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Performance functions for laterally loaded single concrete piles in homogeneous clays

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Abstract. A key parameter in the design of a laterally loaded pile is the determination of its performance level. Performance level of a pile is usually expressed as the maximum head deflection and bending moment. In general, uncertainties in the performance of a pile originates from many factors such as inherent variability of soil properties, inadequate soil exploration programs, errors taking place in the determination of soil parameters, limited calculation models as well as uncertainties in loads. This makes it difficult for practicing engineers to decide for the reliability of laterally loaded piles both in cohesive and cohesionless soils. In this paper, limit state functions and consequent performance functions are obtained for single concrete piles to predict the maximum bending moment, a widely accepted design criterion along with the permissible pile head displacement. Analyses were made utilizing three dimensional finite element method and soil-structure-interaction (SSI) effects were accounted for.

Keywords: laterally loaded pile; clay; maximum bending moment; pile head displacement; response surface method; performance function; soil-structure-interaction.

1. Introduction

Selection of pile dimensions and type are usually based on soil characteristics and loading conditions. Lateral loads become a concern for pile foundations under tall buildings or in seismically active regions. Lateral loading of a pile may be due to 'active' loading where external loads are applied at the pile head or due to 'passive' loading where lateral movement of the soil induces bending stresses in the pile (Fleming *et al.* 1994). Pile sectional forces and pile head displacement are strongly influenced by the interplay between the pile and the soil, which is expressed by the relative pile-soil stiffness factor. In current design practice, performance based design has become a crucial task especially in earthquake prone areas and geotechnical engineers are expected to predict both maximum pile head displacement and moment in the design stage.

Modern analysis methods accounting for the lateral load-deflection behavior of piles have become available since late 1960s. Response of a single pile subjected to lateral loads has been successfully

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modeled by means of finite difference method (FDM) using nonlinear soil-pile deformation (*p–y*) curves. The *p–y* analysis requires use of numerical solution algorithms (Wang and Reese 1993). The finite element method (FEM), which is more versatile than the finite difference method, has been widely used for evaluating soil-pile interaction (Randolph 1981, Kagawa and Kraft 1981). Non-trivial solutions of governing equations with relatively complex boundary conditions were also obtained (Banerjee and Sen 1987, Makris and Gazetas 1992, Catal 2002, Liu *et al.* 2004, Catal 2006, Catal and Catal 2006, Yesilce and Catal 2008, Achmus *et al*. 2009). Among these approaches numerical methods that are based on finite difference and finite element techniques often produce close results since they consider three dimensional and nonlinear behavior of soil around laterally loaded pile (Tand and Vipulanandan 2008). Although this is the case, 3D modeling of the pile and the surrounding soil requires labor intensive work during modeling stage resulting in high analyses costs that are not usually justified for majority of the projects. The complexity of the laterally loaded pile problem, however, not only arises due to the need for expensive analysis procedures but also due to the variability of soil properties and alterations of these properties as a result of pile manufacturing methods. Therefore, probabilistic approaches for reliability analyses are frequently recalled for laterally loaded piles in order to address inherent uncertainties.

The response surface method is a cost effective and efficient means of reliability analysis of laterally loaded pile problem. Previous studies focused on the comparison of reliability analyses using various approximate performance function such as linear, reciprocal and quadratic with Monte Carlo simulation (Tandjiria *et al.* 2000). It was found that approximate response functions can be effectively used for reliability analysis of laterally loaded pile problems. In another study, reliability of rigid laterally loaded piles in cohesionless soils was studied using both response surface and power series approaches (Pula 2007). Explicit forms of performance functions obtained by considering soil-structure interaction effects for laterally loaded piles in cohesive soils are not available in the literature. In this study, behavior of both rigid and flexible single concrete piles were taken into consideration using Broms (1964), Murthy and Subba Rao (1995), *p–y* curve (Reese, 1985), two and three dimensional finite element methods (Randolph 1981, Brinkgreve and Broere 2006). Firstly, the service load level corresponding to allowed lateral pile head deformation is computed using Broms method. Rigid and flexible pile cases were then examined by keeping the pile length constant while varying the pile diameter and the undrained shear strength of a homogenous cohesive soil. It was decided that the three dimensional finite element method better represents complexity of the problem. Simple yet still satisfactory performance functions for laterally loaded piles in homogenous cohesive soils are obtained using the 3D FEM and Response Surface Methods.

