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Research Article

The Design Method of Slope Stabilizing Piles: A Review

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Abstract

A comprehensive literature review was conducted to examine the current state of knowledge regarding passive piles which specifically focused on the recently adopted design methods for landslide prevention. Of all the publications compiled and reviewed for passive loading on piles, numerous efforts were found starting from over the last three decades, where major emphasis was placed on the various approaches ranging from theoretical and analytical to finite element methods. These methods have been adapted to predict the response of the piles, which also incorporates the influence of group interaction factors. Although research on passive piles subjected to lateral soil movement seems to be recent, there seemed to be a missing gap in research for pile groups used as landslide stabilizing piles. The authors believe that all of these state-of-the-art methods are widely accepted as it is supported by comparison with both field and laboratory data. Based on the review, the authors would like to highlight that further three dimensional (3D) modeling would offer another excellent alternative to study the response of those piles for landslide mitigation purposes.

Keywords: *lateral soil movement, reinforced slope, small diameter steel piles, slope stabilizing piles, passive piles.*

1. Introduction

Existing design methods for slope stabilizing piles can be categorized into pressure or displacement-based method (De Beer and Wallays 1972; Ito and Matsui 1975; Poulos, 1995) and numerical methods (Oakland and Chameau 1984; Poulos and Chen 1997). In the first case, the pile is subjected to a presumed slope displacement. This, along with the distribution with depth of the soil modulus and the limiting values of pile-soil contact pressure, has to be pre-specified. In the second case (i.e. numerical methods), the problem is analyzed by employing finite elements or finite differences. These methods can presently tackle the entire 3D problem, taking into account of the exact geometry, soil-structure interaction and pile group effects. Although such methods are in principle the most rigorous, the 3D application is computationally intensive and time consuming.

1.1 Pressure or Displacement Based Methods

In these methods, the pile is modeled as a beam connected with the soil through nonlinear springs, at the support of which the displacement of the slope is imposed. Hence, the assessment of pile lateral capacity is accomplished by solving two differential equations:

1. For the portion of pile above the sliding surface:

$$EI\left(\frac{d^4 y_1}{dz^4}\right) = q(z), \qquad \text{for } z < 0 \tag{1}$$

in which y_1 = pile deflection above the sliding surface (assumed to lie at z=0) and EI = pile's bending stiffness. The force intensity, q(z), is calculated using the principle of plastic deformation of soil.

2. For the portion of pile below the sliding surface:

$$EI\left(\frac{d^4 y_2}{dz^4}\right) = -Ky_2, \qquad \text{for } z \geq 0 \tag{2}$$

where y_2 = pile deflection below the sliding surface and K is related to the modulus of subgrade reaction of soil.

Despite its simplicity, this approach requires predetermining the slope-displacement profile and the distribution of lateral soil modulus (the assessment of which may require extensive field measurements), as well as the limiting lateral pile-soil pressure with depth. A

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number of analytical approaches have been developed for the determination of the latter. Among the most widely accepted are the approaches of Poulos (1973, 1999), Viggiani (1981), and Reese et al. (1992). These methods assume a single laterally loaded pile and correlate the ultimate soil-pile resistance with the undrained shear strength for clays and with the overburden stress and friction angle for sands. A drawback of these methods is that group effects are simplistically taken into account by the application of reduction factors (e.g., Chen and Poulos 1993; Poulos 1995; Guerpillon et al., 1999; Jeong et al., 2003). Ito and Matsui (1975) developed a plastic extrusion-deformation model for rigid piles of infinite length (and not closely spaced) to estimate the shear resistance offered by a row of piles embedded in a slope. Their approach presumes that the soil is soft and deforms plastically around piles. Despite its rigor, the method neglects pile flexibility, pile limited length, and soil arching-phenomena that may all have a substantial effect (Zeng and Liang 2002; Liang and Yamin 2009). This approach has formed the basis of a number of design methods (Popescu 1991; Hassiotis et al., 1997).

