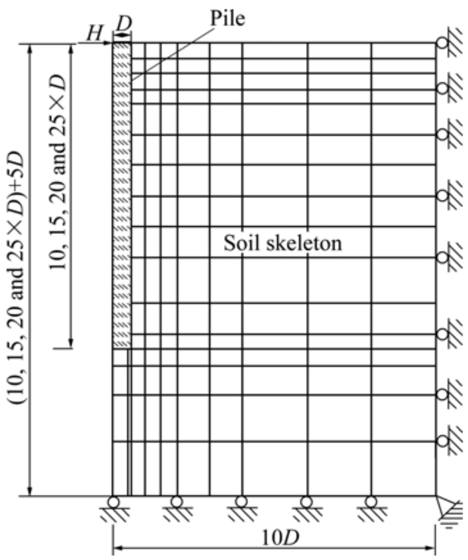

Fig.1 2D finite element mesh

2.2 Pile and soil models

In order to model the pile structural material, linear elastic model (perfect-plasticity) is used to model the pile. This model represents Hooke's law of isotropic linear elasticity used for modeling the stress−strain relationship of the pile material. The model involves two elastic stiffness parameters, namely elastic modulus E, and Poisson ratio v. It is primarily used for modeling of stiff structural member, for example, piles in the soil.

The surrounded soil is represented by Mohr-Coulomb model. This elasto-plastic model is based on soil parameters that are known in most practical situations. The model involves two main parameters, namely the cohesion intercept c' and the friction angle φ'. In addition, three parameters namely elastic modulus E', Poisson ratio v' and dilatancy angle ψ' are needed to calculate the complete σ–ε behavior. The failure envelope only depends on the principal stresses (σ_1, σ_3), and is independent of the intermediate principle stress (σ_2) as referred by POTTS and ZDRAVKOCIC [12] and JOHNSON et al [13].

2.3 Transient formulation

An incremental formulation was used in the current work producing the matrix version of BIOT equation [12] at the element level presented as follows [14]:

$$\begin{bmatrix} \boldsymbol{k}_{\mathrm{m}} & \boldsymbol{c}_{\mathrm{m}} \\ \boldsymbol{c}_{\mathrm{m}}^{\mathrm{T}} & -\theta\Delta t\boldsymbol{k}_{\mathrm{c}} \end{bmatrix} \begin{Bmatrix} \Delta\boldsymbol{u} \\ \Delta\boldsymbol{u}_{\mathrm{w}} \end{Bmatrix} = \begin{Bmatrix} \Delta\boldsymbol{f} \\ \Delta t\boldsymbol{k}_{\mathrm{c}}\boldsymbol{u}_{\mathrm{w}0} \end{Bmatrix} \tag{1}$$

where $\boldsymbol{k}_{\mathrm{m}}$ and $\boldsymbol{k}_{\mathrm{c}}$ are the now familiar solid stiffness and fluid conductivity matrices, respectively; $\boldsymbol{c}_{\mathrm{m}}$ is the connectivity matrix; θ is used for interpolation in time; Δt is calculation time step; $\Delta\boldsymbol{f}$ represents the external load vector which may itself be time-dependent; $\boldsymbol{u}$ and $\boldsymbol{u}_{\mathrm{w}}$ are the displacement and access pore water pressure, respectively.

2.4 Non-dimensional time factor

In order to examine the time-dependent consolidation behavior of the pile, it is convenient to introduce a non-dimensional time factor T, which is defined as [1−2, 15]:

$$T = \frac{c_{\mathrm{v}}t}{D^2} \tag{2}$$

where $c_{\mathrm{v}} = \dfrac{k(1-\upsilon'_{\mathrm{s}})E'_{\mathrm{s}}}{\gamma_{\mathrm{w}}(1-2\upsilon'_{\mathrm{s}})(1+\upsilon'_{\mathrm{s}})}$.

then:

$$T = \frac{k(1-\upsilon'_{\mathrm{s}})E'_{\mathrm{s}}t}{\gamma_{\mathrm{w}}(1-2\upsilon'_{\mathrm{s}})(1+\upsilon'_{\mathrm{s}})D^2} \tag{3}$$

where the coefficient of consolidation c_{v} is defined in terms of permeability k, drained modulus E'_{s}, Poison ratio υ'_{s}, the unit weight of water γ_{w} and the diameter of pile D.

3 Validation of numerical model

The finite element model of the whole geotechnical structure developed was verified based on the results of published cases. Two case studies were used. The first dealt with a full scale lateral load tests reported by ISMAEL [14] to assess the lateral pile response under lateral load in which the lateral settlement was measured directly after short time of loading. The second included a numerical investigation reported by CARTER and BOOKER [2] and TAIEBAT and CARTER [1] to verify the time-dependent effect on the lateral pile response subjected to lateral load. After the numerical model is verified, the model was applied to various cases of pile and time-dependent issues covered in this work.