2. The soil-pile model

Majority of the available laterally loaded pile analysis methods suffer from the disadvantage of not being able to account for the slippage between the soil and laterally deforming pile. Some *p–y* models have been proposed in the past for considering gap formation and shear stress generation on soil-pile interface (Nogami *et al.* 1992). However, their utilization requires establishment of complex *p–y* curves and numerical solution algorithms. During the last decade, finite element method (FEM) has been widely used by researchers. One of the primary advantages of the finite element method is that it can be easily extended to a stratified soil medium by taking material nonlinearity and slippage along the soil-pile interface into account. The pile-soil system can be analyzed in three dimensions. The FEM, however, is computationally expensive compared to other methods since a large number of finite elements with several degrees of freedoms need to be employed in order to accurately model the behavior of the pile. Three-dimensional finite element method using commercially available software was preferred in this study in order to account for soil structure interaction aspects such as soil nonlinearity, soil-pile slippage and relative soil-pile stiffness.

In the pile-soil model of this study, a free head pile with an embedment length of 10 m in fully saturated homogeneous clay is loaded at the top. The soil profile is assumed to be isotropic with constant deformation modulus (E_u) and undrained shear strength (c_u) values to a depth of 15 m. These two parameters are linked to each other by means of a well known empirical relationship (Duncan and Buchignani 1976)

$$E_u = K_{c_u} \times c_u \tag{1}$$

where, E_u is the undrained deformation modulus (kPa), K_{cu} is a factor relating E_u to c_u, and c_u is the undrained shear strength. In this study the empirical adjustment coefficient, K_{cu}, is somehow arbitrarily selected as 200 resulting in the variation of elastic modulus between 1×10^4 and 2×10^4 kN/m^2.

The length-to-diameter ratio of the pile varied between 8.3 and 25 for a fixed pile length of 10 m covering a wide variation range for the pile flexibility parameter, β, as defined by Eq. (2) (Hannigan *et al*. 1998). The pile is considered as long (i.e., flexible) when $\beta L > 2.25$, and short (i.e., rigid) for $\beta L < 2.25$.

$$\beta = \left(\frac{k_h B}{4E_p I_p}\right)^{1/4} \tag{2}$$

In the above equation E_pI_p is the bending stiffness of the pile, k_h is the coefficient of horizontal subgrade reaction, B and L are the diameter and length of the pile, respectively.

The service load level is defined by factoring the load determined according to Broms' Methods (Broms 1964) using the pile diameter, pile length and βL corresponding to the maximum allowable lateral head deflection (i.e., 30 mm). The factoring coefficient is taken as 2.5 as suggested in the literature (Hannigan *et al*. 1998). The soil-pile characteristics and service loads are given in Fig. 1 and Fig. 2, respectively.

