*IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*
*e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 16, Issue 2 Ser. I (Mar. - Apr. 2019), PP 48-53*
*www.iosrjournals.org*

# A Time-Dependent Model For Predicting The Response Of A Horizontally Loaded Pile Embedded In A Layered Transversely Isotropic Saturated Soil

Oliver C. Waka [1], Jian-Fei Lu[2], Aayush Neupane[3], Shoaib Ahmed[4], Jacob Arku Ziama[5],

[1] *Department of Civil Engineering, Jiangsu University, Zhenjiang, Jiangsu, 212013, P.R. China*
[2]*Department of Civil Engineering, Jiangsu University, Zhenjiang, Jiangsu, 212013, P.R. China Email:*
[3]*Department of Civil and Transportation Engineering, Hohai University, Nanjing, Jiangsu, 211100, P.R. China*
[4]*Department of Civil Engineering, Jiangsu University, Zhenjiang, Jiangsu, 212013, P.R. China*
[5]*Department of Architecture and Transportation, Liaoning Technical University, Fuxin, 123000, P.R. China*
*Correspondent Author: Oliver C. Waka*

***Abstract:*** *A time-dependent model designed for estimating the response of a horizontally loaded pile in a layered saturated soil is presented in the present paper. The results of the present model are compared with the results of existing solution; a better agreement is seen thereof, thus verifying this model. The present results show that the shear force of the pile decreases with increasing depth. The results also indicate that the displacement of the pile decreases as the depth increases. In addition, the pore pressure along the pile-length vanishes to zero as the time increases. This model shows the influence of the soil on a single horizontally loaded pile. When the depth of the soil increases, the shear force and displacement of the pile all decrease significantly.*

***Keywords:*** *Foundation, horizontally loaded pile, layered saturated soil, Muki's pile method, Pile, Pile-soil*

---

Date of Submission: 26-02-2019 Date of acceptance: 12-03-2019

---

## I. Introduction

Pile foundations are designed to support high-rise buildings, brides and heavy laterally loaded structures constructed in soils not suitable for a shallow foundation system. The lateral and vertical forces acting on the pile are particularly due to the actions of wind, earthquake and deadweight. [1-4], [5]. Dead loads from tall buildings supported on pile foundations are transferred through the piles to a deeper stratified soil medium. The selection of the type and size of pile foundation to support a tall building involves the consideration of factors that may influence the foundation. Some factors considered in the selection process of a suitable foundation type include the bearing capacity of soils, type of structure, distribution of loadings, durability requirements and construction costs. Furthermore, since weak soils are reinforced with pile foundations to prevent excessive settlements of structures, it is necessary to investigate the behavior of soils on which structures are erected. Thus, the present study analyzes the interaction between a laterally loaded pile and the saturated layered half-space TISS.

Apirathvoraku and Karasuhhi[5] used the fictitious pile method to study the response of a circular cylindrical elastic pile embedded in a saturated elastic half-space and subjected to a moment at the top end. Niumpradit & Karadushi[6] used the Biot's theory combined with the fictitious pile method of [7] to account for the influence of the displacement on the pile-soil interactions. However, only final and initial solutions were obtained in the aforementioned studies.

In spite of the available reports on pile-soil interaction, studies on a single pile embedded in a layered TISS can be seldom found in the literature. Previous studies have only considered the pile-soil interaction problems of a single layered transversely isotropic soil. The present study is an effort toward resolving the problem and closing the gap in the literature.

This paper aims to apply Muki's formulation to the problem of a laterally loaded pile embedded in a layered transversely isotropic saturated soil to predict the response of the pile. The pile-soil problem is decoupled into a half-space and a fictitious pile. The layered TISS is handled as a three-dimensional medium, and the pile is regarded as a one-dimensional pile. The relationship between the layered TISS and the fictitious pile is established with the approximation that the normal strain of the extended layered TISS along the axis of the pile is equal to the vertical strain of the fictitious pile. Then, by combining the fictitious pile method and the basic solution of the layered TISS, the second kind of Fredholm integral equation of the pile is established. Numerical results obtained by this study are compared with the existing results to verify the present study.