3.1 Case 1

The first case study dealt with lateral load in which the deflection response of bored piles in cemented sand was examined by field test on single pile under lateral load [14]. All piles were 0.3 m in diameter and had a length of 3 m or 5 m. The site of this load test was in Kuwait. The soil profile consists of a medium dense cemented silty sand layer to a depth of 3 m. This is underlain by a medium dense to very dense silty sand with cemented lumps to the bottom of the borehole. The same load sequence during pile load test applied in Ref.[14] was also simulated in this study. The properties of soil in the both cases are listed in Table 1.

The comparison between the finite element results and field test data is shown in Fig.2. Comparable data were obtained between the experimental results of the three piles and the present simulation model. The magnitude of lateral settlement of the piles was not very close with the field test due possibly to the variability in soil properties. The numerical simulation is reasonably accurate for the problem of laterally loaded piles and pile-soil interaction over a wide range of deformation for 3 m and 5 m piles. The 5 m-long pile is more resistant (able to carry higher lateral load) compared to 3 m pile.

3.2 Case 2

According to TAIEBAT and CARTER [1] a pile studied with diameter D is embedded in a layer of saturated cohesionless soil that obeys the Mohr-Coulomb failure criterion. The friction angle of the soil is assumed to be $\phi'=30^\circ$. The soil is also assumed to have a submerged unit weight of $\gamma_{sub}=0.7\gamma_w$, where γ_w is the unit weight of pore water, a elastic modulus for fully drained conditions given by $E'_s=3\ 000\ \gamma_w$ and a Poisson ratio $\upsilon'=0.30$. The initial value of the coefficient of lateral earth pressure is $K_0=0.5$. The elastic modulus of the pile material is $E_p=1\ 000\ E'_s$. The problem was analyzed assuming elastic as well as elasto-plastic models for the soil. All elasto-plastic analyses were carried out using eight-node quadrilateral finite elements on the other hand the same sequence of loading. Good comparisons were obtained between the published case results of TAIEBAT and CARTER [1] and the present simulation model at a lateral load intensity of $15\gamma_w\times D^3$, as shown in Fig.3. This loading was maintained constant with time and the analyses were continued, allowing excess pore pressures to dissipate, and thus for the soil to consolidate during a total time of T=0.000 1.

The predicted load−displacement curves for the pile head, for cases where the pile deforms under fully drained state and rapid loading (i.e., undrained) conditions, are presented in Fig.4. Case is plotted for the Mohr-Coulomb soil model. The response of the pile during rapid loading is almost linear and close to the elastic response with head displacement about twice that of elastic analysis. Again, good agreement was observed between present study and results of Ref.[1].

4 Results and discussion

In all the calculations an eight-node quadrilateral element was employed. Each node had three degrees of freedom associated with it and was used to describe shape functions for geometry. The tested pile dimensions and two soil properties used are summarized in Table 2. The responses of the pile in elasto-plastic soil subjected to lateral load simultaneously and deforming under rapid loading conditions followed by consolidation are taken. The lateral load is taken as H=50, 150, 250, 350 and 450 kW.

This study included: (1) the load intensity from 50

Table 1 Geotechnical properties of soil layers [14]

Item	Saturated soil weight/ $(\mathrm{kN{\cdot}m^{-3}})$	Elastic modulus/MPa	Poisson ratio	Cohesion intercept/kPa	Friction angle/(°)
Medium dense cemented silty sand layer	18	13	0.30	20	35
Medium dense to very dense silty sand with cemented lumps	19	13	0.30	1	45
Pile	25	2.0×10^6	0.15	—	—

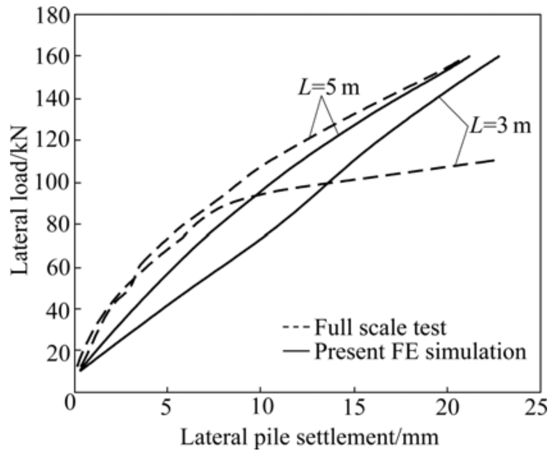

Fig.2 Comparison of finite element results with field test data of ISMAEL [14]