1.2 Numerical Method

Because of the dramatic progress in computing and software power over the last few years, the finite element (FE) and finite difference (FD) methods are increasingly popular. These methods provide the ability to model complex geometries and soil-structure interaction phenomena such as pile-group effects. Moreover, they are able to model the three dimensionality of the problem, and may well capture soil and pile non-linearity. As early as 1979, Rowe and Poulos (1979) developed a two dimensional (2D) finite element approach that, in a simplified way, accounted for the three dimensional (3D) effect of soil flowing through rows of piles. A 3D elastic FE approach has been developed by Oakland and Chameau (1984) for the analysis of stabilization of surcharged slopes with drilled piles. Chow (1996) presented a numerical model in which the piles are modeled using beam elements and the soil is modeled using a hybrid method of analysis, which simulates the soil response at individual piles (using the subgrade reaction modulus) and the pile-soil-pile interaction (using the theory of elasticity). This method has been recently used by Cai and Ugai (2000) to analyze the effect of piles on slope stability. More recently, Kim et al., (2002) and Mujah et al. (2013) introduced a model based on the load-transfer approach to compute the load and deformations of piles subjected to lateral soil movement. Despite their potential rigor, the application of numerical methods in three dimensions requires extensive computational resources, often becoming unattractive to practitioners (Kourkoulis et al., 2012).

2. Recent Development on Slope Stabilizing Piles

Hereafter, some of the current research pertaining to slope stabilizing piles undertaken by some researchers are discussed, taking into consideration the aspects of the newly adopted techniques available in the field at present namely the hybrid method of analysis, uncoupled method of analysis and also the coupled method of analysis.

2.1 Hybrid Method of Analysis

This method was proposed by Kourkoulis et al. (2012) which develop a hybrid method for designing slope-stabilizing piles, combining the accuracy of rigorous three dimensional (3D) finite elements (FE) simulation with the simplicity of widely accepted analytical techniques. It consists of two steps: (1) evaluation of the lateral resisting force (RF) needed to increase the safety factor of the precarious slope to the desired value, and (2) estimation of the optimum pile configuration that offers the required RF for a prescribed deformation level. The first step utilizes the results of conventional slope-stability analysis. A novel approach is proposed for the second step. This consists of decoupling the slope geometry from the computation of pile lateral capacity, which allows numerical simulation of only a limited region of soil around the piles. A comprehensive validation is presented against published experimental, field, and theoretical results from fully coupled 3D nonlinear FE analyses. The proposed method provides a useful, computationally efficient tool for parametric analyses and design of slope stabilizing piles.

2.2 Uncoupled Method of Analysis

The uncoupled method of analysis for slope stabilizing piles stems for the fact that the pile response (i.e. pile displacement, bending moment, shear force and also pile deflection) and slope stability are considered separately according to their specified method of analysis. A study conducted by Jeong et al., (2003) describes a simplified numerical approach for analyzing the slope-pile system subjected to lateral soil movements. The lateral one-row pile response above and below the critical surface is computed by using load transfer approach. The response of groups was analyzed by developing interaction factors obtained from a three-dimensional nonlinear finite element study. The nonlinear characteristics of the soil-pile interaction in the stabilizing piles are modeled by hyperbolic load transfer curves. The Bishop's simplified method of slope stability analysis is extended to incorporate the soil-pile interaction and evaluate the safety factor of the reinforced slope. Numerical study is performed to illustrate the major influencing parameters on the pile-slope stability problem. Through comparative studies, it has been found that the factor of safety in slope is much more conservative for an uncoupled analysis than for a coupled analysis based on three-dimensional finite element analysis.

2.2.1 Uncoupled Analytical Model

2.2.1.1 Analysis of Stabilizing Piles

The sliding soil mass above the failure surface is assumed to be reinforced by the placed rows of piles that resist soil movements and transfer loads to the more stable underlying layers. Figure 1 shows a passive pile subjected to lateral soil movement, where the soil mass is divided into an unstable layer (the passive pile portion) and a stable layer (the active pile portion) (Chen, 1994). In their study, Jeong et al., (2003) has introduced a model to compute load and deformations of piles subjected to lateral soil movement based on the transfer function approach. The problem is decomposed into two components. First, the pressure-displacement (P–δ) curves induced in the sub-stratum are determined either from measured test data or from finite-element analysis. Second, a coupled set of P–δ curves is used as input to study the behavior of the piles which can be modeled as a beam resting on non-linear soil spring supports. Simple numerical solution procedures are developed for fairly general conditions (nonlinear stress-strain behavior at the pile-soil interface and non-homogeneous soil conditions). The governing equation for the pile deflection can be expressed in separate forms for the pile segments along its z axis at node, i above [Equation (3)] and below [Equation (4)] the interface (Figure 2).

$$EI\left(\frac{d^4 w}{dz^4}\right)_i = p = K_i\left[(y_s)_i - w_i\right] = K_i\delta_i \quad (3)$$

$$EI\left(\frac{d^4 w}{dz^4}\right)_i + K_i w_i = 0 \quad (4)$$

Where, w = lateral pile displacement
y_s = free-field soil movement at each depth before pile installation
K_i = elastic constant of soil
E_s = initial tangent stiffness
EI = pile's bending stiffness
δ_i = relative displacement between free-field soil movement (y_s) and lateral pile displacement (w).