## II. Types of foundation

In Engineering, the design of foundation structures is much more critical than that of the design of a superstructure. Defects found in a foundation are much more difficult to rectify than any defects discovered in the superstructure. The properties of the soil under the foundation vary considerably. Although in most design cases, engineers assume that structure is rigid, so the ground pressures are uniform; in reality, soil deposits are not uniform. Soil varies with depth. Thus, when selecting and designing a foundation, it is necessary to consider the types and environmental conditions of foundation as well as the strength and durability of the foundation to avoid failure.

### 2.1 Shallow foundations

Shallow foundation is the type of foundation used when the soil medium below the footing is strong enough to withstand the loads from superstructures. This type of foundation is the most commonly used foundation. It is inexpensive and usually designed to support residential buildings as well as medium size structures, where the bearing capacity of the soil meets design requirements. Usually, the settlement is computed to determine immediate and long term effects.

### 2.2 Mat / Raft foundations

Mat/Raft foundation, as the name suggests, is large in size and distributes weight from superstructure to a large area. This type of foundation can be used to support structures of moderate height. Nevertheless, this foundation type is not suitable for high rise buildings, as this foundation cannot form adequate soil resistance to counter the effect of lateral loadings. The soil parameters used for designing this foundation type should be selected carefully reflecting the variation in both the soil vertical and horizontal directions. The effect of new construction should be considered [8].

### 2.3 Pile foundations

Pile foundation is used when the soil below the footing is not suitable for a raft/mat foundation system. This type of foundation is designed as single piles or pile groups to reinforce the stratum of the weak soil and support the superstructures. In addition, it is used to transfer vertical and imposed loads to the bearing soil stratum and resist lateral forces due to wind and earthquake.

## III. Governing equations and basic solution

In this section, the governing equations for the layered soil are introduced. Then the equations are used to derive the basic solution. The equilibrium equations are written as follows:

$$\frac{\partial \sigma_{rr}}{\partial r}+\frac{\partial \tau_{zr}}{\partial z}+\frac{\sigma_{rr}-\sigma_{\theta\theta}}{r}=0,\ \frac{\partial \sigma_{zz}}{\partial z}+\frac{\partial \tau_{zr}}{\partial r}+\frac{\tau_{zr}}{r}=0 \qquad (1)$$

in which $\sigma_{zz}$, $\sigma_{rr}$ and $\sigma_{\theta\theta}$ as well as $\tau_{zr}$ denote the total normal and shear stress, respectively. Then, the principle of effective stress for the saturated soil is expressed as follows:

$$\sigma=\sigma'+p, \qquad (2)$$

where $\sigma=\left\{\sigma_{rr},\sigma_{\theta\theta},\sigma_{zz},\tau_{zr}\right\}^T$; $\sigma'=\left\{\sigma'_{rr},\sigma'_{\theta\theta},\sigma'_{zz},\tau'_{zr}\right\}^T$; and $p=\left\{p,p,p,0\right\}^T$ represent the total stress, the effective stress, and the pore pressure vectors, respectively.

## IV. Formulation of the Fredholm integral equation for the single pile in a half space soil

This section presents a horizontally loaded pile embedded in a layered transversely isotropic saturated soil and subjected to a static load and a shear force at the top end as shown in Fig.1 the pile is used to exemplify the formulation process of the integral equation for the pile. The Young's modulus of the fictitious pile is obtained by subtracting the elastic modulus of the soil from the elastic modulus of the real pile, written as:

$$E_{p*b}=E_p-E_{vi}\ \ ,i=1,2 \qquad (3)$$

where $E_{p*1}$ and $E_{vi}$ are the Young's moduli of the fictitious pile corresponding to the real pile embedded in the first and second layers of the soil, respectively; $E_p$ is the elastic modulus of the real pile; $E_{s1}$ and $E_{sb}$ are respectively the elastic modulus of the first and second soil layers. The shear forces and moment are written as:

$$Q_0(t) = Q_0(0) + \int_0^t \frac{\partial Q_0(\tau)}{\partial \tau} d\tau \quad , \tag{4}$$

$$M_0(t) = M_0(0) + \int_0^t \frac{\partial M_0(\tau)}{\partial \tau} d\tau \quad , \tag{5}$$

where $Q_0(t)$ the shear force at the top and $M_0(t)$ is the bending moment of the pile.

