Time-dependent Behavior of Piled-raft on Soil foundation with Reference to Creep and Consolidation

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ABSTRACT

It is well known that the time-dependent behavior of soil deformation plays an important role in performance of major structures on soil foundation. The time-dependent behavior of soil results from both properties of viscosity and consolidation which display a certain nonlinear characteristics. In this paper, the time-dependent effects of soil deformation on interaction behaviour of piled rafts and soil foundation by using a fully coupled finite-element method of consolidation in which an elasto-viscoplastic model is incorporated. Through numerical computations, variation in time and distribution in space of excess pore pressures in foundation soil underlying the piled raft and reactions as well as deformations or settlements of raft and piles during loading are examined. It is shown that the coupled creep-consolidation characteristics of soils remarkably affect the time-dependent performance of interaction of piled rafts and soils and the dissipation of excess pore pressures is intimately associated with both Mandel-Cryer effects and creep deformation especially in poor drainage condition. It is demonstrated that the coupled creep-consolidation analysis can give a more rational evaluation of overall performance of interaction of piled raft and soils and conventional analyses which overlooks time-dependency of soil deformation may give rise of inaccuracy in evaluation of interaction behavior and unreliability in design of structures and relative engineering practice.

KEYWORDS: Elasto-viscoplastic, piled-raft, creep, consolidation, time-dependent

INTRODUCTION

In most soft ground, piled rafts are extensively and widely employed in engineering constructions such as high-rise buildings for their advantages of higher bearing capacity, lower differential settlement, and better entirety over other types of foundations. It is known that soils may display strong nonlinear and inelastic characteristics. Furthermore, the viscosity or rheology of soft clays cannot be usually overlooked in the design of major structures founded on soft ground. Especially, rheologic deformation of soils may get considerable under high stress level. In fact, the saturated soft ground usually displays low strength, sensitive thixotropy, and high compressibility. Under such circumstances, it is of practical significance to properly consider the time-dependent behavior of soil deformations in the interaction analysis of piled rafts and soils. The time effects in soil-structure interaction analyses was first considered by Wood *et al*. (1975) on the basis of one-dimensional Terzaghi's model of consolidation by virtue of finite difference method. Then the time-dependent response of the pile-raft-soil interaction system under vertical loading was analyzed by Cheng *et al*. (2004) using two-dimensional FEM based on Biot's theory of consolidation. The linear creep model was incorporated by Viladkar *et al*. (1993) into FEM in interaction analysis and it is found that bending moment, contact pressure and differential settlement vary with time. A simplified rheologic element model was used by Xia *et al*. (1994) to evaluate distribution of raft contact pressure on visco-elastoplastic soil. A three-dimensional FEM is proposed by An *et al.* (2001) to predict creep settlement of foundation on elasto-viscoplastic soil. The interaction analysis considering time effects induced by both viscosity and consolidation was conducted by Wang *et al*. (2001) in which a closed-form fundamental solution of stresses of saturated viscoelastic soil underlying raft under vertical loading is derived by using Laplace-Hankel transformation. It is recognized that the time effects of interaction of piled raft and soils depend on both viscosity and consolidation characteristics of soils. As a result, the time-dependent behavior of interaction of piled raft and soil is investigated in this paper by incorporating a FEM coupling consolidation with an elasto-viscoplastic (EVP) model.

ELASTO-VISCOPLASTIC MODEL OF SOIL

At present, most of viscous constitutive equations based on conventional rheology theory widely applied in geotechnics are established empirically for idealized media. These empirical viscous constitutive models cannot authentically reproduce time-dependent behavior of soils. It is more rational to use elasto-viscoplastic models to describe the time-dependent behavior of soft soils as stated by Adachit (1996). Many elasto-viscoplastic models are based on the concept of Perzyna's over-stress theory (*e.g.*, Liingaard and Augustesen, 2004). Under the framework of Perzyna's overstress theory, a new elasto-viscoplastic model was proposed by Stolle (1999) by combining Rosco's Cam-Clay model with Bjerrum's time-line model in complex stress condition. Such a model will be illustrated as follows.

