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# Numerical analysis of pile-soil system under seismic liquefaction

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ABSTRACT

This study considers the motion of an end bearing single pile with lumped mass embedded in sandy soil deposit subjected to seismic liquefaction. An efficient finite difference model, whose accuracy was validated through experimental results, has been constructed to study the dynamic responses of piles under liquefaction. Effects of parameters such as soil and pile properties, and predominant frequency on the dynamic response of pile are examined. Results reveal that earthquake predominant frequency, pile stiffness, soil relative density and soil-pile relative stiffness, can significantly affect the pile's dynamic response, while pile material densities have negligible effects. Final results demonstrate that with increasing in pile stiffness, soil relative density and soil-pile relative stiffness, maximum moments in piles are increased while with increasing the earthquake predominant frequency, maximum moments in piles and depth of the liquefaction are reduced. Also, the depth in which the maximum value of the moment, $M_{max}$, occurs, depends only on the pile stiffness.

## 1. Introduction

When Pile foundations are exposed to intense dynamic transverse loads during earthquakes, soil–structure interaction (SSI) plays an important role in allocating the response of pile foundations to lateral excitation [1]. Recent observations after major earthquakes have shown that extensive damages and destructions are still likely to be happened to pile foundations. This problem is important particularly for pile foundations in loose saturated cohesionless deposits which are vulnerable to liquefaction and lateral spreading during seismic loading. Design procedures that have been developed for evaluating pile behavior under earthquake loading, have many uncertainties to be used for cases involving liquefaction. The performance of piles in liquefied soil layers is much more complex than that of non-liquefying soil layer as a result of the diminishing of stiffness and shear strength of the surrounding soil over time due to the increase of pore water pressure [2].

Lateral loads on piles are developed by the superstructure inertia as well as the soil movement induced by wave propagation through the soil. Inertial forces are the predominant forces before liquefaction and are mainly responsible for the development of maximum bending moment near the pile head, whereas, kinematic forces which are predominant after liquefaction are responsible for the maximum bending moment observed at the interface of liquefiable and non-liquefiable layers [3]. However, consideration of the mentioned forces simultaneously, could lead to a more accurate analysis. This is due to the fact that the total forces are resulted from an inertial interaction from the oscillation of the superstructure and also a kinematical interaction from the soil deformation and motion.

Tokimastu and Suzuki [4] believe that the peak pile bending moment in the pile with respect to natural period of structure and natural period of ground can be estimated by Square-Root-of-Sum-of-Squares (SRSS) or algebraic addition of kinematic and inertial

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moment.

The complexity of the dynamic soil-pile-structure interaction is attributed to the high degree of the coupling between the modes and the components of the interaction. In recent decades, an extensive range of laboratory tests and numerical approaches has been implemented for the purpose of providing a better understanding of the dynamic behavior of pile foundations in liquefiable soils. Pile foundation behavior in liquefiable soil depends on numerous parameters, including soil type, earthquake parameters, and pile properties.

Ishihara [5] used nonlinear 3-D analysis to show the importance of factors such as inertial interaction, kinematic interaction, seismic pore water pressures, soil nonlinearity, cross stiffness coupling and dynamic pile to pile interaction which typically is neglected in approximate methods in practice.

Wilson et al. [6] conducted a series of centrifuge tests on single piles and pile groups located in liquefiable soils in order to observe the p–y behavior of piles embedded in liquefying sands.

Bhattacharya [7] have evaluated two pile failure mechanisms in fourteen centrifuge tests, and concluded that before lateral spreading of the liquefied soil, slender pile sections face the buckling instability and may fail due to buckling before the action of lateral forces of moving liquefied soil. Further, he pointed out that pile length, diameter, and material strength can affect failure mechanisms of piles. The experimental results by Tang and Ling [8] have shown that decreasing the frequency and increasing the amplitude of earthquake excitation increase the pile bending moment and expedite excess pore pressure buildup in the free-field. Several researches on the dynamic behavior of pile foundations in liquefiable soils were carried out utilizing shaking table tests [9–15].

Bhattacharya et al. [16] after quantitative reappraisal the collapse of Showa bridge, concluded that by increasing the unsupported length of the pile due to liquefaction, the natural period of the bridge tuned with the period of the liquefied ground causing resonance which caused excessive deflection at the pile head.

A number of researchers developed one-dimensional Winkler method for the seismic analysis of piles based on finite element or finite difference methods and liquefaction of surrounding soil was taken into account during analyzing process [17–20], while others used three-dimensional finite element method in for simulating piles in layered liquefying soil [2, 21–25]. Each of these models possesses varying prediction accuracy and certainty. In some of these papers fully-coupled formulation has been employed; while in others the uncoupled formulation, in which soil skeleton displacements and pore water pressure generation were computed separately, has been used.

Liyanapathirana and Poulos [20] modeled piles in liquefying soil with dynamically loaded beam on Winkler foundation and stated that the significance inertia force at the pile head, that depends on the superstructure mass and the acceleration of the superstructure, increases with the increase in relative density that reduce the degree of soil liquefaction and enabling large accelerations to be transmitted through the ground to the superstructure.

Haldar and Babu [26] investigated failure mechanisms of pile foundations in liquefiable soil using a nonlinear constitutive model for soil liquefaction, strength reduction, and pile-soil interaction and performed a parametric study on pile behavior for different pile, earthquake, and soil characteristics. In their study the effect of superstructure inertia has been taking into account by applying a horizontal load about 10% vertical load of the superstructure with a constant direction.

### *1.1. Research significance*

The major objective of this research work is to study the interaction of soil-pile systems (SPS) considering both kinematic and inertia effects on SPS response. The kinematic effect of ground and the inertial interaction effect are evaluated simultaneously, and are combined in a dynamic numerical model. In this study, the bending behavior of pile foundations embedded in different soils are analyzed using a finite difference program, known as Fast Lagrangian Analysis of Continua (FLAC) [27]. Soil liquefaction is taken into consideration utilizing a nonlinear constitutive model (Byrne, 1991) [28]. For the validation of the constitutive model, centrifuge test results obtained from the literature [6]. For examining the response of a single end bearing pile in the liquefiable soil, four different earthquake predominant frequency values, three different ranges of soil relative densities, and concrete and steel tube piles with six different diameters are considered.

## 2. Model description

Dynamic liquefaction analysis is performed by a two-dimensional, plain strain model in FLAC based on an explicit finite difference scheme. Analysis of soil-structure interaction is possible by coupling FLAC formulation to the structural element model. Damping and energy-absorbing characteristics of the real soil are captured using the hysteresis curves for sandy soil.

The dynamic loadings are applied as acceleration time histories to the base of the model. Wave reflections at model boundaries are minimized by specifying free-field boundary conditions, which cause the outwards waves to be absorbed properly, at the two sides of the model.

The selection of mesh size for the FLAC dynamic model is conducted based on Kuhlemeyer and Lysmer [29] formula, to ensure accurate wave transmission. For providing reasonable runtime, the maximum frequency that can be modeled accurately is

$$f_{\max} = \frac{V_S}{10\Delta L} \quad (1)$$

where Vs, and $\Delta L$ are the shear wave velosity, and the maximum dimensions of mesh, respectively. By filtering the history and