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Research Paper

An elastoplastic model for the analysis of a driven pile extended with a micropile

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ABSTRACT

An elastoplastic model for the analysis of a driven pile extended at the bottom with a micropile under axial load is presented. The model is an extension of the integral equation method of Poulos and Davis. The finite-difference scheme used to obtain the pile displacements is reformulated to take into account the discontinuity in the stress distribution at the joint between pile and micropile. The results obtained with the proposed method are compared with the outcomes of a more sophisticated finite element simulation, and also with data from full-scale load tests. Reasonably good agreement is obtained in both cases.

1. Introduction

A driven pile extended at the bottom with a micropile can be a competitive solution for the problem of resisting loads in tension and compression and the necessity of penetrating deep rock layers. For example, in cases when the driving is stopped by a thin layer of hard soil or rock that might be underlain by caves or less compact soils, this system allows the penetration of the hard layer and the foundation of the pile in more compact soils below.

In a recent contribution [1], the authors introduced the problem of a driven pile extended with a micropile and characterized its load-settlement behavior through finite element method (FEM) analysis and load tests. They concluded that the response of the pile/micropile system to a combination of compression, tension and lateral loading was advantageous compared to that of a conventional pile. It was also found that the cross-section discontinuity could in some cases constitute an additional difficulty for setting up a FEM model. For example, the Plaxis 3D embedded pile model could not be used due to its inability to reproduce the step between pile and micropile.

Furthermore, while the FEM provides the most rigorous approach to the problem, its computational requirements make the method rather expensive, requiring an excessive amount of preparation for normal design purposes. In this context, an analytical model is still valuable for the routine design of pile foundations of this kind.

A number of analytical methods have been developed for the study of the load-settlement behavior of piles under axial load: load-transfer methods [2], finite layer methods [3], integral equation methods [4,5] and energy methods using a variational approach [6,7]. Among them, the integral equation method (based on Mindlin's equations for an elastic continuum) was considered to be the most appropriate to deal with the irregular geometry of the pile/micropile compound and the more complex boundary conditions.

Although the integral equation method was initially devised for a homogeneous soil under elastic conditions, subsequent adaptations of the model have made it suitable for a more realistic representation of pile-soil interaction problems, including non-homogeneous soil conditions [8] and yielding at the pile-soil interface [9, p. 80]. Extension of the method to consider piles with a non-uniform cross-section (*e.g.* step-tapered piles) was initiated by Poulos [10], but the formulation developed was restricted to the case of uncompressible piles.

In this paper, the Poulos method for step-tapered piles has been extended to take into account the compressibility of the pile. As a result, an elastoplastic model is presented for the analysis of the load-settlement behavior of a driven pile extended at the bottom

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with a micropile. The model requires a reduced set of parameters that can be easily estimated from typical in-situ tests. The formulation developed here is valid for square and circular piles in multilayered soils and allows simulation of tension and compression loads within loading-unloading-reloading cycles. Yielding (slippage) at the pile-soil interface has also been considered.

2. Method of analysis

2.1. Definition of the problem and basic assumptions

The configuration under study consists of a precast concrete driven pile extended at the base with a micropile [1]. To allow for the installation of the micropile, the driven pile is initially hollow.

The precast concrete pile is first driven by an impact pile hammer. Then, after drilling downwards from the toe of the precast pile, a micropile is installed along the hollow of the pile (Fig. 1). First, its steel casing is introduced. After that, concrete is poured up to the top of the hollow pile. The bottom of the upper section rests on the harder soil layer since the precast concrete pile may be driven until refusal, for example in agreement with a dynamic formula.

For Mindlin's equations [11] to be applicable, the soil is initially considered to be a homogeneous isotropic elastic half-space. Modifications of the basic analysis for more realistic soil conditions will be subsequently introduced and are explained in the following sections. The pile is divided into a number of elements which are considered to be subject to constant stress. The solution to the problem is obtained by imposing compatibility of displacements between the pile and the surrounding soil.

The case developed in this paper corresponds to a driven pile of square section, although the extension of the analysis to the case of a driven pile of circular section is straightforward.

2.2. Pile and soil discretization

The pile and micropile are discretized as shown in Fig. 1. The pile is divided into m hexahedral elements and the micropile is divided into m-n cylindrical elements, each loaded by a constant shear stress p_i. The pile and micropile bases are modeled as planar elements having a uniform vertical stress p_{n+1} and p_{n+2} respectively. The micropile base is a circular element while the pile base is assumed to be an annular element whose area is equal to the difference between the section of the pile and that of the micropile. The problem is formulated in terms of two sets of variables: the stresses p_i at the pile-soil interface and the pile vertical displacements w_i at the center of each element.