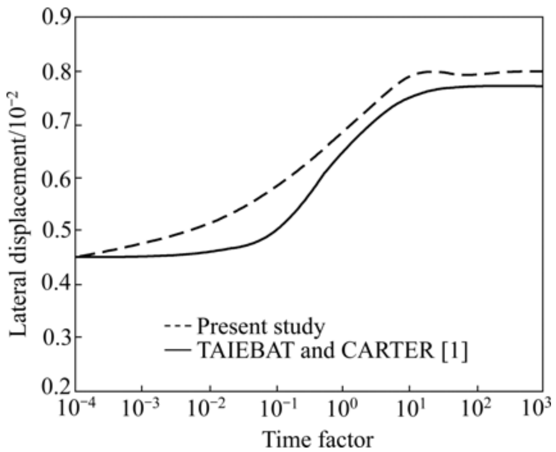

Fig.3 Comparison of lateral displacements (δ/D) of pile head in elasto-plastic soils

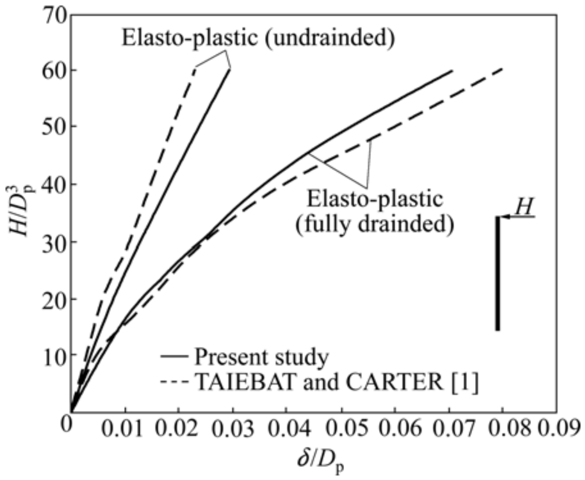

Fig.4 Lateral displacement relationships for laterally loaded piles under drained and undrained conditions

to 450 kN. In the case of slenderness ratio two values of 250 and 450 kN were used, (2) for rapid load and long time conditions, the time factor started from 0.000 1 to 1.0, (3) two type of soils were considered (i.e., cohesionless and cohesive soil) and (4) four slenderness ratios (L/D) were used (i.e., L/D=10, 15, 20 and 25). The influence of those mentioned factors was summarized in the following sections.

Table 2 Pile and soil properties

Material	Unit weight/ ($kN\cdot m^{-3}$)	Elastic modulus/ MPa	Poisson ratio	Cohesion intercept	Angle of internal friction/ (°)
Clay	18.0	10	0.35	5.0	25
Sand	20.0	13	0.30	0	31
Pile	—	2.9×10^4	0.15	—	—

4.1 Development of pile lateral displacement with time

One of the main important factors affecting the lateral behavior of pile is its lateral displacement. For pile under lateral loading, one main criterion that should be satisfied is that it should be safe pile against lateral deflection [16]. Fig.5(a) shows the lateral deformation of the pile with depth in both types of soil. In addition, it shows the influence of time on the lateral response of pile with respect to increasing of lateral load applied. It can be noticed that in case of smaller lateral loads the response of pile is close to be linear and also gives smaller difference in deformation with time. The difference becomes more significant with increasing lateral loads. Fig.5(b) shows lateral displacements of the pile at time factor T=1.0 under different load intensities. In this figure, the lateral response is assessed using undrained and drained soil which represents rapid and maintained load, respectively. It can be shown that the level of loadings is largely effect on the lateral pile displacement with depth. In general the maximum lateral displacement occurs at the tip of pile; in addition the point of rotation occurs at L/D of 2.0 from base of pile.

The predicted load−displacement relationship under rapid loading and long time loading is presented in Fig.6. The figure shows the region between these two cases of loads stages that means the consolidation effect zone. The lateral response of the pile during T=0.000 1 is almost linear and similar to the elastic performance of the pile. The lateral displacement of the pile increases with the increase of the load level and time. The load–displacement relationship of pile during the consolidation is represented in the shaded area between the lowest and the highest lateral load intensities in this work. This area can be used to predict all the displacements that result from any loading value between 0−500 kN. As conclusion, higher displacements with time were observed due to consolidation process and as it can be noticed that the higher the applied lateral load, the higher the percentage of increase in displacements with time, as mentioned also by TAIEBAT and CARTER [1].

