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On predicting displacement-dependent earth pressure for laterally loaded piles

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Abstract

This paper presents the derivation of a depth-dependent soil displacement model for laterally loaded piles for use in the calculation of displacement-dependent earth pressure. A set of fourth-order differential equations are proposed to compute the pile deflection profile along the pile length. The radial displacement of the soil due to pile movement can be evaluated based on the geometric compatibility requirements. The soil displacement pattern is then used in the earth pressure model to provide the pattern of earth pressure distributed around the pile circumference. The experimental data of the pile response, in terms of the *p-y* curves reported in the literature, are employed for a comparison with calculations from the proposed approach and other analytical models. The advantages of the developed calculation framework have been demonstrated, namely, that it can accurately reproduce the experimental measurements of soil reactions acting on a pile at different depths and that the influence of the pile installation can be taken into account. An illustrative example of cantilever sheet piles is finally provided to show the ability of the proposed method to analyse complicated problems.

Keywords: Pile; Lateral pressure; Displacement; Soil-pile interaction; *p-y* curves

1. Introduction

Pile foundations have generally been used in a variety of infrastructures, such as high-rise buildings, hydraulic structures, highways, railways, bridges and nuclear power stations. During the design of these structures, a pile can be loaded axially to transfer loads from the superstructure to the surrounding soil (Ni et al., 2017a, 2017c, 2017d). In addition to axial loads, a pile can experience relative pile-soil movement in the horizontal plane due to lateral loads induced by wind, ground vibration and lateral spreading during earthquakes, and inclined slope terrain. Fig. 1(a) presents the typical behaviour of a laterally loaded pile, where the pile resists the forces (or moments) at the head. The soil-pile interaction mechanism (*p-y* curve, where the soil reaction is calculated by the integration from soil pressure) is dependent on the stiffness of both the pile and the soil. On many occasions, the pile design, in terms of geometry (i.e., cross-section shape, dimension and length), pile type (i.e., pile end fixity) and spatial variation (i.e., spacing), is based on an analysis of the effect of lateral loads.

The analysis of laterally loaded piles can be categorized into two tasks: one is to discretize the soil medium and the pile structure using finite elements and to solve the interaction problem based on continuum mechanics; the other is to measure the *p-y* curves experimentally and to match

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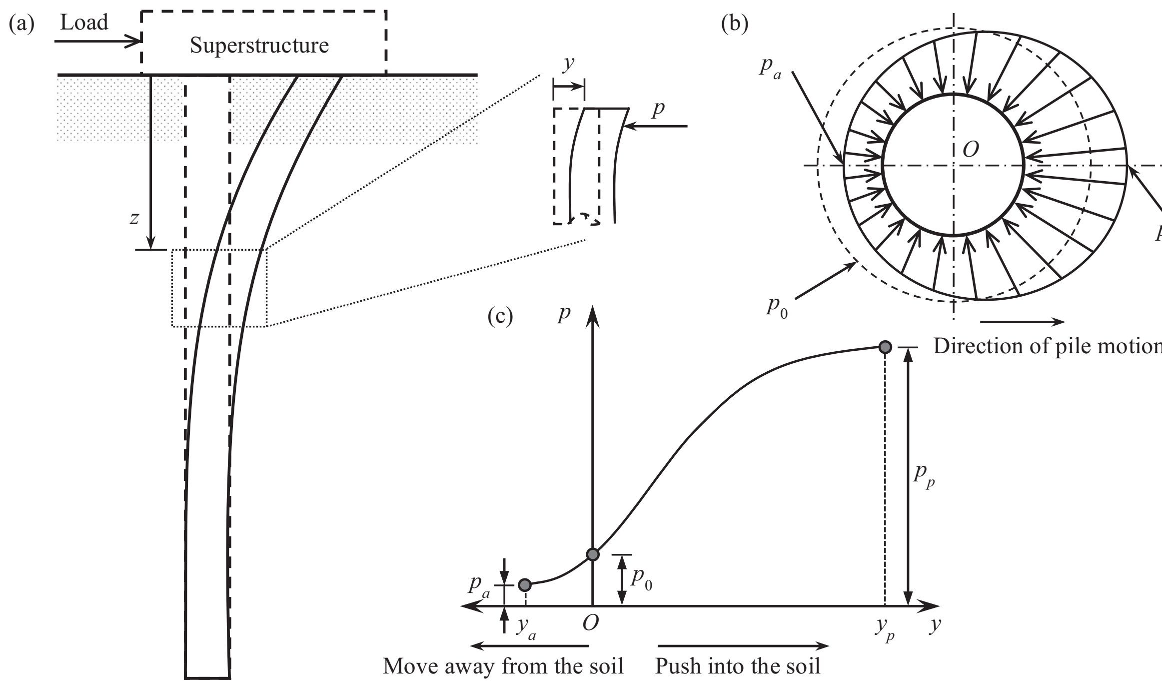