Referring to the yield surface in the $p' - q$ space as shown in Fig.1, admissible stress states in the proposed model are confined to the region below Mohr-Coulomb failure envelope. It is postulated that the time-dependent deformations depend on a stress measure p^{eq} which is defined as

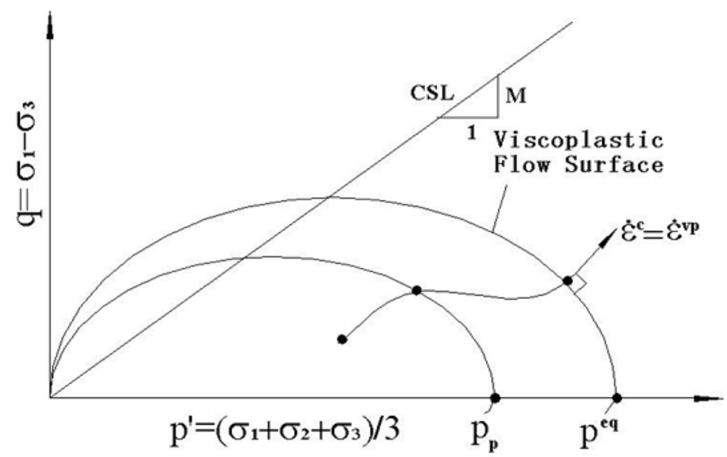

Figure 1: The yield surface in the $p'-q$ space of elasto-viscoplastic constitutive model.

$$p^{\mathrm{ep}} = p' + \frac{q^2}{p' M^2_{\mathrm{cs}}}, \quad M_{\mathrm{cs}} = \frac{6 \sin \phi_{\mathrm{cs}}}{(3 - \sin \phi_{\mathrm{cs}})} \tag{1}$$

where M_{cs} represents the slope of the critical-state line related to the friction angle ϕ_{cs}, p' and q are mean principal stress and deviatoric stress respectively.

As illustrated in Fig.1, the equivalent pressure p^{eq} can be derived from modified Cam-Clay model which is an elliptic surface in $p'-q$ space. The volumetric creep rate is constant on such a surface. The isotropic prior consolidation pressure, p_{p}, is density-dependent. The creep rates can be negligible when $p^{\mathrm{eq}} < p_{\mathrm{p}}$ whereas when $p^{\mathrm{eq}} > p_{\mathrm{p}}$, the time-dependent characteristics of deformation rates become noticeable. The creep deformation of soil is assumed to be given by the following equation of state that relates the volumetric creep rate $\dot{\varepsilon}_{\mathrm{v}}^{\mathrm{c}}$ to ratio $p^{\mathrm{eq}}/p_{\mathrm{p}}$ and the current accumulated creep strain $\varepsilon_{\mathrm{v}}^{\mathrm{c}}$ which plays a role of strain hardening parameter

$$\dot{\varepsilon}_{\mathrm{v}}{}^{\mathrm{c}} = \frac{\mu^*}{\tau} \left(\frac{p^{\mathrm{eq}}}{p_{\mathrm{p}}} \right)^{\lambda^* - \kappa^* / \mu^*} \tag{2}$$

in which p_{p} is defined as

$$p_{\mathrm{p}} = p_{\mathrm{p0}} \exp\left(\frac{\varepsilon_{\mathrm{v}}^{\mathrm{c}}}{\lambda^* - \kappa^*} \right) \tag{3}$$

where p_{p0} is the reference pressure which at the beginning which is linearly related to the initial overconsolidation ratio OCR_0 and the consolidation pressure p_0 as below

$$p_{p0} = \mathrm{OCR}_0\ p_0 \tag{4}$$

where λ^*, κ^* and μ^* are respectively modified compression index, modified swelling index and modified creep index of soil (Stolle, 1999).

Based on Perzyna's overstress theory, the total strain is decomposed of two components of elastic strain and creep strain as following

$$\{\dot{\varepsilon}\} = \{\dot{\varepsilon}^{\mathrm{e}}\} + \{\dot{\varepsilon}^{\mathrm{c}}\} = \{\dot{\varepsilon}^{\mathrm{e}}\} + \{\dot{\varepsilon}^{\mathrm{vp}}\} \tag{5}$$

The creep strain is to be determined by the flow rule in analogue to plasticity while the elastic strain is given by following generalized Hooke's law,

$$\{\dot{\sigma}\} = [D^{\mathrm{e}}]\{\dot{\varepsilon}\} \tag{6}$$

where

$$\{\dot{\varepsilon}\} = [\dot{\varepsilon}_1\ \dot{\varepsilon}_2\ \dot{\varepsilon}_3]^{\mathrm{T}}, \quad \{\sigma\} = [\sigma_1\ \sigma_2\ \sigma_3]^{\mathrm{T}},$$

$$[D^{\mathrm{e}}]^{-1} = \frac{\kappa^*}{3(1-2\nu_{\mathrm{ur}})p'}\begin{bmatrix} 1 & \nu_{\mathrm{ur}} & \nu_{\mathrm{ur}} \\ \nu_{\mathrm{ur}} & 1 & \nu_{\mathrm{ur}} \\ \nu_{\mathrm{ur}} & \nu_{\mathrm{ur}} & 1 \end{bmatrix}$$