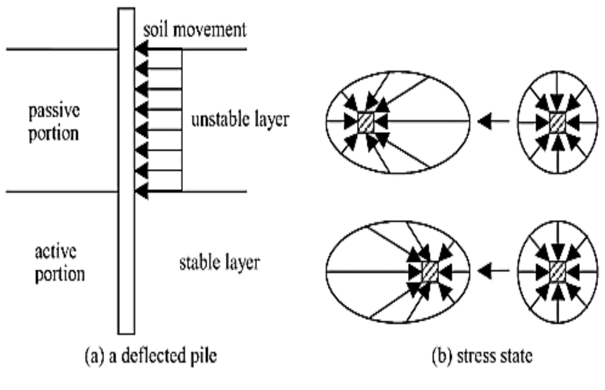

Figure 1: A pile undergoing lateral soil movement (Jeong et al., 2003)

The elastic constant (K_i) is related to the coefficient of subgrade reaction and a coupled set of P–δ curves is used as input to study the behavior of piles which can be modeled as a beam resting on nonlinear soil spring supports. A hyperbolic function was used to describe the relationship of the P–δ curve (Figure 3) which has an ultimate pressure (P_u) and an initial tangent stiffness (E_s). The initial tangent stiffness used in this study (Reese et al., 1992) was assumed to vary linearly with depth, z as specified in FE analysis case.

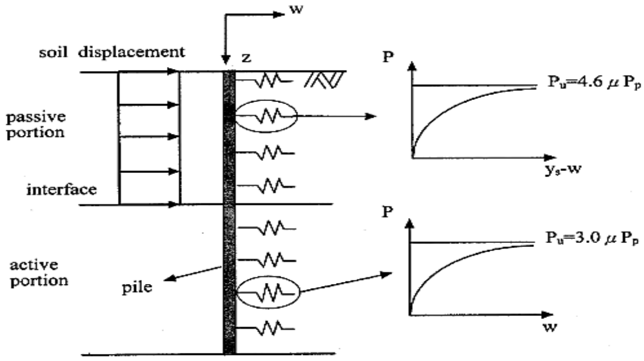

Figure 2: A pile subjected to lateral soil displacement (Jeong et al., 2003)

In P–δ curve analysis, it is common practice to estimate a different ultimate lateral soil pressure P_u for each pile in a group. In their study, the P_u value for each pile in a group was assumed to be equal to that adopted for the single pile multiplied by the group interaction factor, μ. Here the P_u value for the single pile was taken to 4.6 P_p for passive portion and 3.0 P_p for active portion, where P_p is the Rankine's passive pressure (Figure 2). A similar approach has been used successfully to study the effects of the Pu value on the response of each pile in a group (Poulos, 1995). A finite difference scheme was chosen to solve Equations (3) and (4). It has been found that a convenient and powerful procedure for solving the problem for nonhomogeneous soil profiles and complicated inelastic P–δ curves is to formulate a full set of nonlinear equations by applying those equations and prescribed pile head condition. In this study, the following four possible pile head conditions were considered: (1) free head (allows both displacement and rotation); (2) hinged head (allows rotation without displacement); (3) unrotated head (allows displacement without rotation); and (4) fixed head (allows neither displacement nor rotation). The nonlinear analyses were done to take into account the theoretical P–δ curves for subgrade reaction modulus through an iterative procedure. For each iteration, the pile displacements from the previous solution are used to enter the nonlinear P–δ curves and solution procedures are repeated until two successive iterations obtain sets of displacements that agree with a user specified closure tolerance at all nodal points.

