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# Comprehensive three dimensional finite element analysis, parametric study and sensitivity analysis on the seismic performance of soil–micropile-superstructure interaction

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ABSTRACT

A comprehensive dynamic three dimensional finite element model, which includes the effect of lots of important parameters on the micropiles seismic performance, has been presented. The validation of the built model has been carried out using remodeling a single degree of freedom shaking table test done by Mc Manus at the University of Canterbury. The gained results proved the accuracy of the constructed model. Then, using the parametric analysis, effects of all the earthquake characteristics, soil properties, superstructure and micropiles′ cap and micropiles structure on the seismic performance of micropiles have been investigated by means of presenting internal forces and displacements which occurred as the main result of earthquake. Furthermore, using the data analysis, the most and the least influential parameters on internal forces are obtained based on the Cosine Amplitude Method (CAM).



## 1. Introduction

Deep foundations include pile and micropile foundations. They can be used to retrofit lots of existent structures in seismic areas, also, for making the new structures safe [1,2]. Thus, they have been widely studied by the majority of researchers from different aspects like their installation types and procedure, their performance and their effects [3–14]. Also, lots of geotechnical problems are analyzed dynamically under earthquake loads [3], [12–16].

Micropiles are one of the most in demanding tools, which are commonly used to reinforce the foundations constructed on problematic soils such as liquefiable sandy soils.

Indeed, micropiles can be considered as piles with small diameters, diameters less than 300 mm. There are lots of advantages for using micropiles instead of piles [11].

Micropiles′ performance and behavior is influenced by lots of parameters [17]. One of these affecting parameters is the behavior of surrounding soils. Therefore, remarkable number of researches has been conducted to gain the true behavior of surrounding soils [4,5,18,19]. In most of these researches, the analysis is done in the frequency domain and behavior of the soil is assumed to be elastic [4,5,18,19]. Studies on the recent devastating earthquakes (e.g., Kocaeli 1999, Loma prieta 1989, Kobe 1995), have shown that assuming a non-linear behavior for surrounding soil presents better results in designing of micropile foundations for seismic areas [20–22]. In these researches, three major approaches have been utilized to apply the non-linear behavior of soil in their modeling. Equivalent linearization technique, discrete system of mass, spring and dashpot and the finite element method based on the non-associated Mohr–Coulomb plasticity, Drucker–Prager plasticity, HISS, etc., were the commonly applied methods for considering the soil′s non-linear behavior.

The equivalent linear method was firstly presented by Idris and Seed to model the non-linear hysteretic behavior of soil [23]. Due to its simplicity, till now, it has been considered as one of the most well-known methods in the analysis of soil response.

Maheshwari and Watanabe [20,24] used the equivalent linear method to include the material non-linearity of the soil in the frequency domain [20,24]. But, at the strong earthquakes, the level of shear strain gained by this method was significantly lower than the expected one. In such cases, strong earthquakes, non-linear analysis is better conducted in time domain. Therefore, in recent years, the focus has been on the time domain.

Also, some of researchers used a system of discrete elements such as mass, spring and dashpot for modeling of non-linear

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behavior of soil in the time domain [3,6,25,26]. Results obtained from these studies showed that it is difficult to properly represent damping and inertia effects of continuous semi-infinite soil media when using such systems. Therefore, the finite element method, a widely applied numeric method [11], based on Mohr–Coulomb criterion, Drucker–Prager, HISS, etc., was used and applied as one of the most appropriate methods [27]. Soil hardening was not considered in the Benteley and El Naggar′s research. Also, in the Cai′s research, using the finite element method in time domain and advanced model of HISS for seismic response of soil–pile-structure interaction in homogenous clay soil, horizontal displacement of the lateral boundaries have been neglected [28]. This modeling seems not to be appropriate enough for simulation of infinite medium. Furthermore, in the finite element modeling carried out by Turan et al., based on the Mohr–Coulomb criterion, hardening behavior of the soil has not been considered [29].

In this paper, to accurately consider the role of non-linear behavior of the surrounding soil, a comprehensive 3D finite element model based on non-associated Mohr–Coulomb plasticity is considered.

In addition, as mentioned, seismic performance of micropile groups is affected by a variety of parameters, such as the inclination of micropile group, non-linear behavior of soil, number of micropiles, micropiles′ slenderness, etc. Influence of some of these parameters such as plasticity and micropiles inclination on the seismic performance of micropile groups has been investigated in previous studies [11,17,22]. But, the effects of some other parameters on the micropiles responses have not yet been investigated. In addition to the lack of a comprehensive research, which includes the role of all the affecting parameters, some of these researches have used simplifications, such as neglecting the existence of superstructure in their modeling.