Fig. 1. Schematics of (a) laterally loaded pile, (b) soil pressure around circumference of pile and (c) displacement-dependent *p-y* curve proposed by Mei et al. (2009).

these measurements empirically with analytical solutions. The continuum-based approach is attractive since it can explicitly consider the material nonlinearity, the variation in stiffness of both the pile and the soil and the soil stratigraphy. For instance, Bransby and Springman (1999) investigated the influence of pile spacing and soil nonlinearity on the load transfer mechanism (*p-y* function) using plane strain numerical analyses; Pan et al. (2002) evaluated the response of a single pile with differing flexural stiffness subjected to lateral soil movements using three-dimensional finite element models; Yang and Jeremić (2002) conducted calculations for a single pile under lateral loads in layered elastic–plastic soils numerically. A finite element tool has also been developed to analyse the behaviour of sheet pile walls subjected to surcharge loads (Georgiadis and Anagnostopoulos, 1998) and of single piles in sloping grounds (Georgiadis and Georgiadis, 2010, 2012).

Extensive experimental studies have been performed to facilitate an understanding of the pile response due to lateral loads. Gabr et al. (1994) proposed an interpretation of dilatometer tests to derive the *p-y* curves for piles in clay. Reduced model-scale (Kim et al., 2004) and large-scale laboratory tests (Zhu et al., 2011) were conducted to investigate the performance of a single pile under lateral static loads, and the testing results were compared with the existing *p-y* models. It was seen that pile groups can lower the load capacity more than individual piles (Rollins et al., 1998; Rollins and Sparks, 2002). Studies on single piles represent an upper bound solution to the problem by providing conservative estimations at the design stage. The influence of cyclic lateral loading on the pile response has been explored experimentally in centrifuge (Abdoun and Dobry, 2002; Abdoun et al., 2003) and in large-scale tests (Dunnavant and O'Neill, 1989). Brown et al. (1988) indicated that there was a negligible effect of the load cycles on the group efficiency and that cyclic loads could only densify the surrounding soil. However, the current *p-y* approaches could potentially overestimate the pile head deflection for monopiles (Hokmabadi et al., 2012), since the influence of the pile length and the diameter (in the order of 40 m and 2 m, respectively) was not included.

A suitable length for a pile is often required in order to provide an adequate ultimate axial load capacity (to resist differential settlement). Velez et al. (1983) defined an active length beyond which the pile would behave the same as an infinitely long pile in the lateral direction (i.e., fully flexible). In practice, lateral loads are usually not sufficient to deform the entire length of a pile and the relative pile-soil displacement below the active length can be disregarded (Goit et al., 2014). This raises questions as to the current understanding of *p-y* curves (Kondner, 1963; Matlock, 1970; Reese et al., 1974; O'Neil and Murchison, 1983; Gazioglu and O'Neill, 1984; Murchison and O'Neill, 1984; Norris, 1986; Ashour and Norris, 2000; Basu et al., 2009), where the difference between rigid and flexible piles is always ignored. Kim et al. (2009) have reported in their experimental and numerical work that flexible piles could behave quite differently in terms of bending moment and lateral displacement compared to rigid piles. The deficiency of empirical soil reaction models has also been observed for other similar structures such as pipelines (Saiyar et al., 2016). Due to lateral loads, a zone of passive soil reaction

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