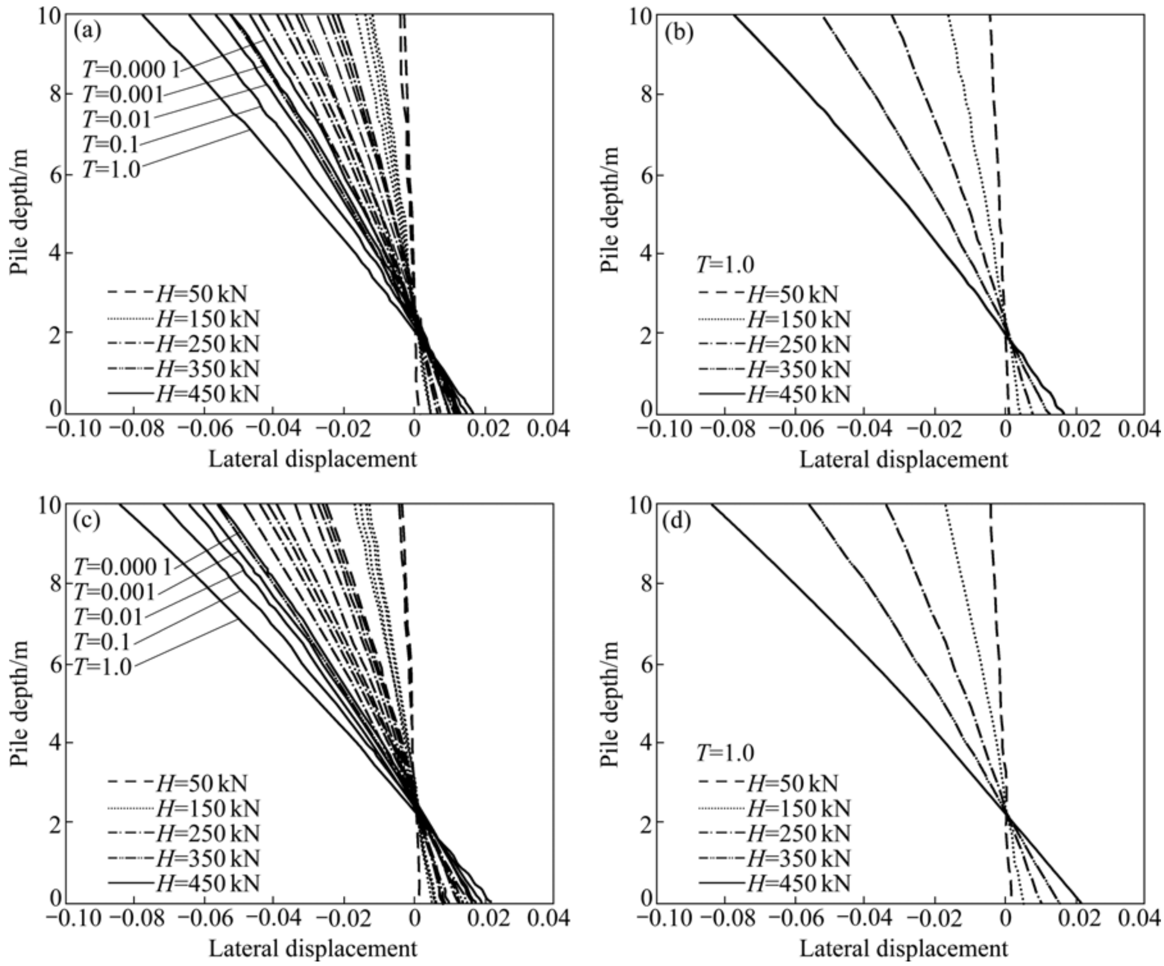

Fig.5 Lateral pile displacement under different intensities of lateral load in cohesionless soil ((a) and (b)) and cohesive soil ((c) and (d))