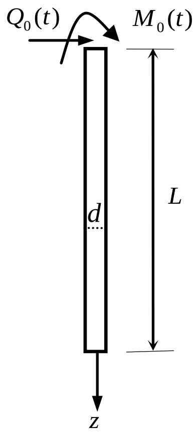



**figure 1** Schematic of a single pile

## V. Numerical results and analyses

First, numerical results computed by the proposed model for the analysis of pile embedded in a layered TISS are presented. Then, the results of this model are compared with those of existing solutions to validate the accuracy of the present model. Finally, a parametric study to investigate the effect of various parameters on the behavior of a single pile is carried.

Some quantities used in this paper are defined as:

$$z^* = \frac{z}{L_c}, \; R^* = \frac{r}{L_c}, \; t^* = \frac{k_c t}{L_c}, \; u^* = \frac{u_z(\mathrm{z})}{L_c}$$

$$N* = \frac{N(z)}{\mu_c L_c^2}, \; p^* = \frac{p(z)}{Q_o / d^2}, \; Q^* = \frac{Q\ (z)}{Q_0}, \; M^* = \frac{M\ (z)}{Q_0 d} \tag{6}$$

in which $L_c$, $\mu_c$ and $k_c$ represent the reference length, the shear modulus and permeability, respectively. Furthermore, the quantities with asterisk namely $z^*$, $R^*$ ,$u^*$, $N^*$ , $p^*$, $t^*$ $Q$ and $M$ denote the depth, radius, displacement, pile axial force, pore pressure, time, shear force and the moment, accordingly.

### 5.1. Verification of the proposed model

To verify the accuracy of the method used in this study, a numerical example is presented to show the final solution of the pile's response. The results obtained by the present model are compared with the existing results presented by [5]as shown in Fig.2. The relevant parameters used are given as: the pile length-diameter ratio $l/d = 20$, the soil Poisson's ratio $v = 0.3$ *and* the pile-soil Young's modulus ratio $E_p / E$. From the graphical representation thereof as depicted in Fig. 2, it is easy to notice that as the time $t$ approaches infinity, the pore pressure tends to zero, thereby validating the reliability of the proposed model.

### 5.2 Influence of the stratified property of the soil on the behavior of the pile

In this section, two examples with pile length $L$ are presented to check the effect of the stratified property of the soil on the response of the pile. The shear force and displacement of the pile together with the pore pressure of the soil at different times (seven days, $t = 6.048 \times 10^5$ s) and (twenty-eight days,

$t = 2.4192 \times 10^6$ s) are given. A layered half-space of three layers with different Young's moduli is used here. Three different cases are considered. Case A corresponds to a softer middle layer with shear moduli ratios as: $\mu_{v1} : \mu_{v2} : \mu_{v3} = 5:1:5$. Case B represents a homogeneous soil. Case C denotes a harder middle layer with shear moduli ratio given as: $\mu_{v1} : \mu_{v2} : \mu_{v3} = 2:3:2$. The stiffness ratio $\eta = 2.5$ is constant in the examples. Moreover, the soil parameters used in the examples are given in Table 1. The pile parameters are presented as the pile length $L = 20$ m; the pile radius and Young's modulus are held constant, $R = 0.25$ m, and $E_p = 2.6 \times 10^9$ Pa. In similar way, the thickness, shear modulus $\mu_v$ and coefficient of permeability $k_h$ of the first layer of the soil are given as the reference length $L_c$, shear modulus $\mu_v$ and coefficient of permeability $k_c$, accordingly.

Fig. 3 (a) shows that the depth increases with decreasing shear force of the pile for Case C and increases with increasing shear of the pile for Case A. However, Fig. 3 (b) shows that in the case of the softer middle layer(Case A), the shear force increases with increasing depth, while the depth increases with decreasing shear force for the harder middle layer (Case C). Moreover, Fig. 4 shows that for the harder middle layer Case C, the displacement of the pile is larger than that of (Case A). As shown in Fig. 5 (a) and (b), the pore pressure of the soil along the pile length gets larger for Case A and gets much smaller in Case C. In addition, the pore pressure of the soil decreases with time in the case of the homogeneous layer (Case B). From Fig. 3 and 4, the shear force and displacement of the pile decrease with increasing depth and also increase with increasing time. On the other hand, in Fig. 5, the pore pressure of the soil tends to zero as the time increases.