2.3. Soil displacement equations

The soil displacements are calculated by integrating Mindlin's equations for the displacement caused by a point load within a homogeneous, elastic half-space. As a result, the vertical displacement of the soil adjacent to element i can be expressed as:

$$w_i = \sum_{j=1}^{n+2} I_{ij}^{s} \cdot p_j \tag{1a}$$

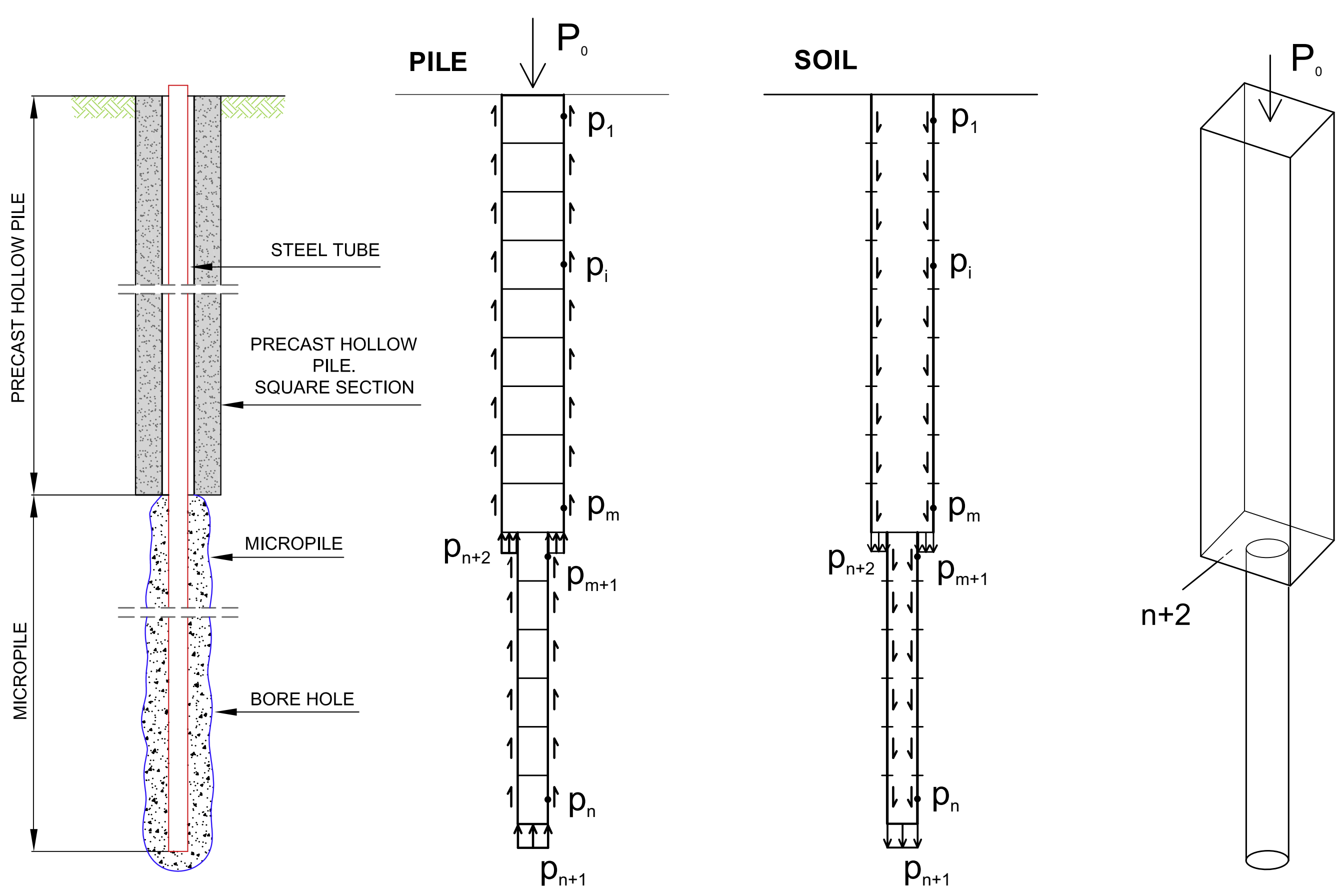

Fig. 1. Pile and soil discretization with stresses acting on pile and in adjacent soil.