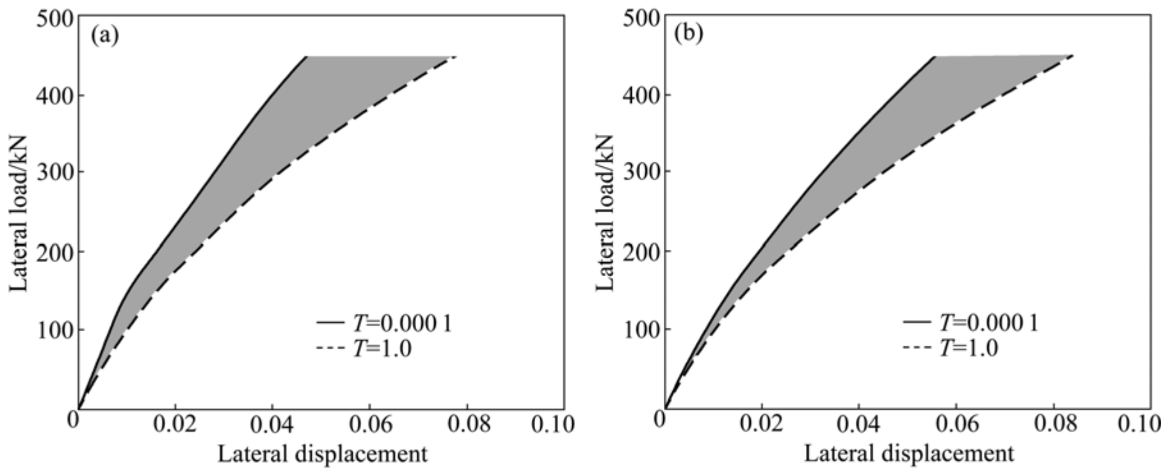

Fig.6 Lateral load-displacement relationships for laterally loaded piles in cohesionless soil (a) and cohesive soil (b)

It can be noticed that the pile has large resistance to lateral load (less lateral displacement) in cohesionless soil compared with cohesive soil. This is due to the large soil resistance for cohesionless soil. On the other hand, the percentage of lateral displacement increment between T=0.000 1 and T=1.0 is large for cohesionless soil, which is calculated using the following equation:

$$\delta' = \frac{\delta_{T=1.0} - \delta_{T=0.0001}}{\delta_{T=1.0}} \times 100\% \tag{4}$$

where δ' is the percentage of lateral displacement increment between T=0.000 1 and T=1.0; $\delta_{T=1.0}$ is the lateral displacement δ/D at T=1.0 (effect of consolidation time); and $\delta_{T=0.000\ 1}$ is the lateral displacement δ/D at T=0.000 1 (rapid load).

This means that the pile in cohesionless soil can resist more at the rapid loading and resist less at long time loading compared with the pile in cohesive soil, as illustrated in Table 3. This is due to the fact that cohesionless soil has more voids due to the higher permeability value compared to cohesive soil, thus in the case of rapid loading causes the pore water to carry more part of the applied load. Therefore, the pore pressure increased the pile resistance by reducing the lateral displacement. However, in long term more water dissipated, which caused the decrease in lateral pile resistance and as a result, large displacement occurred.

Table 3 Percentage of lateral displacement increment

Load intensity/kN	Cohesionless soil			Cohesive soil		
	$\delta_{T=0.000\,1}/10^{-2}$	$\delta_{T=1.0}/10^{-2}$	δ'/%	$\delta_{T=0.000\,1}/10^{-2}$	$\delta_{T=1.0}/10^{-2}$	δ'/%
50	0.334	0.438	23.7	0.385	0.465	17.0
150	1.180	1.650	28.5	1.320	1.730	23.7
250	2.210	3.250	32.0	2.550	3.450	26.1
350	3.390	5.270	35.7	3.980	5.650	29.6
450	4.720	7.800	39.5	5.600	8.410	33.4

The prediction of normalized lateral displacement of pile head (δ/D) in the applied load direction (H) verses time factor (T) is illustrated in Fig.7. This figure shows that the lateral displacements for both soil types increase with increasing the lateral load and the time factor, respectively. Also the differences in displacements with time factor are observed more clearly at high loading intensities. Also from these figures it can be seen that change in the lateral displacement with time is small in case of low loading intensities and becomes large when higher lateral load is applied.

4.2 Development in lateral soil pressure and soil friction stress

A key element in the design of laterally loaded piles is the determination of ultimate lateral resistance that can be exerted by soil against the pile [14, 17] particularly the ultimate soil pressure occurred in the middle of the pile [18]. Many researches have also been performed to study the response of laterally loaded piles in different types of soil. A preliminary survey of the literatures available on this topic was given by MATLOCK and REESE [19], and BROMS [20], but very few knowledge regarding the effect of time-dependent factor on the lateral soil pressure developed during consolidation. In addition, the soil friction stress also occurred due to lateral load and effects on the lateral response of pile, which were caused from the friction between soil material and pile surface. Soil pressure and friction stress distribution with depth are illustrated in Fig.8.