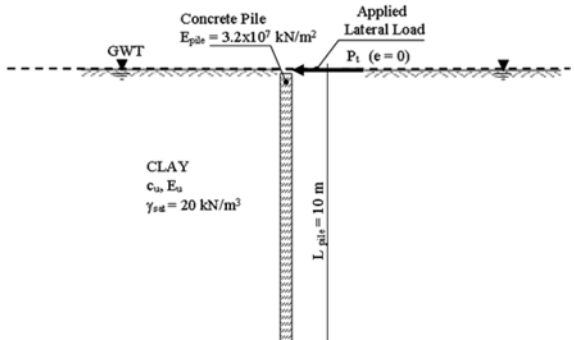

Fig. 1 Schematic view of soil-pile model used in the analysis

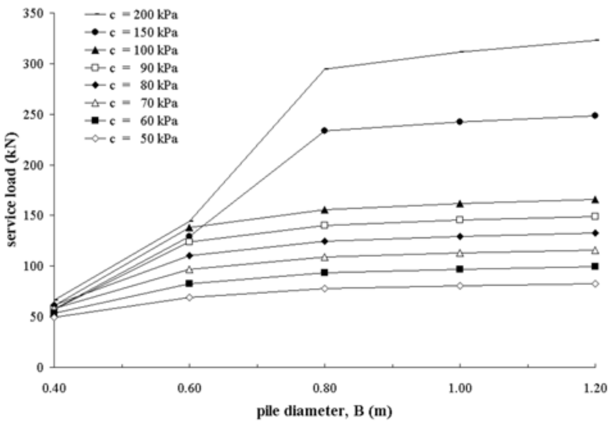

Fig. 2 Service loads on piles

Table 1 Material properties of the cohesive soil

Parameter	Name	Value	Unit
Material model	Model	Mohr-Coulomb	-
Type of material behavior	Type	Undrained	-
Unit weight of soil above phreatic level	γ_{unsat}	19	kN/m^3
Unit weight of soil below phreatic level	γ_{sat}	20	kN/m^3
Young's modulus (constant with depth)	E_{ref}	200×c_u	kN/m^2
Poisson's ratio	ν	0.495	-
Undrained cohesion (constant with depth)	c_u	50-60-70-80-90-100-150-200	kN/m^2
Friction angle*	ϕ	1	o
Dilatancy angle	ψ	0	o

*for numerical stability purposes.

Table 2 Material properties of the pile

Parameter	Name	Value	Unit
Material model	Model	Linear Elastic	-
Unit weight of soil above phreatic level	γ_{unsat}	25	kN/m^3
Young's modulus (constant)	E_{ref}	2.7×10^7	kN/m^2
Poisson's ratio	ν	0.2	-

The constitutive soil model in FEM analyses was the Mohr-Coulomb model. Soil elements are assumed to be homogeneous and isotropic. Total stress conditions are taken into consideration. The soil-pile interface strength parameter is set to two-thirds of the corresponding soil strength parameter by means of the interface parameter (R_{inter}) so that strength reduction due to slippage of the soil around the pile is taken into consideration. The pile was modeled as a linear elastic massive circular pile. Details of the soil and pile models are given in Table 1 and Table 2, respectively. The three dimensional nature of the pile and the surrounding soil was modeled using a fine mesh consisting of

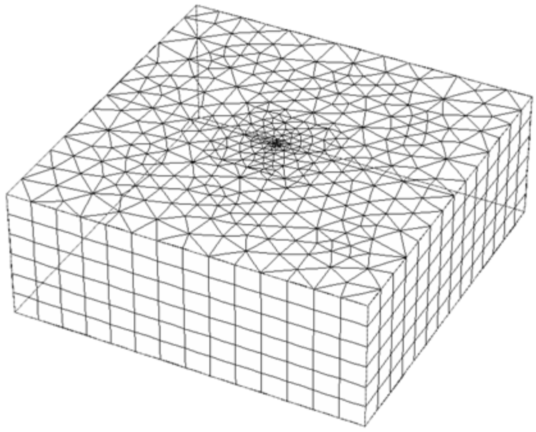

Fig. 3 Finite element mesh of model

4380 fifteen node wedge elements. The number of finite elements and model dimensions were decided upon several FEM analyses trials until discretization and boundary effects became negligible. It was found that forty times the diameter of the pile was satisfactory for one side of the square working plane of which the pile is positioned at the centre. Several FEM runs were performed for different pairs of pile diameter and undrained shear strength. Pile diameter varied between 40 and 120 cm whereas the variation range for undrained shear strength was 50 to 200 kPa. Pile head deformation and bending moment data calculated via the FEM method were found to be in good agreement with those of a previous study (Randolph 1981). A typical model and the FEM mesh are shown in Fig. 3.

3. Development of performance functions

Contemporary methods for risk assessment of various geotechnical problems often require development of performance functions since computational costs can be reduced in this manner by avoiding repeated solution of governing equations during probabilistic analyses. The multiple linear regressions (MLR) and the response surface methods (RSM) are generally utilized in order to achieve such functions. This approaches were also applied to the reliability analysis of retaining systems and differential settlement problems in the past (Mahadevan and Shi 2001, Park *et al.* 2007).

Bending moment and pile head displacement are the key parameters for structural design of laterally loaded piles. In this study, the maximum bending moment has been chosen as the dependent variable during RSM analyses. Pile head displacement, however, is implicitly taken into consideration by defining the service lateral load as the forty percent of the load resulting in 30 mm pile head displacement which is the generally accepted displacement criterion.