The subscript 'ur' is introduced to emphasize that Poisson's ratio is to be determined during unloading-reloading process. Similar to the modified Cam-Clay model, the visco-plastic potential function is defined as

$$g^{\mathrm{c}} = p^{\mathrm{ep}} \tag{7}$$

from which the visco-plastic strain is obtained as below

$$\{\dot{\varepsilon}^{\mathrm{vp}}\} = \dot{\lambda}\frac{\partial g^{\mathrm{c}}}{\partial\{\sigma'\}} = \dot{\lambda}\frac{\partial p^{\mathrm{eq}}}{\partial\{\sigma'\}} \tag{8}$$

where $\dot{\lambda}$ is a scale multiplier rate. Considering the generalized Hooke's law, substitution of Eq. (8) into Eq. (5) yields to the total strain rate

$$\{\dot{\varepsilon}\} = \{\dot{\varepsilon}^{\mathrm{e}}\} + \{\dot{\varepsilon}^{\mathrm{vp}}\} = [D^{\mathrm{e}}]^{-1}\{\dot{\sigma}'\} + \dot{\lambda}\frac{\partial p^{\mathrm{eq}}}{\partial\{\sigma'\}} \tag{9}$$

where the equivalent pressure p^{eq} is used as a plastic potential function to gain the individual creep strain-rate components. In fact, the viscoplastic deformation is interpreted as creep deformation. The volumetric viscoplastic strain rate can be denoted as

$$\dot{\varepsilon}_{\mathrm{v}}^{\mathrm{vp}} = \dot{\varepsilon}_{\mathrm{v}}^{\mathrm{c}} = \dot{\lambda}\frac{\partial p^{\mathrm{eq}}}{\partial p'} = \dot{\lambda}\alpha \tag{10}$$

Substituting Eq. (10) into Eq. (9) leads to the resulting strain rate

$$\begin{aligned}\{\dot{\varepsilon}\} &= [D^{\mathrm{e}}]^{-1}\{\dot{\sigma}'\} + \frac{\dot{\varepsilon}_{\mathrm{v}}^{\mathrm{vp}}}{\alpha}\frac{\partial p^{\mathrm{eq}}}{\partial\{\sigma'\}} \\ &= [D^{\mathrm{e}}]^{-1}\{\dot{\sigma}'\} + \frac{1}{\alpha}\frac{\mu^*}{\tau}\left(\frac{p^{\mathrm{eq}}}{p_{\mathrm{p}}}\right)^{\lambda^*-\kappa^*/\mu^*}\frac{\partial p^{\mathrm{eq}}}{\partial\{\dot{\sigma}'\}}\end{aligned} \tag{11}$$

AN EXAMPLE ANALYSIS

Computational Model of FEM

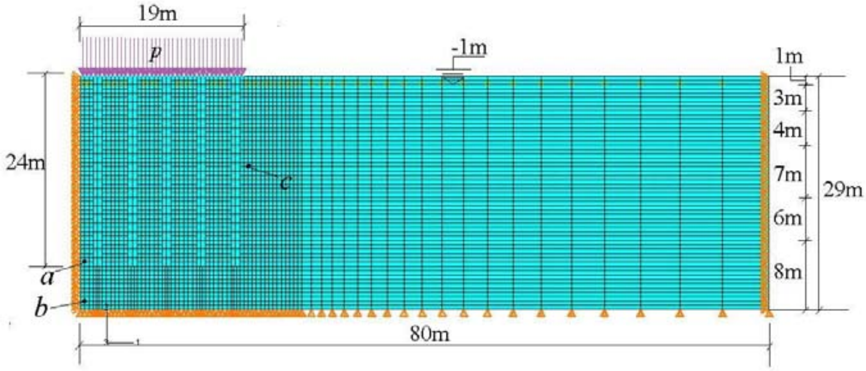

Figure 2: The finite element model used in computation

Table 1: The parameters used for different cases

Case	Raft Modulus	Pile Modulus
Case 0	$E_r=3\times 10^4$MPa	$E_P=1.6\times 10^4$MPa
Case 1	0.6667 E_r	E_P
Case2	0.8333 E_r	E_P
Case 3	1.1667 E_r	E_P
Case 4	E_r	1..25 E_P
Case 5	E_r	1..50 E_P
Case 6	E_r	1.75 E_P
All cases	Poisson's ratio ν_r=0.15	Poisson's ratio ν_p=0.15

