Lateral Loaded Pile Response in Liquefiable Soil

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Abstract: This paper provides a new analysis procedure for assessing the lateral response of an isolated pile in saturated sands as liquefaction develops in response to dynamic loading such as that generated during earthquake shaking. This new procedure predicts the degradation in pile response and soil resistance due to the free-field excess porewater pressure generated by the earthquake, along with the near-field excess porewater pressure generated by lateral loading from the superstructure. The new procedure involves the integration of the developing (free- and near-field) porewater pressure in the strain wedge (SW) model analysis. The current SW model, developed to evaluate drained response (a nonlinear three-dimensional model) of a flexible pile in soil, has been extended in this paper to incorporate the undrained response of a laterally loaded pile in liquefied sand. This new procedure has the capability of predicting the response of a laterally loaded isolated pile and the associated modulus of subgrade reaction (i.e., the $p-y$ curve) in a mobilized fashion as a result of developing liquefaction in the sand. Current design procedures assume slight or no resistance for the lateral movement of the pile in the liquefied soil which is a conservative practice. Alternatively, if liquefaction is assessed not to occur, some practitioners take no account of the increased free-field porewater pressure, and none consider the additional near-field porewater pressure due to inertial interaction loading from the superstructure; a practice that is unsafe in loose sands.

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Introduction

Soil liquefaction during an earthquake is one of the major sources of damage to structures. The potential of soil to liquefy is one of the critical research topics of the last few decades. Several studies and experimental tests have been conducted for a better understanding of the potential of soil to liquefy in both the free- and/or near-field soil region (Castro 1969; Seed and Idriss 1971; Seed et al. 1983; Vaid and Thomas 1995; etc.). However, predicting the response of pile foundations in liquefied soil or soil approaching liquefaction is very complex. The profession still lacks a realistic procedure for the design of laterally loaded piles in liquefied soil.

The most common practice employed is that presented by Wang and Reese (1998) in which a traditional $p-y$ curve is used but based on the undrained residual strength (S_r) of the sand. As seen in Fig. 1 from Seed and Harder (1990), S_r can be related to the standard penetration test (SPT) corrected blowcount, $(N_1)_{60}$. However, a very large difference between values at the upper and lower limits at a particular $(N_1)_{60}$ value affects the assessment of S_r tremendously. It should be noted that even if an accurate value of S_r is available, S_r occurs at a large value of soil strain and higher peak undrained resistance is ignored in such claylike modeling. This is extremely conservative. Furthermore, the $p-y$ curve reflects soil-pile interaction, not just soil behavior. Therefore, the effect of soil liquefaction (i.e., degradation in soil resistance) does not reflect a one-to-one change in soil–pile or $p-y$ curve response. Instead, the undrained stress–strain relationship of the soil should be used in a true soil–pile interaction model to assess the corresponding $p-y$ curve behavior. This approach is pursued in this paper based on the strain wedge (SW) model analysis introduced by Ashour et al. (1998).

The new procedure presented in this paper predicts the behavior of laterally loaded piles in sand under developing and fully liquefied conditions. The current SW model approach (Ashour et al. 1998) that employs the drained behavior of sand has been extended in this paper to incorporate the undrained stress–strain relationship of sand-based soil–pile interaction analysis to predict $p-y$ curve behavior that can be checked against available field and scaled model data. The extension of the SW model is only one component of the new procedure. Due to the shaking from an earthquake and the associated lateral load from the superstructure, excess porewater pressure in the free and near field develops and reduces the strength of loose-to-medium sand around a pile. It should be noted that this procedure incorporates the whole undrained stress–strain curve (at any level of loading) not just the residual strength of the sand.

This new procedure provides the pile head load–deflection (P_o-Y_o) and pile head load–bending moment (P_o-M) relationship corresponding to different levels of anticipated load, P_o. As a result, the equivalent static load during the earthquake and the corresponding Y_o and M_{max} values are obtained from the predicted P_o-Y_o and P_o-M curves, respectively. The presented technique yields the $p-y$ curves in liquefied soil (undrained $p-y$ curves) along the deflected length of the pile, showing a distinct change from the corresponding drained soil–pile interaction response. The undrained SW model takes into account the effect of pile properties as well as the properties of the sand on the resulting nonlinear $p-y$ curves and, hence, the pile–head response. The analysis considers the developing or mobilized wedge of re-

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