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Simplified solution for tunnel-soil-pile interaction in Pasternak's foundation model

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ABSTRACT

The current design practice for predicting the interaction mechanics for tunnel-soil-pile is generally based on Winkler's foundation, which is subject to some important limitation, such as ignoring the continuity of the soil foundation. Furthermore, the current analytical studies are mostly employed the plane strain analyses and do not consider the influences of lateral soil displacements on pile behaviour. To improve the accuracy for the pile behaviour prediction induced by tunnelling, the analytical method should account for the effects of a number of parameters, such as the ground shearing displacements, and the influence of lateral soil displacements next to the pile. This paper focuses on a simplified solution based on Pasternak's foundation model to predict the lateral displacements and internal forces of a single-pile and group-piles induced by tunnelling considering the effects of lateral soil displacements. First, the simplified solution of tunnel-soil-pile interaction, which reflects the influence of shearing displacements of foundation, is established on Pasternak's foundation model. Second, the equivalent concentrated forces are supplied to the pile through the shear layer to consider the influence of lateral soils beside the pile. The validity of the solutions is verified by the boundary element program results, centrifuge test data, and field measurements. The calculated results are also compared with and without considering the effects of tunnel-soil-pile interaction. When the influences of lateral soil displacements are considered, the results are shown to be closer to the monitored in-situ data and the centrifuge test data. In addition, the influencing factors of a single-pile and group-piles displacements are also investigated, including the shear layer modulus, pile diameter, ground-loss ratio, pile-tunnel distance, and pile spacing. The influence of soil shear displacements on pile response cannot be ignored, and an error may occur when Winkler's foundation model is used to solve this problem.

1. Introduction

The rapidly increasing demand for public transport construction in congested urban areas will promote tunnel excavation adjacent to existing buildings and services due to the lack of surface space. Adverse effects on nearby pile foundations may be appeared due to changes in ground stress and, hence, building movements. Accurate predicting of effects of tunnelling on pile foundations poses a major challenge during civil engineering design and construction.

Increasing attention has been paid to evaluating the effects of shield tunnelling on adjacent piles. The methods used for analyzing this problem may be broadly classified into three categories: numerical analyses, simplified analytical methods and laboratory tests. A variety of research has been conducted on this subject based on the numerical approaches (Surjadinata et al., 2006; Jongpradist et al., 2013; Hong et al., 2015; Fu et al., 2016). The most common method is finite element (FE) method and the simulation results are obtained with the condition on the tunnel, pile and soil as a whole. Several researchers investigated the effects of tunnelling on the bearing capacity and deflection of the piles by the centrifuge model tests (Loganathan et al., 2000; Jacobsz et al., 2004; Lee and Chiang, 2007; Marshall and Mair, 2011; Ng and Lu, 2013; Ng et al., 2013, 2014; Franza and Marshall, 2018). In addition, some researchers performed experimental tests in laboratory to study the effects of tunnelling on pile foundations (Lee and Bassett, 2007; Meguid and Mattar, 2009; Bel et al., 2016).

Researchers have been studying different analytical approaches to predict the pile responses during tunnel excavation (Chen et al., 1999; Huang et al., 2009; Mu et al., 2012; Xiang and Feng, 2013; Basile, 2014;

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Marshall, 2012; Marshall and Haji, 2015; Franza et al., 2017). In order to obtain a better mechanical understanding of the effects of tunnelling on adjacent piles and provide a rapid predication of the response characteristics of existing structures, a simplified two-stage approach is presented in their study. The simplified method to analyze such a problem is carried out in two steps: first, the estimation of green-field ground movements induced by tunnelling, which would occur if the existing piles were not present; second, the calculation of the response of the existing piles to green-field ground movements.

Recent studies (Huang et al., 2009; Mu et al., 2012) have investigated the effects of tunnelling on existing piles and evaluated the complex pile-soil interaction, which usually relies on Winkler's foundation model. According to Winkler's foundation model, the soil is modelled as a series of closely spaced, mutually independent, linear elastic lateral springs, which provide resistance in direct proportion to the deflection of the pile. In Winkler's foundation model, the soil properties are described only by the sub-ground parameters, which represent the stiffness of the lateral springs. However, due to its inability to take into account the soil continuity or cohesion, Winkler's foundation model is considered a rather crude approximation of the mechanical behaviour of soil material. Therefore, it cannot always give accurate predictions. The model assumes that an applied load is transmitted to each individual spring without any interaction between other springs, also resulting in the influence of the soil on either side of the pile being overlooked. For a uniformly distributed load applied to a homogenous pile, the behaviour of the elastic pile corresponds to that of a rigid body without the existence of the bending moment and shear force inside it. In reality, however, piles may not be perfectly rigid and can show curvilinear displacement profiles, as seen in Fig. 1. To overcome this weakness, the two-parameter elastic foundation models have been suggested, such as Pasternak's foundation model (Pasternak, 1954; Tanahashi, 2008). In this model, a shear layer is added to the Winkler's model to provide mechanical interaction among spring elements. The first parameter represents the stiffness of the springs, as in Winkler's foundation model. The second parameter is introduced to account for the coupling effect of the linear elastic springs. Lee et al. (2004) analyzed the retaining wall movements caused by ground excavations based on Pasternak's two-parameter beam-column model. Zhang and Zhang (2013) estimated the longitudinal deflection and internal forces of existing pipelines due to tunnelling using Kerr's three-parameter elastic foundation model (Kerr, 1965). However, the tunnel-pile interaction analyses are generally based on Winkler's foundation model and further studies must be conducted based on Pasternak's foundation model.