The need for an accurate and comprehensive model is obvious. Thus, to accurately investigate the role of all the affecting parameters on the seismic performance of micropile groups, three dimensional finite element modeling has been considered and based on the validated soil–micropile-superstructure modeling, parametric analysis has been done to cover the gap between existent models and the reality.

## 2. Modeling

### 2.1. Geometry of the model

Fig. 1 indicates the arrangement of micropiles group and placement of them in homogenous sandy soil. In this study, a 3-D model for analysis of soil–micropile-structure has been used. Using symmetry features greatly reduces the scope of the analyses and the analysis can be conducted on half the pile foundation. Hence, only one half of this symmetrical geometry was modeled to decrease the number of degrees-of-freedom (DOF) and thus to reduce the computational time. It should be noted that since the model has two sides with viscous dampers for outgoing waves, while the other two sides are just mirrors reflecting pile′s image, when the model is subjected to the lateral ground motions, mirror images of the side soil may exhibit all symmetric development of plastic zones, which never occurs in reality. To overcome this difficulty, pile–soil–pile spacing is substantially so large that asymmetric inelastic nature of the side soils can be neglected. Micropiles have been fully placed in a homogeneous soil with $2 \times 2$ arrangement. So, the distance between the end of soil mass and the micropile tips are equal to the length of micropiles [30].

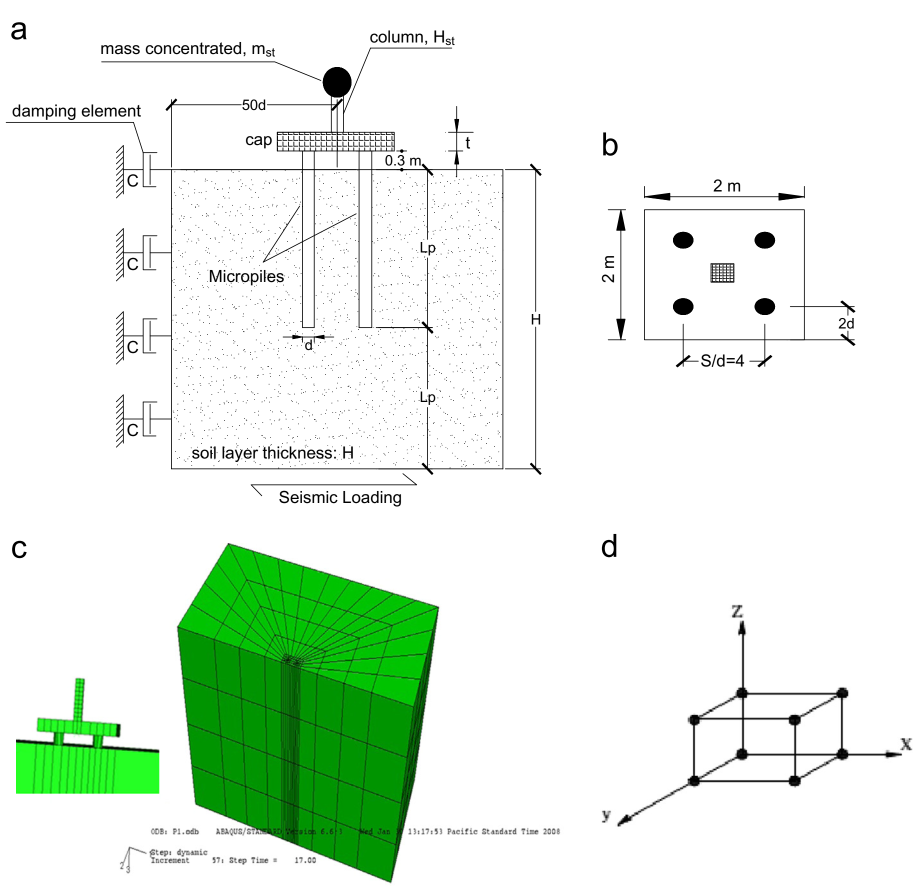


Fig. 1. Geometry, model, meshes and characteristics of the reference model. (a) Section of the model, (b) Arrangement of the micropiles, (c) 3D finite element meshes used in the analysis of soilmicropile-superstructure system and (d) Eight-node hexahedron element for simulation of soil mass.