Table 2: Soil parameters for FEM analysis

Soil layer	$k(\mathrm{m\cdot d^{-1}})$	λ^*	κ^*	μ^*	c'(kPa)	$\varphi'(^\circ)$
1	8.7E-05	0.650	0.065	4.00E-03	6	26
2	8.7E-05	0.450	0.045	4.50E-03	6	26
3	2.63E-05	0.293	0.022	5.0E-03	6	25
4	1.33E-05	0.325	0.030	5.0E-03	6	26
5	6.00E-06	0.395	0.039	6.0E-03	6	26
6	2.31E-06	0.391	0.039	8.0E-03	6	30
All layers		Unit weight of soil		Saturated conditions: γ_{sat}=18kN/m^3 Dry conditions: γ_{dry}=16kN/m^3		

In order to simplify the analysis of the complicated of interaction between piled raft and soil, the equivalent stiffness formula was developed by Prakoso (2001) to examine interaction behavior of piled raft and soil in plane-strain condition and the rationality of simplified representation of the original three-dimensional problem by plane-strain modeling was verified by comparison with experimental tests. In this paper, based on the elasto-viscoplastic model presented above and Biot's consolidation theory, numerical analyses for the interaction system under plane-strain condition are conducted by virtue of FEM computer program ABAQUS and coding its related interface subroutine UMAT to examine the coupling effects of creep and consolidation on interaction behavior of piled raft and soil.

Considering the symmetry of the problem under consideration, the half of a rectangular zone with 80m×27m is used for FEM modeling as given in Figure 2. The phreatic line is designated at 1m below the ground surface. The piled raft is assumed to be of edge length of B_r =19m and thickness of T_r =2m. The uniform load of q=100kPa invariable of time is imposed on the raft. The pile length was L_p=24m and the pile diameter was D=1m. The parameters of piled raft used in the finite element analysis are listed in Table 1. And the mechanical properties of soil are given in Table 2. For convenience of analysis, five piles in the model are respectively defined as Pile1, Pile2, Pile3, Pile4 and Pile5 from the center of raft foundation to the edge.

Analysis and Discussions of Numerical Results

Characteristics of Variation of Pore Pressure of Soils under Piled Raft with Time

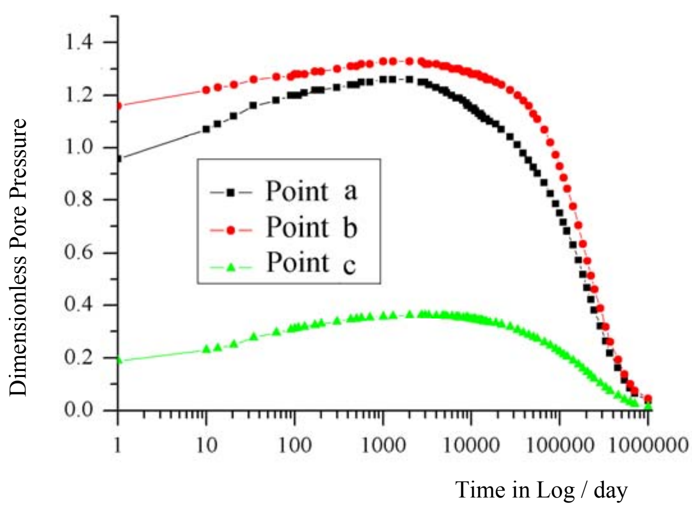

Figure 3: Variation of excess pore-water pressure of soils with time at three locations of foundation under piled raft

The excess pore-water pressure will be induced in the soils under piled raft during loading. In order to conduct comparative study, the excess pore-water pressure normalized by the corresponding static hydraulic pressure is called as dimensionless excess pore-water pressure. For the typical soil elements located in different positions denoted by a, b and c in piled raft and foundation, the variations of dimensionless excess pore pressure with time are displayed in Figure 3. It is shown that build-up and development of pore-water pressure are associated with both Mandel-Cryer effect and viscous effect as stated by Zhu and Yin (2001). It is interpreted that Mandel-Cryer effect results from increase of total stress due to volumetric strain compatibility by Schiffman, Chen and Jordan (1969). The viscous effect causing pore-water pressure increase arises from the rheological or creep compression of soil and retarded dissipation of pore-water pressure. When the increase rate of pore-water pressure resulting from the coupled viscous and Mandel-Cryer effects is identical to the decrease rate of pore-water pressure due to drainage, the pore-water pressures in soil elements will gain their peak. For a given soil layer, the higher the modified creep index μ^* and the lower permeability, the more considerable the delay of the pore-water dissipation. The same phenomenon has been observed and interpreted in different ways by Zhu and Yin (2001), and Sun (1999). In the example under consideration, the maximum pore-water pressure occurs nearly at 2000 days after constant loading was imposed. Before the peak pore-water pressures are attained, the coupled viscous and Mandel-Cryer effects are dominated over drainage while the mobilization of drainage gets to be predominate in the post-peak phase.

