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Research Paper

Parametric investigation on the responses of laterally loaded piles in overconsolidated clay using nondimensional solutions addressing nonlinear soil-pile interaction

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ABSTRACT

This paper presents nondimensional solutions and parametric studies of the responses of laterally loaded piles in overconsolidated clay. Nondimensional expressions of a nonlinear *p-y* model, termed as the H-model, and the governing equation of laterally loaded piles were derived and solved. Parametric studies by virtue of the nondimensional solutions were conducted, which revealed that the pile head response is highly sensitive to the change in the soil undrained shear strength (s_u), the maximum lateral bearing factor ($n_{p(max)}$), and the ratio of the elastic modulus of subgrade reaction to the soil undrained shear strength (n_k), but is insensitive to other parameters in the model.

Introduction

Pile foundations are often used to resist lateral loads induced by ocean waves and/or wind load on offshore structures, high-rise buildings, and bridges. Over many decades, various calculation approaches have been proposed to analyze and design laterally loaded piles. Some of these approaches are the subgrade reaction method [1,2], the *p-y* method [3–12], the finite element with soil as an elastic material [13], the finite element method with soil as an elasto-plastic material [14–17], and the analytical method [18,19]. Among these approaches, the *p-y* method is probably the most widely used in engineering practice as it can be used to model soil nonlinearity with manageable computational effort.

Early *p-y* curves were often formulated on the basis of field test results. Later on, based on either field observations or theoretical derivations, a number of *p-y* models were developed to simulate the behavior of piles subjected to lateral loads [3,6,8,20–22]. On the one hand, many ingredients of the models are empirical or semi-empirical, and there are significant differences between the assumptions adopted by the different models. For example, a variety of formulas have been proposed to calculate the distribution of the ultimate soil resistance (p_{ult}) with depth for sand, and different formulas usually result in significantly different p_{ult}-distributions [8]. In case of overconsolidated clay, the lateral bearing factor at ground surface, the maximum lateral bearing factor, and the critical depth at which the lateral bearing factor reaches the maximum level are important parameters that are used to delineate the p_{ult}-distribution. The values suggested by the different studies [9] may have multi-fold differences. On the other hand, some soil properties are needed as inputs for the *p-y* models. However, measurement uncertainty of the properties in field or laboratory is unavoidable. The uncertainty might arise from disturbance of soil sample, non-uniform distribution of soil in the field or different testing methods [23]. For example, Marsland [24] found that the undrained shear strength of clay, back calculated from in-situ plate-load tests, was only approximately 25% of the value of strength determined using field vane tests. Yet, the impact of variation in the values of model parameters and soil properties on the prediction of laterally loaded piles has not been systematically investigated.

This study presents nondimensional solutions to the responses of laterally loaded piles, which render parametric investigation feasible and convenient. Piles embedded into idealized ground having a constant elastic subgrade reaction and demonstrating a bilinear distribution of the ultimate soil resistance with depth were examined. A *p-y* model, termed as the H-model, was proposed to describe the nonlinear soil-pile interaction, in which a parameter *h* is used to characterize the degree of nonlinearity (*i.e.*, shape) of the *p-y* curve. By introducing a reference displacement, the H-model and the governing equation of the laterally loaded piles can be normalized and expressed in nondimensional forms. The nondimensional solutions for both free- and fixed-head piles can then be obtained and compared. With the help of the

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Notation

B	Diameter of the pile
E	Young's modulus of the pile
E_s	Soil elastic modulus
F	Shear force
F_n	Normalized shear force
h	Scaling factor for the plastic modulus
h'	Scaling factor for the plastic modulus above the critical depth
I	Second moment of the pile cross sectional area
k_e	Elastic modulus of subgrade reaction
k_p	Plastic modulus of subgrade reaction
L_{crit}	Critical length of pile
M_n	Normalized bending moment
M	Bending moment
n_k	Ratio of the elastic modulus of subgrade reaction to the soil undrained shear strength
n_p	Lateral bearing factor
n_{p0}	Lateral bearing factor at the ground surface
$n_{p(max)}$	The maximum lateral bearing factor
p	Soil resistance per unit length
p_n	Normalized soil resistance
p_{ult}	Ultimate soil lateral resistance
$\widetilde{p}_n$	Normalized soil resistance that is normalized by $p_{ult(max)}$
$p_{ult(max)}$	Ultimate soil lateral resistance below the critical depth
s_u	Undrained shear strength of soil
T	Relative stiffness factor
y	Lateral displacement of the pile
y_e	Elastic component of the displacement
y_p	Plastic component of the displacement
y_n	Normalized displacement
$\widetilde{y}_n$	Normalized displacement that is normalized by $\widetilde{y}_{ref}$
y_{n50}	Normalized displacement when the soil resistance reaches an half of the ultimate resistance
y_{ref}	Reference displacement
$\widetilde{y}_{ref}$	Reference displacement below the critical depth
z	Depth below the ground surface
z_{crit}	The critical depth
z_n	Normalized depth

nondimensional solutions, parametric investigation was carried out to shed light on the influence of soil properties and other key model parameters on the pile response.