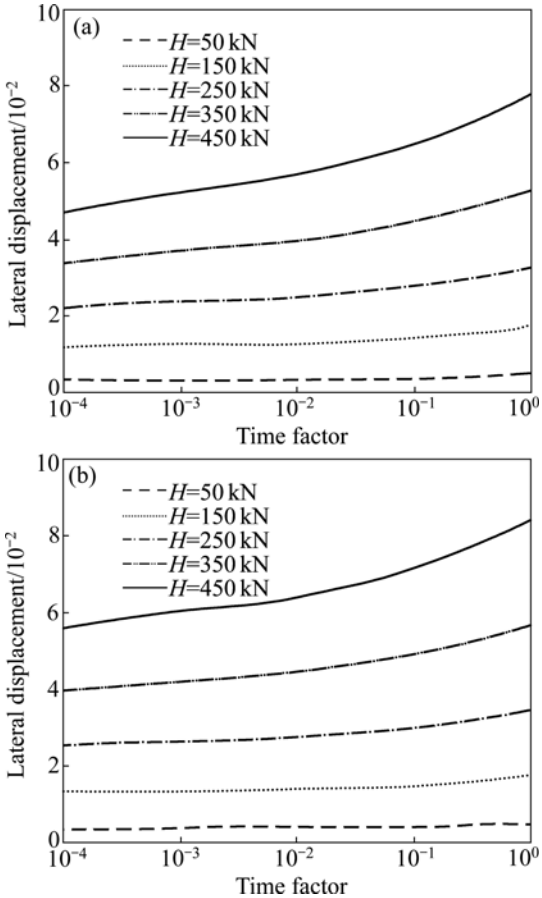

Fig.7 Relationship between lateral displacement verses time factor: (a) Cohesionless soil; (b) Cohesive soil

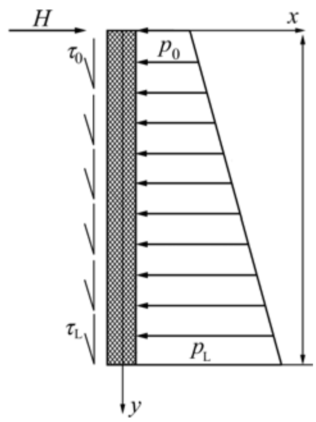

Fig.8 Lateral soil pressure distribution (p) and soil friction stress distribution (τ) with depth

Lateral soil pressures p in soil resulting from the lateral loads is shown in Fig.9. It can be seen that the pressure increased with time. Higher values of pressure occurred at the position of L/D between 6 and 8 when lateral loads of 250, 350 and 450 kN were applied and the increase of pressure with time reached 28.6% and 27.0% from the pressure results from rapid loading in cohesionless and cohesive soil type, respectively. Also at L/D=2, which is the point of rotation, near values of lateral soil pressure can be seen. As concluded from the results, the pile in cohesionless soil is less safe against ultimate soil pressure failure and has less resistance against lateral pile displacement failure.

Finally, the soil friction stress with depth under different loadings and time factors is shown in Fig.10. The friction stress has the lowest values at the top of pile (near the surface) and then increases with depth to reach the maximum values at L/D=2 from the base of pile. This stress assists to increase in lateral pile resistance. On the other hand one can also note little difference in the friction stress with different time of consolidation because it is less influenced by pore water pressure effect.

4.3 Influence of pile slenderness ratio (L/D)

According to KARTHIGEYAN et al [8] the influence of pile slenderness ratio is an important parameter to be considered in pile design. The influence of the pile slenderness ratio (L/D) under the effect of consolidation time was studied by performing 2D finite element simulation of a 1.0 m diameter circular pile with four pile lengths of 10D, 15D, 20D and 25D. The analyses were carried out for both cohesionless and cohesive soil types separately. Two values of load were used in this part of investigation, i.e., 250 and 450 kN and constant width of pile (1.0 m). Based on the analysis and results obtained, the lateral displacement (δ/D) with respect to different