Behavior of laterally loaded pile is a function of the stiffness of the pile relative to that of the soil. Piles are either defined as rigid or flexible piles depending on their deformed shape under lateral load. The pile rigidity factor as defined previously is used while deciding whether a pile is rigid or flexible. It can be noticed in Fig. 4 that the transition from rigid to flexible pile behavior occurs for the data pair of c_u = 100 kPa and B = 60 cm. Similar shifts on pile behavior are also observed in

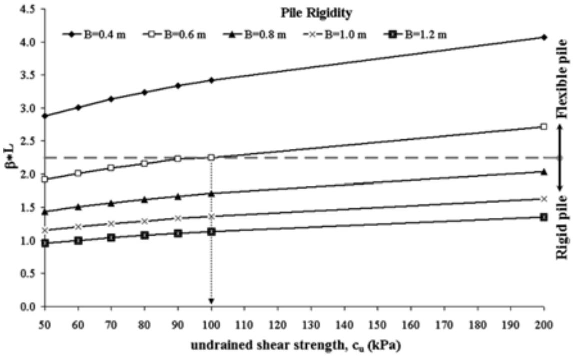

Fig. 4 Pile diameter-pile rigidity relationship at various undrained shear strength values

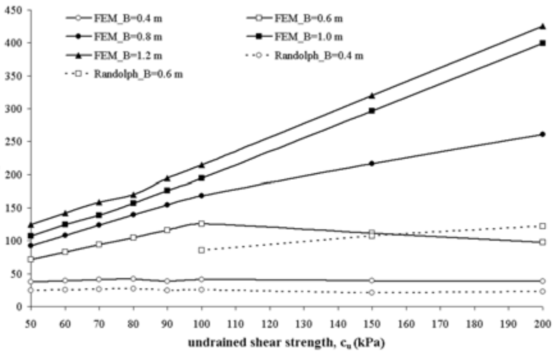

Fig. 5 Variation of the maximum bending moment with undrained shear strength and pile diameter

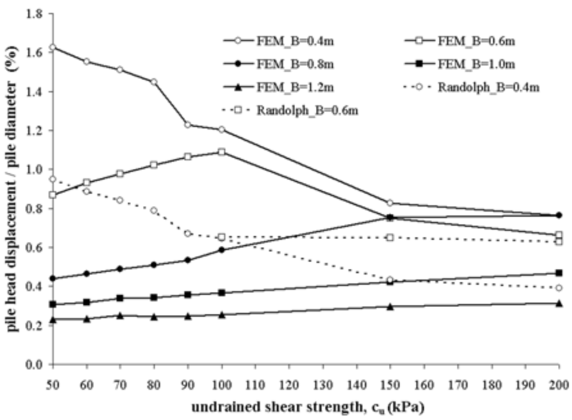

Fig. 6 Dimensionless pile head displacement parameter as a function of undrained shear strength and pile diameter

Fig. 5 and Fig. 6. One should note in Fig. 5 that bending moment is not as sensitive to undrained shear strength for flexible piles. Computed pile responses for flexible piles via FEM are also in good agreement with those reported by Randolph (1981). Piles with diameters 80, 100 and 120 cm mostly behave as rigid. Following the evaluation of the data from this point of view, performance functions were developed for both rigid and flexible pile behavior utilizing RSM approach.

The undrained shear strength (c_u), which is linearly correlated with elastic modulus of soil (E_u), and the pile diameter (B) were used as independent variables. The following limit state functions have been developed for both rigid (short) and flexible (long) piles for maximum bending moment (Eq. (3) and Eq. (4))

Limit State Function of Maximum Moment for Rigid Piles (LSFRP)
$$= 151\ \mathrm{B} - 1.66\ c_u - 124\ \text{(kNm)} \tag{3}$$

Limit State Function of Maximum Moment for Flexible Piles (LSFFP)
$$= 352\ \mathrm{B} - 0.0382\ c_u - 97.2\ \text{(kNm)} \tag{4}$$