**Table 1** Parameters and values of the soil used in the example

| Layer number | $h$ / m | $\mu_v$ / Pa | | | $\nu_h$ | $\nu_{hv}$ | $\gamma_w$ / N·m$^{-3}$ | $k_v, k_h$ / m·s$^{-1}$ |
|---|---|---|---|---|---|---|---|---|
| | | Case A | Case B | Case C | | | | |
| 1 | 6 | $1.0\times10^7$ | $1.0\times10^7$ | $1.0\times10^7$ | 0.25 | 0.3 | $9.8\times10^3$ | $1.2\times10^{-7}$ |
| 2 | 6 | $2.0\times10^7$ | $0.5\times10^7$ | $1.0\times10^7$ | 0.25 | 0.3 | $9.8\times10^3$ | $1.2\times10^{-7}$ |
| 3 | - | $1.0\times10^7$ | $1.0\times10^7$ | $1.0\times10^7$ | 0.25 | 0.3 | $9.8\times10^3$ | $1.2\times10^{-7}$ |

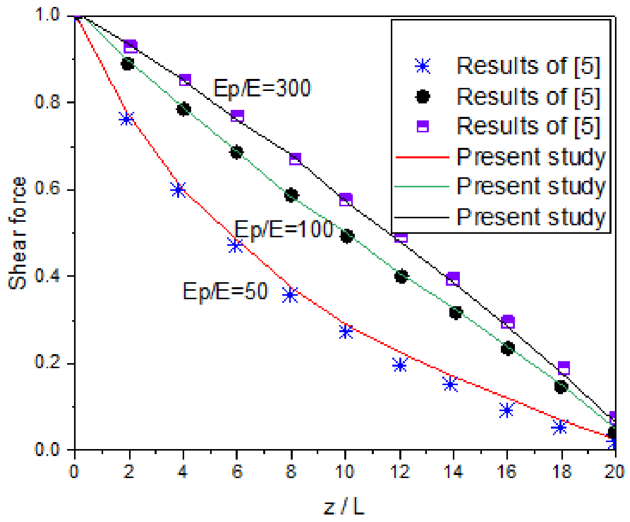
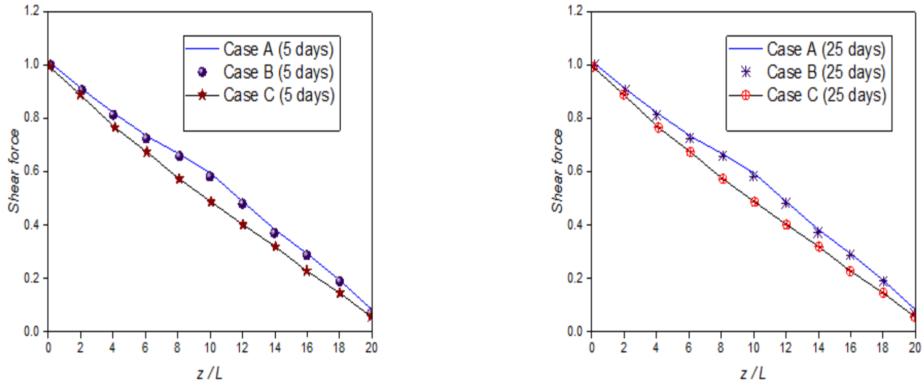
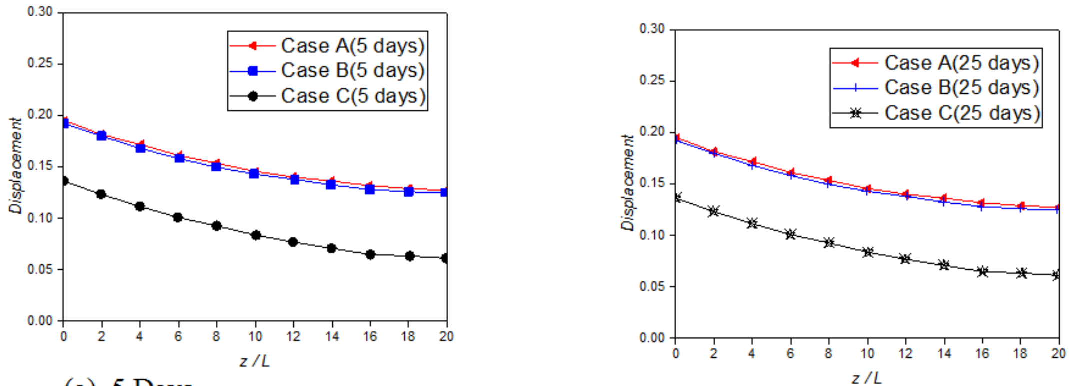