Time-dependent Behavior of Reaction and Deformation Characteristics of Raft

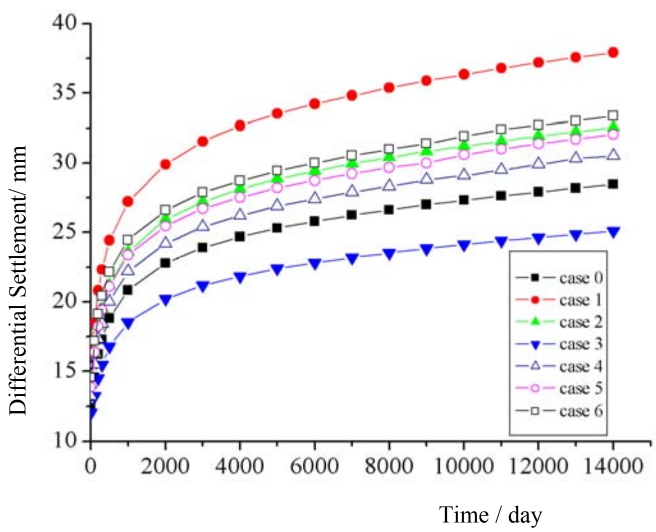

Figure 4: Variation of differential settlements of raft with time for different stiffness of piled raft foundation

For different cases with various stiffness of raft as given in Table 2, the variation of raft differential settlements with time computed is manifested in Figure 4 while the distributions of raft bending moments at different instants are shown in Figure 5. Obviously, raft differential settlements increase with time gradually and finally approach to a certain value while the bending moment is grown at a descending rate. For piled raft on elastic soils, consolidation analysis by Cheng and Chen (2004) has shown that the bending moments increase with time at beginning while slight descending with time may occur at final stable stage. The difference of such an analysis from the current example analysis may result from the fact that the visco-plasticity of soils is taken into account in this paper in addition to consolidation. In fact, the distribution of pore-water pressure is an important factor in affecting directly the distribution of effective stress and deformation of soils. For the piled raft on soil foundation with lower permeability, the sufficient consolidation cannot be usually accomplished, the raft differential settlement will vary with time in the similar pattern as shown in Figure 4. Otherwise, i.e., for the piled raft on soil foundation with higher permeability, the consolidation can be completed in a shorter period. The variation of raft differential settlement with time will take the characteristics as illustrated by Cheng and Chen (2004). As an alternative, the variations of raft maximum bending moments with time for different cases are depicted in Figure 6. It can be seen that the variations of bending moments with time display the same patterns as those of differential settlements.

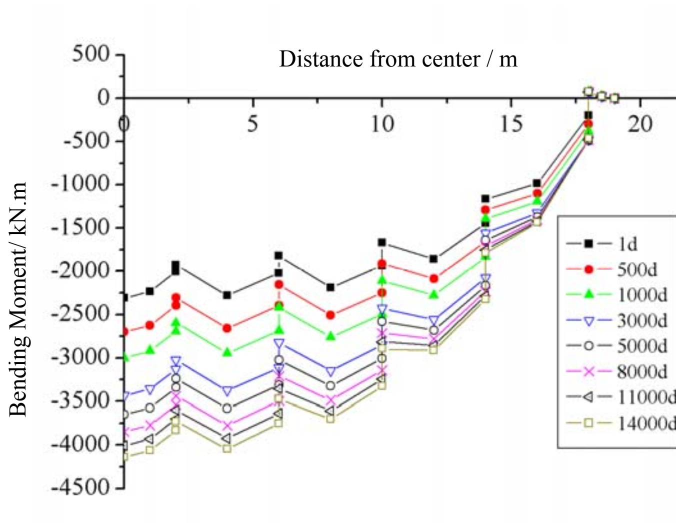

Figure 5: Distribution of bending moments of raft foundation at different instants

While equivalent elastic modulus E_p of piles keeps constant, raft bending moments increase and the differential settlements decrease with raft elastic modulus E_r at a given instant. The larger elastic modulus of raft E_r makes the duration to attain the maximum differential settlement of raft shorter. It is evident that the raft modulus E_r directly governs the bearing capacity and deformation of raft. While the elastic modulus E_r of raft keeps constant, both raft bending moments and the differential settlements increase with the equivalent elastic modulus E_p of piles at a given time. The larger value of equivalent elastic modulus of pile may make the duration to attain their maximums longer. The reason to display such a pattern is that the larger rigidity E_p of piles may make compatibility of pile deformation with raft deformation worse. It is implied that the differential settlement is directly related to the level of bending moment when the elastic modulus E_r of raft is constant.