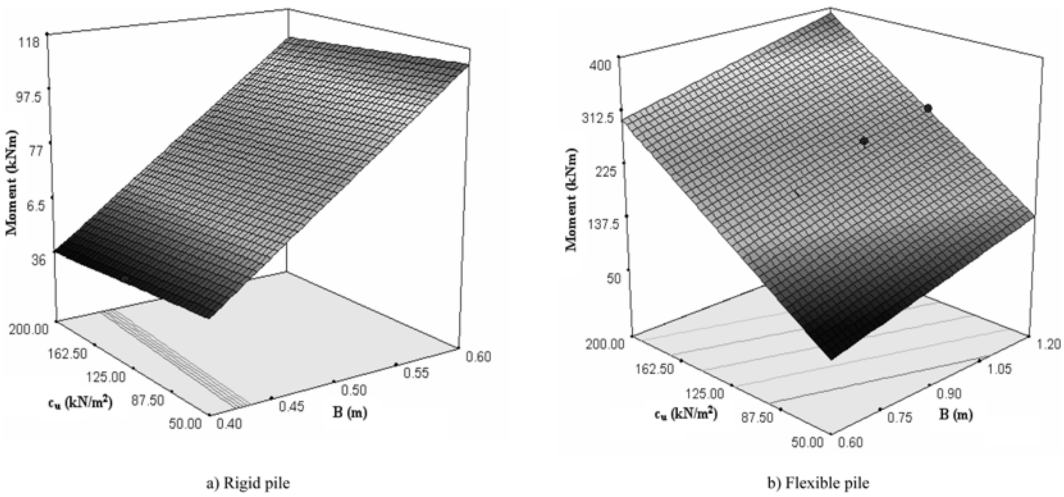

Fig. 7 Variation of the estimated maximum bending moment with undrained shear strength and pile diameter

where the pile diameter (B) is in units of meter, and undrained shear strength (c_u) is in units of kN/m^2. The limit state functions as proposed here yield the maximum moment values for both short and long piles satisfactorily. In these linear relations, the coefficients of correlation (R) for short and long pile cases were determined as 0.97 and 0.99, respectively. The variation of the maximum bending moment estimated using limit state functions is given in Fig. 7.

Respective performance functions for reliability analysis of laterally loaded single piles in homogenous clays can be defined by Eq. (5) and Eq. (6) for rigid and flexible piles. The ultimate moment, M_u, carrying capacity of a particular pile is used while defining these functions. It should be noted that ultimate moment capacity of a pile depends on its structural design.

$$\text{Performance function for Rigid Piles (PFRP)} = \text{LSFRP} - M_u \tag{5}$$

$$\text{Performance function for Flexible Piles (PFFP)} = \text{LSFFP} - M_u \tag{6}$$

4. Conclusions

A parametric study was performed using three dimensional finite element method to obtain simple performance functions that can be readily used for reliability analysis of laterally loaded single piles in homogenous and isotropic clay soils. In the case of flexible pile ($B = 0.4$ m and $B = 0.6$ m where $c_u > 100$ kPa), the maximum moments determined by the mentioned five different methods, are also the same in spite of increasing undrained shear strength. Nevertheless, in the case of rigid piles ($B = 0.6$ m where $c_u < 100$ kPa, $B = 0.8$ m, 1.0 m, 1.2 m), the maximum moment values increase parallel to the increasing of undrained shear strength. The head displacement of flexible piles decreases while the shear strength increases, whereas that of rigid piles increases. Analysis results shows that pile performance functions can be effectively evaluated taking soil-structure-interaction into account. One needs to determine the relative soil-pile stiffness factor in order to decide for the proper performance function to be utilized in reliability analyses. Maximum bending moment is expressed as a linear function of undrained shear strength and pile diameter. The proposed limit state functions should be considered as linear solution planes of the lateral pile response bounded by the predetermined pile head displacement, variation range of the undrained shear strength and pile diameter. The ultimate bending moment of the performance function is governed by the structural design of a reinforced concrete particular pile. It should be noted; however, that reinforcement ratio of a concrete pile may alter its response and may cause even a smaller diameter pile to behave as a rigid one under certain conditions. The engineer should be cautious while deciding for the type of the performance function. An inspection of the moment-curvature relationship for a reinforced concrete section using an appropriate concrete model may be beneficial at this stage. The methodology presented in this study can be applied to other cases such as piles in cohesionless soils and different pile materials.

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