The simplified analytical methods available in the literature have mostly focused on the analyses of passive piles subjected to tunnelling without considering the effects of lateral soil displacements. These methods may not be accurate in evaluating the behaviour of piles subjected to concurrently tunnel excavation and lateral soil displacements. In fact, the interaction between tunnel and pile is a three-dimensional effect issue. The lateral displacements of soil will also have an impact on the pile deflection. Current analytical studies are mostly based on the plane strain analysis and ignore the effects of lateral soil displacements on pile behaviour. Fig. 2 shows three tunnelling conditions of short-range excavated (Fig. 2(a)), medium-range excavated (Fig. 2(b)) and fully excavated (Fig. 2(c)), which mean the whole excavation process. The condition selected in this paper is the worst operating condition, that is, the third condition (Fig. 2(c)). As shown in Fig. 2(c), surface A in this figure shows the ground displacements without piles. Due to the limitations of the pile, the soil displacement in a piled foundation is slightly smaller than it is without the pile. Surface C shows the soil displacements in a piled foundation without considering the effect of lateral soil displacements, which is a plane-strain case. In fact, the existence of the pile constrains the lateral soil displacements within a certain range, whereas the displacements value of the lateral soil far from the pile is approximately equal to free soil displacements. The actual soil displacements in the piled foundation is shown as surface B in Fig. 2(c), and the calculation error may occur in the current plane strain analyses.

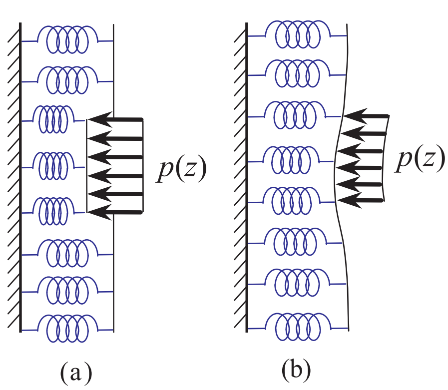

Fig. 1. Foundations under uniformly distributed loads: (a) Winkler's foundation model; (b) actual displacement of foundations.

In this paper, a simplified method based on Pasternak's two-parameter foundation model is presented for estimating the lateral deflection and internal forces of existing piles. It is interesting that the proposed method can consider the shearing displacements of foundation and the influence of lateral soil displacements beside the pile. A parametric analysis is performed to discuss the influence of various factors on the deflection and bending moment of single and group-piles, and the reliability of the proposed method is demonstrated by comparing predictions with the boundary element program results, centrifuge test data, and field measurements.

2. Pile response without considering the influences of lateral soils

2.1. Analysis of single-pile response

The two-parameter foundation model for tunnel-soil-pile interaction is deduced using finite difference method. As shown in Fig. 3, in Pasternak's foundation model, a shear layer is added to Winkler's foundation model to consider interaction among spring elements. The basic assumptions of the model are as follows: (a) in the longitudinal direction, the pile is considered as a rectangular beam, with width of D and stiffness of EI; (b) the shear force can be transferred between springs, and the shear layer produces only shear displacement (x-direction); (c) the pile connects closely with surrounding soil and pile displacements is equal to displacements at the pile-soil contacting surface; and (d) there exists the friction in x-direction only, and the lateral friction between foundation and pile is not considered.

When the effects of lateral soil displacements beside the pile are not considered, the equilibrium equation of a single-pile is established as follows:

$$EI\frac{d^4w}{dz^4}-GD\frac{d^2w}{dz^2}+kDw=pD \tag{1}$$

where w is the lateral displacement of pile; p is the additional load on the pile; D and EI are equivalent width and bending stiffness of the pile, respectively; and k is the stiffness of the springs (Vesic,1961) and G is the stiffness the shear layer, and are calculated as follows (Tanahashi, 2008):

$$k=\frac{0.65}{D}\left(\frac{E_sD^4}{EI}\right)^{\frac{1}{12}}\frac{E_s}{1-\nu_s{}^2}\text{ and} \tag{2}$$

$$G=\frac{E_st}{6(1+\nu_s)} \tag{3}$$

where E_s and ν_s are the elastic modulus and Poisson ratio of soils, respectively, and t is the thickness of the shear layer and is related to the