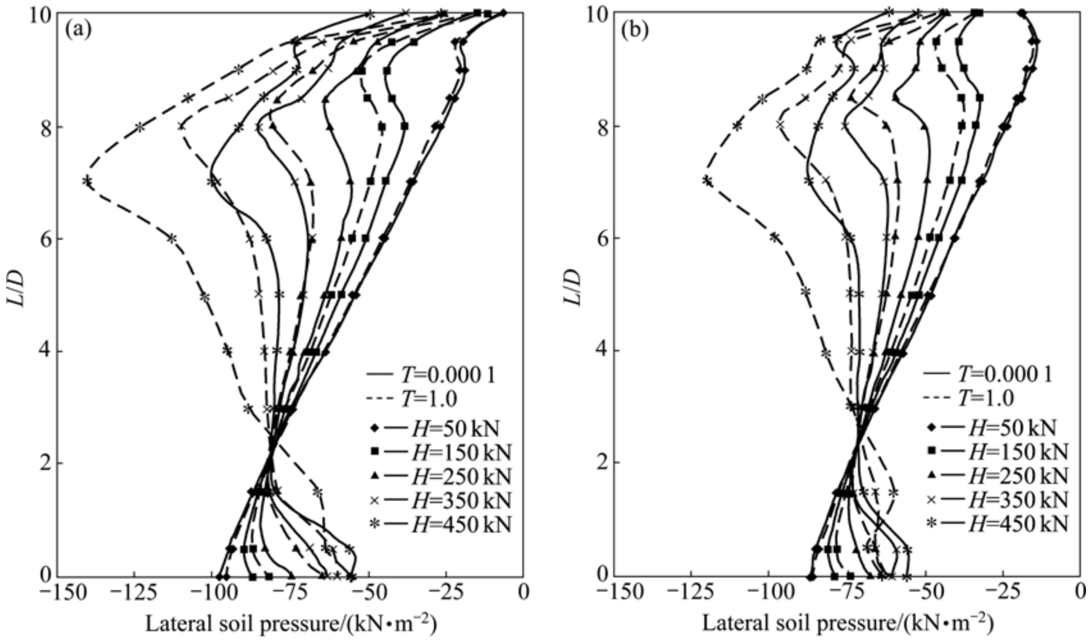

Fig.9 Lateral soil pressure with depth under different loads and time factors: (a) Cohesionless soil; (b) Cohesive soil

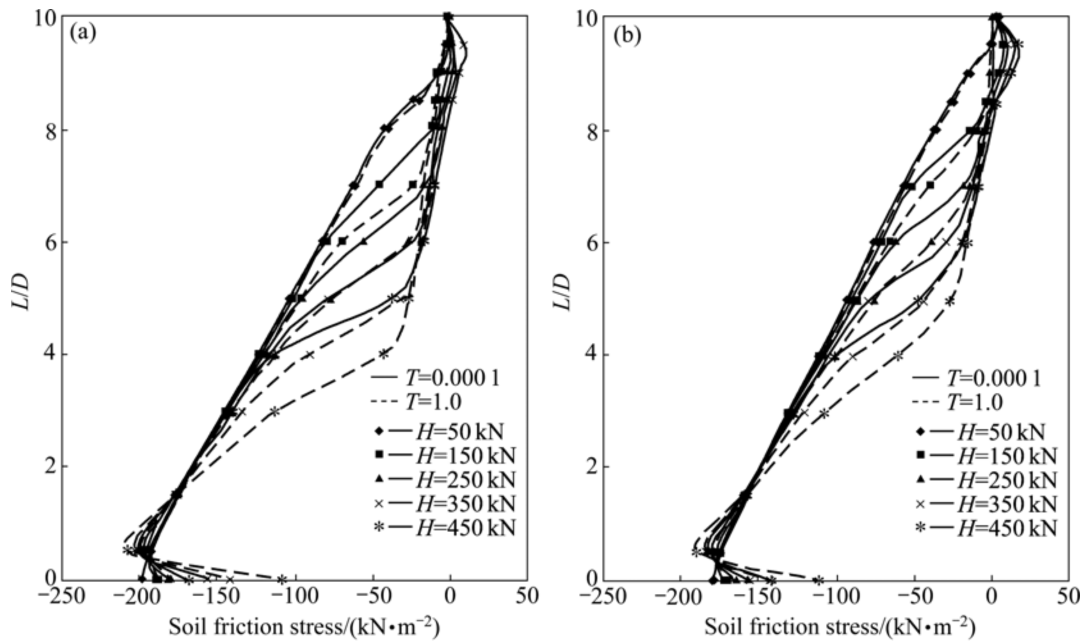

Fig.10 Soil friction stress with depth under different loads and time factors: (a) Cohesionless soil; (b) Cohesive soil

time factors has been drawn verses the slenderness ratio (L/D).

The results show that the lateral pile displacements increase with increasing time factor and also increase with decreasing pile slenderness ratio in both cohesionless and cohesive soil type, as shown in Fig.11 and Fig.12, respectively. In general, it was found that the influence of time factor on lateral pile displacement with respect to the slenderness ratio is more obvious in case of cohesionless soil than in cohesive soil.

In both cases of soil type and two loads considered, the lateral displacement increased with the increase of time factor at all slenderness ratios studied. In the case of cohesionless soil, large change clearly appeared in the lateral pile displacement at the slenderness ratio (L/D) between 10 and 17, and small change appears for large slenderness ratio values L/D more than 17 at both load values. However, in the case of cohesive soil, the large increasing in lateral pile displacement appeared at the slenderness ratio (L/D) between 10 and 20 at both load intensities considered. This means that the cohesionless soil provides more resistance than cohesive soil (for the assessment of lateral pile displacement), possibly because the increase in the surrounded soil resistance with depth.