2.2.1.2 Safety Factor of Stabilized Slope

The slope-pile stabilization scheme analyzed in their study is shown in the Figure 4. The conventional Bishop simplified method is employed to determine the critical circular sliding surface, resisting moment M_R and overturning moment M_D. The resisting moment generated by the pile is then obtained from the pile shear force and bending moment developed in the pile at the depth of the sliding surface analyzed. It is assumed that the lateral soil movement exerted by the sliding slope on the pile results in the mobilization of shear forces and bending moment. Thus, the safety factor of the reinforced slope with respect to circular sliding is calculated as:

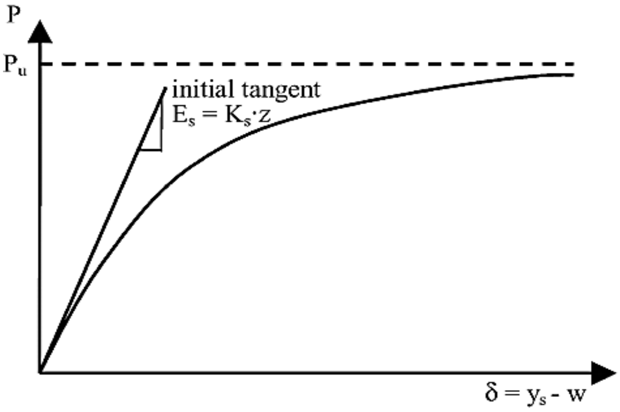

Figure 3: Hyperbolic P–δ curve (Jeong et al., 2003)

$$F = F_i + \Delta F$$
$$= \frac{M_R}{M_D} + \frac{V_{cr}.R.\cos\theta - M_{cr} + V_{head}.Y_{head}}{M_D}$$

Where, F_i = safety factor of un-stabilized slope
ΔF = increased safety factor of slope reinforced with pile
M_{cr} = bending moment at critical surface
V_{cr} = shear force at critical surface
V_{head} = shear force at pile head.

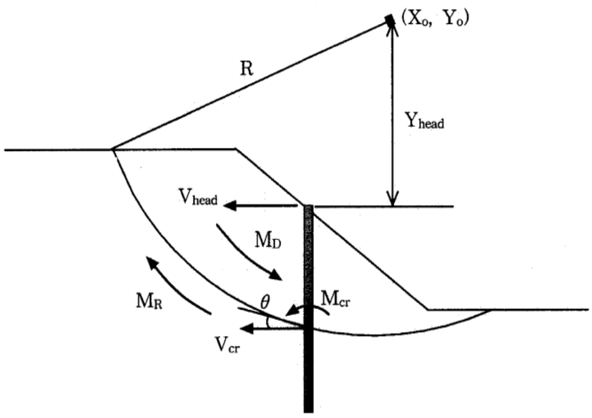

Figure 4: Forces on stabilizing piles and slope (Jeong et al., 2003)

2.3 Coupled Method of Analysis

Coupled method of analysis is used whenever both pile response and the slope safety factor are considered into account in the stability analysis of slope stabilizing piles. The applicability of this method recently was undertaken by Ashour and Ardalan (2012) in their paper which presents a new procedure for the analysis of slope stabilization using piles. The developed method allows the assessment of soil pressure and its distribution along the pile segment above the slip surface based on soil-pile interaction. The proposed method accounts for the influence of pile spacing on the interaction between the pile and surrounding soils and pile capacity. The paper also studies the effect of soil type, and pile diameter, position and spacing on the safety factor of the stabilized slope. Specific criteria are adopted to evaluate the pile capacity, ultimate soil-pile pressure, development of soil flow-around failure and group action among adjacent piles in a pile row above and below the slip surface. The ability of the proposed method to predict the behavior of piles subject to lateral soil movements due to slope instability is verified through a number of full scale load tests.

The characterization of the problem of slope instability and the use of piles to improve the stability of such slopes requires better characterization of the integrated effect of laterally loaded pile behavior, pile-structure-interaction, and the nonlinear behavior of pile materials (steel and/or concrete) on the resultant slope stability condition. The driving force of the soil mass that acts along the pile segment above the slip surface is transmitted to the lower (stable) soil layers, as shown in Figure 5. Such a scenario requires representative modeling for the soil-pile interaction above the failure surface that reflects and describes actual distribution for the soil driving force along that particular portion of the pile. In addition, the installation of closely spaced pile row would create an interaction effect (group action) among adjacent piles not only below but also above the slip surface. The presented method allows the determination of the mobilized driving soil-pile pressure per unit length of the pile (P_D) above the slip surface based on soil-pile interaction in an incremental fashion using the strain wedge (SW) model technique developed by Norris (1986) and Ashour et al., (1998). The buildup of P_D along the pile segment above the slip surface should be coherent with the variation of stress/strain level that is developed in the resisting soil layers below the slip surface. The mobilized non-uniformly distributed soil pressure (P_D) is governed by the soil-pile interaction (i.e. soil and pile properties) and developing flow-around failure above and below the slip surface. In addition, the presented technique allows the calculation of the post-pile installation safety factor (i.e. stability improvement) for the whole stabilized slope, and the slope portions uphill and downhill the pile. The size of the mobilized passive wedge of sliding soil mass controls the magnitudes and distribution of the soil-pile pressure (P_D) and the total amount of the driving force (P_D) transferred via an individual pile in a pile row down to the stable soil layers. The presented technique also accounts for the interaction among adjacent piles (group effect) above and below the slip surface. Figure 6 shows the soil-pile model as employed in the proposed technique. The ability of this method to predict the behavior of piles subject to lateral soil movements due to slope instability is verified through a comparison with two case histories. Also, the efficiency of using stabilizing pile in a slope is discussed by examining the influence of pile location in the slope, pile spacing, pile diameter and stiffness.