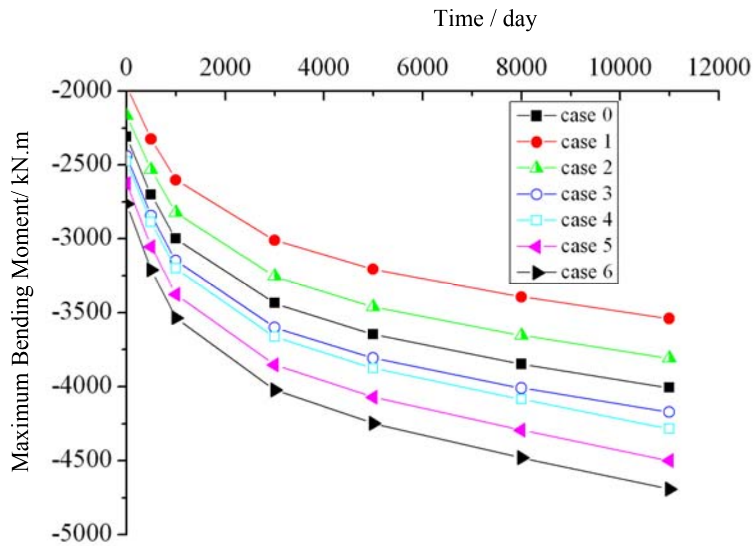

Figure 6: Variation of maximum bending moments of raft foundation with time for different stiffness of piled raft

Time-dependent Behavior of Reactions and Deformations Characteristics of Piles

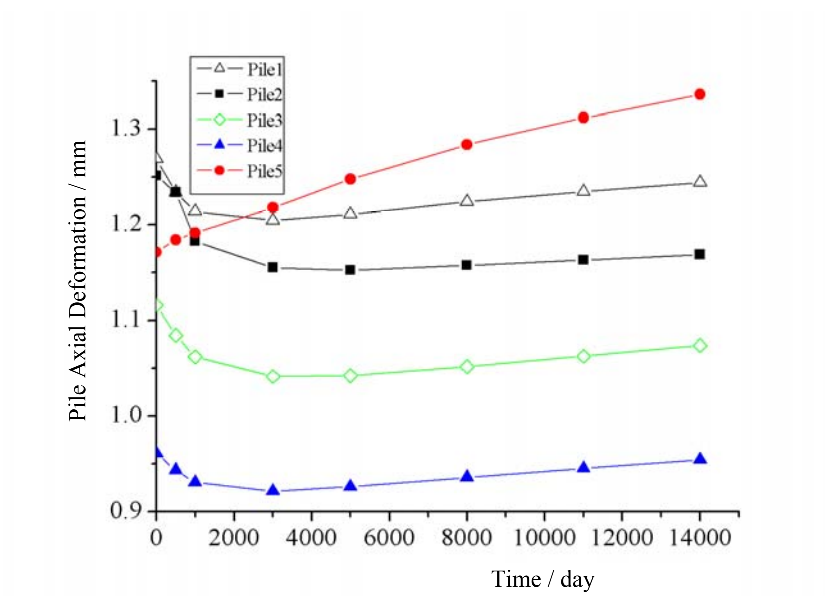

Figure 7: Variation of axial deformations of piles with time

Presented in Figure 7 is the variation of axial deformations of piles with time. The axial deformations of the four central piles in Figure 2 decrease at beginning and increase afterwards. By contrast, deformations of the edge piles increase monotonically with the time. Such time-varying characteristics of deformations of piles under raft are related to variation in time and distribution in space of pore-water pressure of soil beneath piled raft foundation. The soils adjoining to the four central piles are influenced more considerably by coupled viscous and Mandel-Cryer effects. Effective stresses of soils around central piles decreases at beginning and then increases. On the contrary, both viscous and Mandel-Cryer effects have minor influence on soils surrounding the edge piles. With the drainage of pore water, high effective stress will be induced in soils in the central area. Alternatively, the confining effect of soils on central piles decrease at beginning and then increase while the confinement of soils on edge piles gets to harden all the time.