**Figure 2** Comparison with existing results for the shear force of the pile



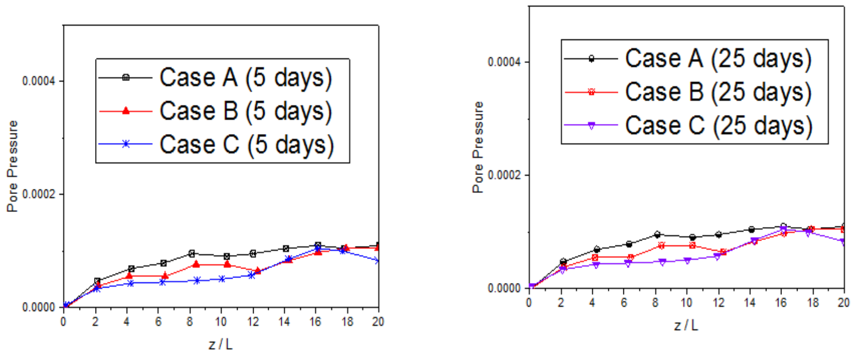

(a) 5 Days (b) 25 Days

**Figure 3** Variation of the pile shear force along the depth at time (a) 5 Days and (b) 25 Days




(a) 5 Days (b) 25 Days

**Figure 4** Variation of the pile displacement along the depth at time (a) 5 Days and (b) 25 Days




(a) 5 Days (b) 25 Days

**Figure 5** Variation of the pore pressure at the pile length along the depth at time (a) 5 Days and (b) 25 Days

## VI. Conclusion

In this study, the soil is regarded as a three-layered transversely isotropic saturated soil with two overlying layers and one underlying layer half-space. Numerical results of the present model are validated through comparison with the results of existing solutions. Numerical results of this paper show that time has a huge influence on the pore pressure of the soil. As validated, over a long period of time, the pore pressure along the pile-length vanishes to zero. This model is suitable for estimating the response of a horizontally loaded pile undergoing small deflection.

## References

[1]. Z. Y. Ai, Y. F. Chen, and X. B. Jiang, "Behavior of laterally and vertically loaded piles in multi-layered transversely isotropic soils," *Applied Mathematical Modelling,* vol. 51, pp. 561-573, 2017.

[2]. J. Booker and J. Small, "A method of computing the consolidation behaviour of layered soils using direct numerical inversion of Laplace transforms," *International Journal for Numerical and Analytical Methods in Geomechanics,* vol. 11, pp. 363-380, 1987.

[3]. S. Lee, Y. Kog, and G. Karunaratne, "Laterally loaded piles in layered soil," *Soils and foundations,* vol. 27, pp. 1-10, 1987.

[4]. S. Yimsiri and K. Soga, "Cross-anisotropic elastic parameters of two natural stiff clays," *Géotechnique,* vol. 61, p. 809, 2011.

[5]. V. Apirathvoraku and P. Karasudhi, "Quasi-static bending of a cylindrical elastic bar partially embedded in a saturated elastic half-space," *International Journal of Solids and Structures,* vol. 16, pp. 625-644, 1980.

[6]. B. Niumpradit and P. Karasudhi, "Load transfer from an elastic pile to a saturated porous elastic soil," *International journal for numerical and analytical methods in Geomechanics,* vol. 5, pp. 115-138, 1981.

[7]. R. Muki and E. Sternberg, "On the diffusion of an axial load from an infinite cylindrical bar embedded in an elastic medium," *International Journal of Solids and Structures,* vol. 5, pp. 587-605, 1969.

[8]. H. G. Poulos, "Tall building foundations: design methods and applications," *Innovative Infrastructure Solutions,* vol. 1, p. 10, 2016.

Oliver C. Waka. "A Time-Dependent Model For Predicting The Response Of A Horizontally Loaded Pile Embedded In A Layered Transversely Isotropic Saturated Soil." IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) , vol. 16, no. 2, 2019, pp. 48-53