Pre-Liquefaction and Post-Liquefaction Responses of Axially Loaded Piles in Sands

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Abstract: This paper presents a methodology for predicting the mobilized response of axially loaded piles in sands in the states of pre-liquefaction and post-liquefaction. The proposed procedure calculates shaft and skin resistance of axially loaded piles in sands with and without liquefaction. Sands with limited liquefaction (mostly medium-dense sands), in which the shear strength of the sand drops under a cyclic loading (seismic events), were the focus of this study. The proposed approach provides the load transfer-settlement (t-z) curve and the pile-head axial-load versus pile settlement in sands before and after the development of soil liquefaction. It also considers the variation of pore-water pressure (PWP) in the near-field soil caused by axial loading combined with free-field PWP that is generated by cyclic loading as a postseismic event. The mobilized pile skin and tip resistances were determined on the basis of two constitutive models (of stress–strain relationship) for sands under drained and undrained conditions. A computer code was developed to implement the presented technique. **DOI: 10.1061/(ASCE)GM.1943-5622.0000968.** *© 2017 American Society of Civil Engineers.*

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Introduction

Piles in cohesionless soil gain support from the tip resistance and transfer of axial load via the pile wall–shaft resistance along the shaft length. The contribution of pile shaft resistance to the axial load carried by the pile proportionally increases with pile-embedded length. It is noteworthy that both the pile tip and skin resistance are interdependent. The estimation of the pile axial capacity relies heavily on empirical correlations. Pile shaft resistance is influenced by the state and properties of soils within the critical zone immediately surrounding the pile. In addition, the method utilized for driving the pile, the roughness of the pile surface (i.e., pile materials), and the state of the pile end (closed or opened) influence pile shaft resistance. Furthermore, in reality, soil profiles often consist of multiple layers of soils that may contain sand, clay, and silt. The technique presented by Ashour et al. (2009) for axially loaded piles in clay was combined with the current procedure to analyze the axially loaded piles in sand and clay soil deposits.

The assessment of the mobilized load transfer of a pile in sand depends on success in developing a representative t-z relationship. This success can be achieved via empirical relationships or numerical methods. The load-transfer-settlement, t-z, curve method is the most widely used technique to compute the response of axially loaded piles, and it is particularly useful when the soil behavior is clearly nonlinear and/or when the soil surrounding the pile is stratified. This method involves modeling the pile as a series of elements (segments) supported by discrete nonlinear springs, which represent the soil–pile skin friction (t-z springs), along with a nonlinear pile tip (end-bearing) Q_p–z_p spring. Building on this work and on the basis of additional empirical results, general recommendations for estimating t-z and Q_p–z_p curves for axially loaded piles in sands have been proposed by Vijayvergiya (1977), API (1993), Altaee et al. (1992), Alawneh et al. (2001), and Seo et al. (2009).

Using a theoretical approach related to the shear stiffness of the soil surrounding the pile, t-z curves can be constructed satisfactorily. Several methodologies to develop theoretically based load-transfer curves were proposed, such as those by Kraft et al. (1981), Chow (1986), McVay et al. (1989), and Randolph et al. (1994).

Salgado et al. (2011) presented a mathematical formulation to perform a load-settlement analysis for a pile with a circular cross section installed in multilayered elastic soil that accounted for both vertical and radial soil displacements. The analysis follows from the solution of the differential equations governing the displacements of the pile-soil system obtained using variational principles. The method was an extension of the method of Seo and Prezzi (2007), which considered only vertical soil displacement. Kojima et al. (2014) proposed a simplified analysis method for the effect of soil liquefaction on earthquake-pile response by using the response spectrum. This method takes soil liquefaction into account by introducing the *p-multiplier* method.

API (1993) recommended the use of empirical t-z curves for sands assuming the mobilized-unit side shear stress, τ, to change linearly with pile segment displacement, z, until τ reaches a maximum value, τ_{max}, at z_c of 0.25 mm. Vijayvergiya (1977) suggested an empirical nonlinear formula, similar to the one recommended by API, to calculate τ as a function of z_c. Hoit et al. (2007) presented a study on the assessment of t-z curves in sand on the basis of the API recommendations, which are also used in some design software packages.

Coyle and Castello (1981) proposed design correlations for piles in sand using a δ average that was assumed equal to the residual angle of shearing resistance of the sand friction angle φ. Randolph and Wroth (1978) presented an approximate analytical solution for the analysis of the settlement of a single pile using theoretical

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