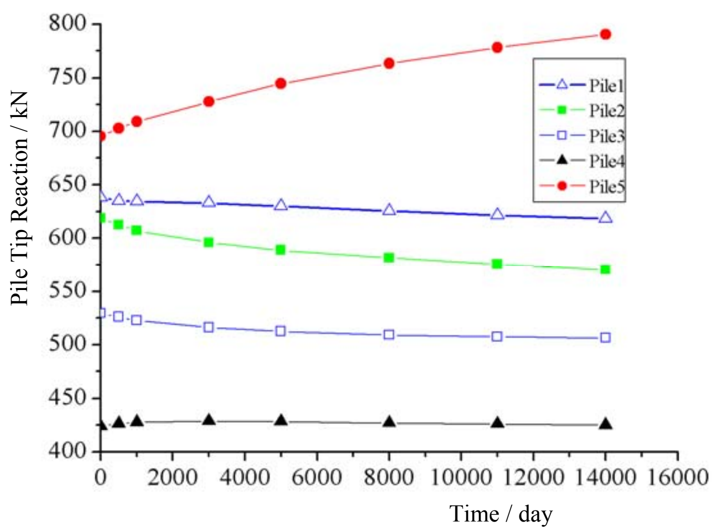

Figure 8: Variation of tip reaction of piles with time

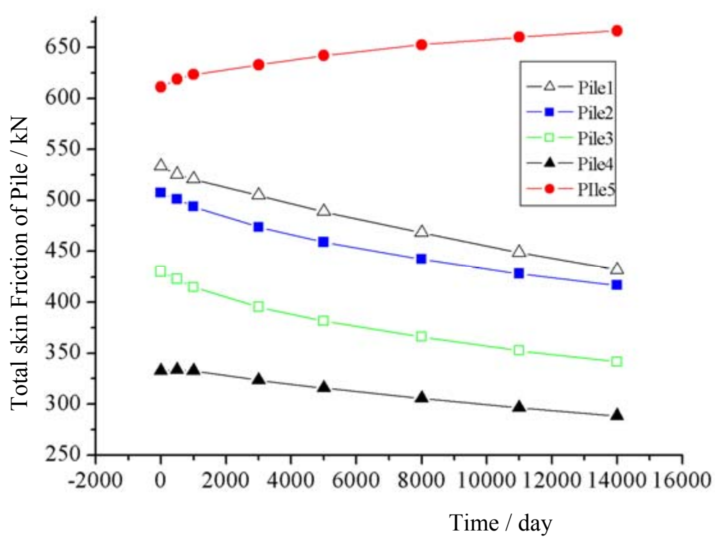

Figure 9: Variation of Total skin resistance of piles with time

It can be seen from Figure 8 which shows the variation of tip reactions of piles under raft with time that the edge pile behaves in different features from the four central piles. The tip reactions of four central piles decrease slightly with time while the tip reaction of edge pile increases all the time after loading. Such characteristics of tip reactions of piles are in accordance with those of bending moments at different time. It is indicated that piles under raft are able to reduce differential settlements and bending moments of raft. For the example condition under consideration, the increments of bending moments and settlements in the central area of raft are larger than those in the edge area of raft. As a consequence, the differential settlements increase. The tip reaction of edge pile will be enlarged to compatible with differential settlements and bending moments of raft. Furthermore, the variation of overall skin resistance of piles with time is shown in Figure 9 It can be observed that the overall skin resistance display the similar characters to that of tip reaction of piles.

The typical distributions of axial forces along depth from ground surface at different instants are given in Figure10 for the edge pile. In general, the axial forces of piles increase with time. In fact, such a characteristic coincides with variation of axial deformation with time as shown in Figure 7 At a given time, axial forces of edge pile increase in upper part due to negative skin friction while axial forces in lower part are reduced. Therefore, negative skin friction exists in upper portion of pile and should be duly considered in design of foundation under soft soil condition.