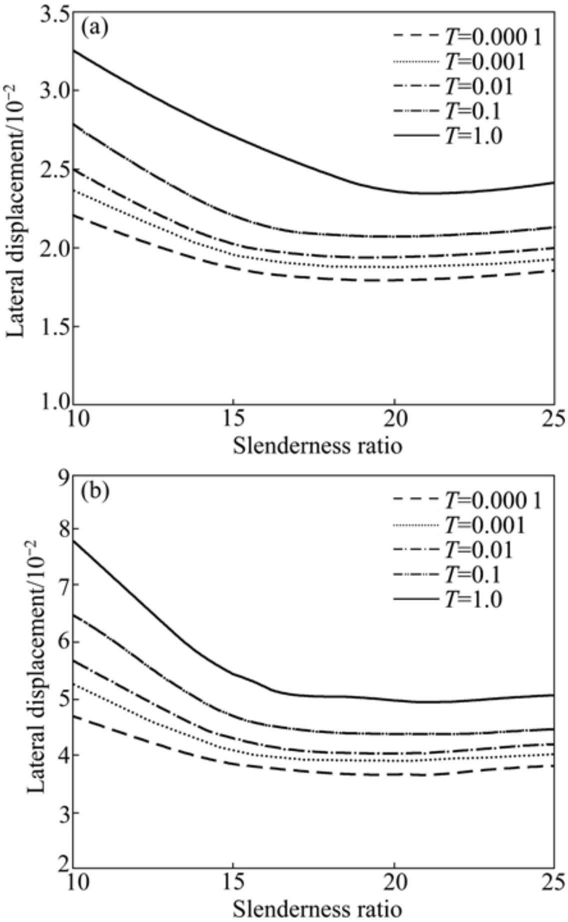

Fig.11 Lateral displacement versus slenderness ratio for cohesionless soil: (a) H=250 kN; (b) H=450 kN

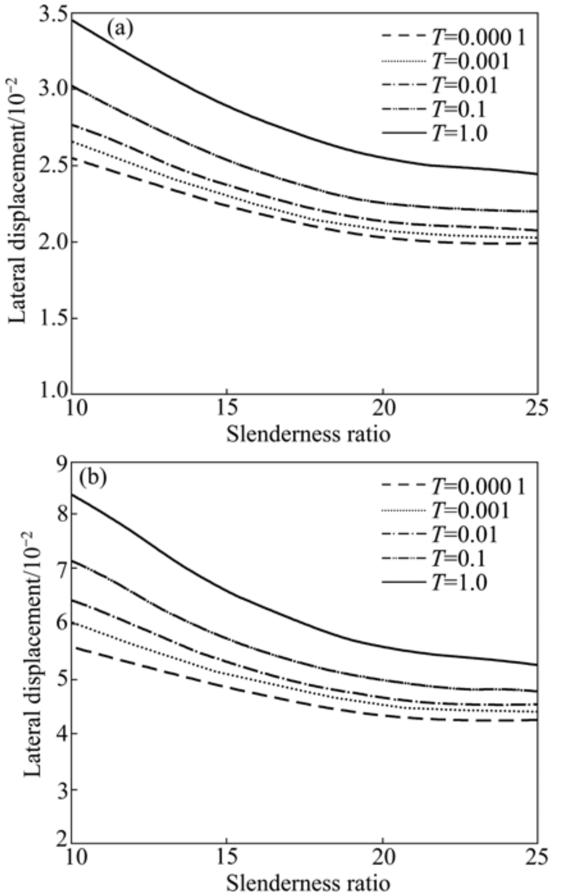

Fig.12 Lateral displacement versus slenderness ratio for cohesive soil: (a) H=250 kN; (b) H=450 kN

5 Conclusions

(1) A finite element technique is presented, which provides an efficient analysis of the consolidation of piles subjected to lateral loading. The results indicate that pile in cohesionless soil resists more in the rapid loading and resists less in case of long time loading condition than the pile in cohesive soil.

(2) The performance of the piles under rapid load is almost linear and similar to the elastic performance of the pile. During consolidation and also with load increase, the lateral displacement of the pile increases and the behavior is close to real case of elasto-plastic model.

(3) Large increase in lateral soil pressure and small increase in frictional shear stress with time were observed when the lateral load increases from low to high magnitude. Higher values of pressures with time occurred near the tip of pile and observed at high intensity loading in both types of soil. The frictional stress begins from the lowest values at the top of pile (near to the surface) and then increases with respect to depth to reach the maximum values at L/D of 0.5.

(4) Smaller displacements with respect to time are observed due to consolidation process when the pile

slenderness ratio increases for both cohesionless soil and cohesive soil.

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