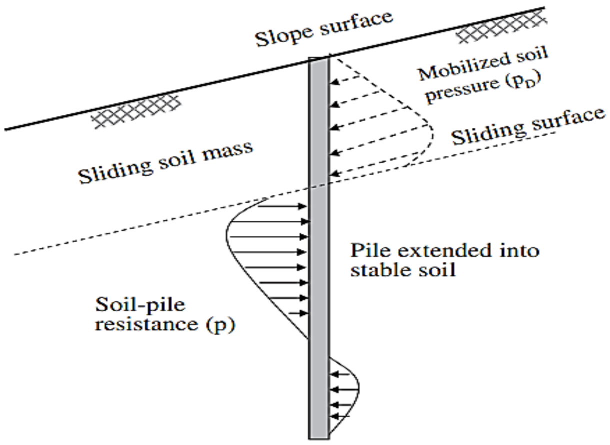

Figure 5: Driving force induced by displaced soil mass above the sliding surface (Ashour and Ardalan, 2012)

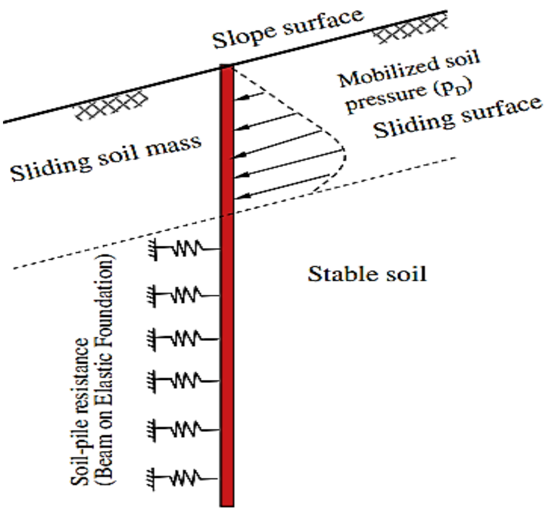

Figure 6: Proposed model for soil–pile analysis in pile stabilized slopes (Ashour and Ardalan, 2012)

3. Conclusion

The significance of passive piles subjected to lateral soil movement has gained interest of researchers from the beginning of the last decades as field test and laboratory test data have been presented for single and pile groups in landslide stabilizing piles. Of all the methods reviewed, it seems that the currently developed hybrid method of analysis is gaining popularity due to its rigor in combining the accuracy of three dimensional (3D) finite element (FE) simulations with the simplicity of widely accepted analytical techniques. The proposed method provides a useful, computationally efficient tool for parametric analyses and design of slope stabilizing piles. Meanwhile, the uncoupled method of analysis for slope stabilizing piles stems for the fact that the pile response and slope stability are considered separately in their respective analysis. Though this method offered the best output due to its calculation procedure complexity but it is considered to be time consuming and rather conventional in determining the slope stability factor. On the other hand, the coupled method of analysis is used whenever both pile response and the slope safety factor are considered simultaneously in the stability analysis of slope stabilizing piles. In contrast to the hybrid method of analysis, this method only focuses on the application of the finite element analysis using computer software while the former takes into consideration the use of theoretical procedures as check and balance in its analysis.

The authors believe that all of these state-of-the-art methods are widely accepted as it is supported by comparison with both field and laboratory data however it is also important to note that previous researchers have emphasized that effective and reliable prediction of the pile's response could only be carried out only if the accurate magnitude of lateral soil movement could be known, which for most cases is a source of great uncertainty. Therefore, the authors would like to highlight that further three dimensional modeling would offer another excellent alternative to study the response of those piles for landslide mitigation purposes. Conclusively, this review indirectly highlights another area of research that is significant and would contribute to the existing literature and the slope stabilization industry.

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