p–y curve and lateral response of piles in fully liquefied sands

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Abstract: This paper provides a technique to assess the response of laterally loaded piles and associated *p–y* curves in fully liquefied soils (where *p* is the soil–pile reaction and *y* is the pile deflection). The technique accounts for the variation of water pressure in the liquefied soils around the pile and its impact on the shape of the *p–y* curves and the pile lateral response. A constitutive undrained stress–strain model for fully liquefied saturated sands using the basic properties of sand is established to predict the post-liquefaction varying resistance of liquefied sands at different levels of loading assuming fully undrained conditions. The degradation in soil strength due to the free-field excess pore-water pressure ($u_{xs,ff}$), caused by an earthquake and resulting in full liquefaction, is considered along with the near-field excess pore-water pressure ($u_{xs,nf}$) induced by lateral loading from the superstructure. The presented procedure also accounts for the influence of the overburden pressure and sand density on the variation of excess water pressure in the near-field soil, the rebound of sand strength, and the shape of the *p–y* curve due to the dilative behavior of sands.

Key words: lateral loads, piles, soil liquefaction, *p–y* curve, undrained stress–strain, monotonic loading.

Résumé : Cet article présente une technique servant à évaluer la réponse de pieux sollicités latéralement, ainsi que les courbes *p–y* associées (où *p* représente la réaction sol–pieu et *y* est la déflection du pieu), dans des sols complètement liquéfiés. Cette technique considère la variation de la pression interstitielle dans les sols liquéfiés autour du pieu, et son impact sur la forme de la courbe *p–y* et la réponse latérale du pieu. Un modèle constitutif en contrainte-déformation non drainé pour des sables saturés complètement liquéfiés est établi afin de prédire la résistance variable post-liquéfaction des sables liquéfiés à différents niveaux de sollicitations, en supposant des conditions totalement non drainées. La dégradation de la résistance du sol due aux pressions interstitielles excessives en champ libre ($u_{xs,ff}$), causées par le séisme et qui provoquent la liquéfaction complète, est considérée en même temps que la pression interstitielle excessive en champ proche ($u_{xs,nf}$) induite par les sollicitations latérales de la superstructure. La procédure présentée considère aussi l'influence de la pression des terres et de la densité du sable sur la variation de la pression interstitielle excessive dans le sol en champ proche, de la résistance au rebond du sable, et de la forme de la courbe *p–y* due au comportement dilatant des sables.

Mots-clés : sollicitations latérales, pieux, liquéfaction, courbe *p–y*, contrainte–déformation non drainé, sollicitation monotonique.

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Introduction

The potential of loose and medium dense saturated sands to liquefy during seismic events has been one of the critical research topics of the last few decades. Several studies and experimental tests have been conducted for better understanding of (*i*) the potential of soil to liquefy in both free- and (or) near-field soil regions and (*ii*) the effect of soil liquefaction on the pile lateral response (Ishihara 1993; Liu and Dobry 1995; Norris et al. 1997, 1998; Cubrinovski et al. 1999; Yahata et al. 2001; Finn and Fujita 2002; Ashour and Norris 2003; Rollins et al. 2005*b*; Weaver et al. 2005, etc.). However, predicting the response of pile foundations and the associated *p–y* curves (where *p* is the soil–pile reaction and *y* is the pile deflection) in liquefied soil or soil approaching liquefaction is very complex. It should be noted that the shape of the *p–y* curve is a function of soil and pile properties. Therefore, the assessment of the post-liquefaction behavior (stress–strain relationship) of sand is a crucial element in determining the varying response of piles in liquefied soils. The presented methodology predicts the *p–y* curve based on using the static monotonic undrained stress–strain relationship of liquefied sands (i.e., post-liquefaction analysis). Allotey and El Naggar (2008), Gerolymos and Gazetas (2005), and Boulanger et al. (1999) present cyclic *p–y* modeling methods to assess a nonlinear dynamic *p–y* curve that accounts for soil–pile stiffness degradation under cyclic loading.

The technique presented predicts the post-liquefaction response of laterally loaded piles in sand in a full liquefaction state. Due to the shaking from an earthquake and the associated lateral load from the superstructure, free- and near-field excess water pressure ($u_{xs,ff}$ and $u_{xs,nf}$, respectively) develop into the soil around the pile. The soil experiences developing (limited) liquefaction from free-field excitation if the excess

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