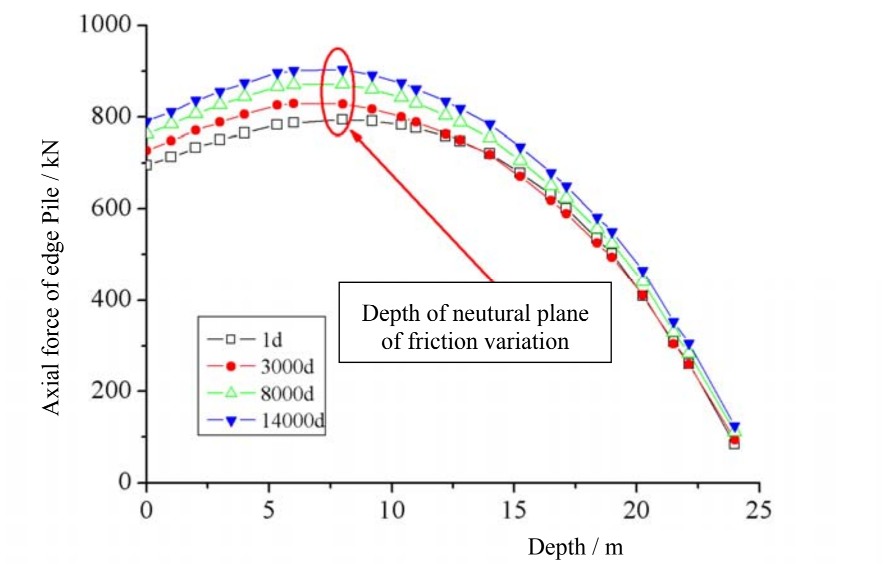

Figure 10: Variation of axial forces of edge pile along depth at different time

The relative rigidity of piled raft poses appreciable influences on internal forces of pile. Here only the tip reaction of edge pile is taken as an example for discussion. As shown in Figure11, the tip reaction of edge pile increases with raft elastic modulus E_r at a given time when equivalent elastic modulus E_p of piles keeps constant. In reality, the higher the raft elastic modulus E_r may improve load-carrying performance of piled raft. Consequently, the load carried by soils under raft will be reduced while the piles will share much bigger component of total loads. The tip reaction of edge pile decreases with equivalent elastic modulus E_p at a given time when the raft elastic modulus E_r

keeps constant. Obviously, the higher rigidity E_p of piles may not be easily to fulfill compatibility requirement of pile deformation with raft deformation, the load which piles carry will be reduced to lead a lower tip reaction of piles.

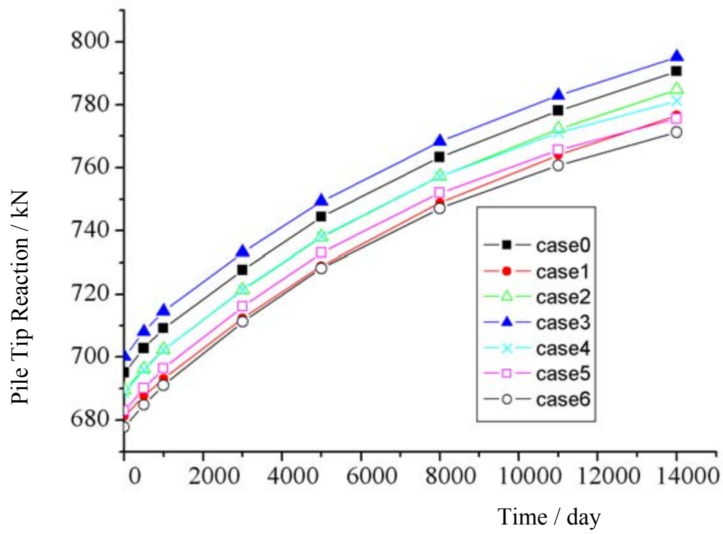

Figure 11: Variation of tip reaction of edge pile with time for different cases with various modulus of piles and raft

CONCLUDING REMARKS

Comparative studies for a typical system of piled raft and subsoils have been made by the proposed numerical method based on FEM for interaction between piled raft and soils in which the time-dependent behavior coupling rheology and consolidation is duly considered. The general time dependent characteristics of reactions and deformations of piles and raft are emphasized and the effects of relative stiffness of raft and piles are examined. Through the numerical analyses, the following findings can be recognized.

(1) For a given soil layer, the higher the modified creep index and the lower permeability, the more considerable the delay of pore-water dissipation. Therefore, for soft soils under poor drainage conditions, the time-dependent behavior of piled raft arising from both creep and consolidation has to be rationally considered.

(2) The pore-water pressure predicted with considering creep effect in addition to consolidation displays different patterns from those obtained by conventional consolidation analysis with no consideration of creep.

(3) While both effects of creep and consolidation are considered, the rigidity of piled raft plays a significant role in governing variation modes of reactions and deformations of piled raft with

time. Furthermore, the edge pile displays different time-dependent behavior of internal forces and deformations from those of the central piles.

(4) The skin friction of pile may also display the nature of time-dependency. During loading, negative skin friction may occur in the pile segments near ground surface under soft soil condition and cannot be negligible in engineering design.

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