1. Idealized ground model for overconsolidated clay

An overconsolidated clayey ground is idealized by a constant elastic subgrade reaction k_e [25] and a bilinear variation of the ultimate soil resistance p_{ult} with depth was assumed for analyzing soil-pile interaction in the overconsolidated clay. Following [3,9,26], a linear relationship between k_e and the soil undrained shear strength s_u was adopted, given by

$$k_e = n_k s_u \tag{1}$$

where n_k is a dimensionless constant (Fig. 1(a)). Taking into consideration $k_e/E_s = 2$ where E_s is the Young's modulus of the soil [26] and $200 \leqslant E_s/s_u \leqslant 500$ in which larger values are more appropriate for clays with higher strengths [27], Table 1 shows the suggested value of n_k. The values were adopted in subsequent analyses, as described in subsequent sections of this study. Some past studies [28,29] pointed out that k_e also depends on the relative stiffness between the pile and the soil, which means that n_k can be expressed as a function of this relative stiffness. These aspects, though, are beyond the scope of this paper.

Utilizing the theory of bearing capacity, the ultimate soil resistance p_{ult} can be expressed as

$$p_{ult} = p_{ult}(z) = n_p(z) s_u B \tag{2}$$

where $n_p(z)$ is the depth-varying lateral bearing capacity factor and B is the pile diameter. Many different functions had been proposed to describe $n_p(z)$ [3,9,20–22,30]. In this study, a bilinear variation of $n_p(z)$ was adopted, where $n_p(z)$ increases linearly from the ground surface down up to a critical depth z_{crit}, below which $n_p(z)$ remains constant (see Fig. 1(b)).

As has been proposed in past studies, the lateral bearing factor at ground surface, denoted by n_{p0}, ranged between 2 and 4.83, and the maximum lateral bearing factor, denoted by $n_{p(max)}$, was between 8 and 12.2 [9]. As summarized in Table 2, the ratio between n_{p0} and $n_{p(max)}$ ranged between 0.18 and 0.40 with an average of approximately 0.29. In this study, it was assumed that $n_{p0} = n_{p(max)}/3$.

Different values of z_{crit}, often expressed in a function of pile diameter B, were proposed. It was reported as $z_{crit} = 1.5B$ [21], $3B$ [31], and $3.5B$ [35]. In this study, however, z_{crit} was assumed to take the value of the relative stiffness factor T given by

$$z_{crit} = T = \left(\frac{EI}{k_e}\right)^{1/4} \tag{3}$$

where E is the Young's modulus of the pile and I is the second moment of the pile cross-sectional area. Note that T has units of length. The use of $z_{crit} = T$ was to facilitate the derivation of nondimensional solutions that will be presented later in this paper. The impact of change in z_{crit} on the pile responses will be discussed in a later section. In fact, for a circular pile $I^{1/4}$ and thus z_{crit} in Eq. (3) can also be written as a linear function of B. In summary, the bilinear distribution of $p_{ult}(z)$ as adopted in this study can be expressed as

$$\begin{cases} p_{ult}(z < z_{crit} = T) = \left(\frac{1}{3} + \frac{2z}{3T}\right) n_{p(max)} s_u B \\ p_{ult}(z \geqslant z_{crit} = T) = p_{ult(max)} = n_{p(max)} s_u B \end{cases} \tag{4}$$

where z is the soil depth measuring from the ground surface.

2. The *p-y* formulation: H-model

In a *p-y* relationship, p (units of force/length) represents the soil resistance per unit length of pile at a given depth and y denotes the lateral displacement of a pile at the same depth. This elasto-plastic nonlinear *p-y* relationship is written in an incremental form in which the displacement increment Δy is decomposed into the elastic Δy_e and the plastic components Δy_p, given by

$$\Delta y = \Delta y_e + \Delta y_p \tag{5}$$

One can write

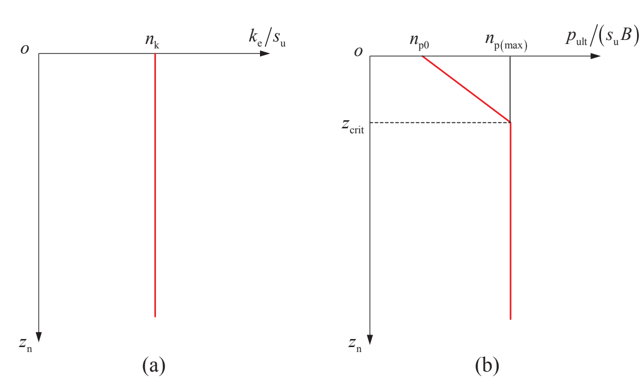

Fig. 1. Distribution of (a) k_e with depth; (b) p_{ult} with depth.