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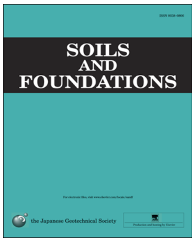

Effects of tunnelling on pile foundations

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Abstract

An efficient analysis method is presented for estimating the effects induced by tunnelling on existing pile foundations. The method is based on a two-stage procedure: (1) an estimate of the free-field ground movements caused by the tunnel excavation, and (2) an analysis of the pile group subjected to the computed free-field ground movements. The first step may be carried out using alternative approaches, ranging from empirical methods to 3D numerical analyses. The second step is performed by PGROUPN, a computer program for pile-group analysis based on a non-linear boundary element solution. The validity of the approach is assessed by comparing it with alternative numerical solutions and field measurements. The results indicate that the method is capable of generating reasonable predictions of pile response for many cases of practical interest, thus offering substantial cost savings over a complete 3D analysis of tunnel–soil–pile interaction.

Keywords: Piles; Pile groups; Tunnels

1. Introduction

Tunnelling in soft grounds inevitably causes ground movements, both vertical and lateral, which may have an impact on existing pile foundations. In such cases, at least two important aspects must be considered by the designer:

(1) The movements of the piles caused by the ground movements in order to ensure structural serviceability;
(2) The additional forces and/or bending moments induced in the piles by the ground movements in order to ensure structural integrity of the piles.

Current analysis methods to evaluate the effects of tunnelling on existing pile foundations belong to two categories:

(a) Simplified two-stage approaches involving the initial separation of the soil and the piles so that the soil movements are first computed and then imposed on the piles;
(b) Complete numerical analyses including simultaneous modelling of the piles, the soil, and the tunnel excavation.

The latter category is generally based on three-dimensional finite element (FEM) or finite difference (FDM) analyses which provide a complete solution to the tunnel–soil–pile interaction (e.g., Mroueh and Shahrour, 2002; Zhang and Zhang, 2013). While such solutions are the most powerful

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numerical tools currently available, they are very expensive in terms of data preparation (pre- and post-processing) and computational time. The cost of such analyses may become prohibitively high if non-linear soil behaviour and complicated construction sequences are to be taken into account. In addition to the computational requirements, complete 3D numerical analyses are complex when use for design purposes, particularly when non-linear behaviour is to be considered. Major difficulties are related to the construction and the interpretation of the 3D model (modelling errors are easily overlooked), the high mesh dependency, the uncertainty in assigning mechanical properties to the pile–soil interface elements, the interaction with adjacent structures, and the modelling of the excavation sequence (e.g., Poulos, 2001; Brinkgreve and Broere, 2003). Thus, a complete 3D analysis is more suitable for obtaining the benchmark solutions (against which simpler analyses can be checked) or for obtaining the final design solution for major projects, than for use as a practical tool for less demanding problems or in the preliminary design stages (in which multiple tunnel configurations and scenarios have to be examined).

In order to overcome the above shortcomings, simplified approaches have emerged (e.g., Chen et al., 1999; Xu and Poulos, 2001; Loganathan et al., 2001; Kitiyodom et al., 2005; Surjadinata et al., 2006). Such approaches are based on a two-stage procedure:

(1) evaluation of the free-field ground movements caused by the tunnel excavation;
(2) analysis of the piles subjected to the computed free-field ground movements.

In simplified approaches, the tunnelling-induced ground movements are generally evaluated in free-field conditions, i.e., in the absence of piles. This generally is a conservative assumption as the presence of piles increases the soil stiffness, thereby reducing the induced ground movements, as demonstrated numerically by Mroueh and Shahrour (2002).

1.1. Estimation of soil movements

Estimation of tunnelling-induced ground movements can be carried out using alternative procedures, namely, empirical methods, analytical expressions, and numerical analyses. Each method has its own strengths and weaknesses.

Empirical methods are based on a Gaussian error function (Peck, 1969; Mair et al., 1996) and are widely employed in engineering practice. The main limitations are related to their applicability to different tunnel geometries, ground conditions, and construction techniques, and in the limited information they provide about horizontal movements and subsurface settlements.

In light of the above limitations, a number of closed-form analytical solutions have been proposed (Sagaseta, 1987; Verruijt and Booker, 1996). In particular, the analytical expressions developed by Loganathan and Poulos (1998) for the estimation of surface settlements, subsurface vertical movements, and subsurface horizontal movements, even though strictly valid for a linear elastic half-space, have the advantage of being able to take into account the various construction methods and the non-linear ground movements (due to an oval-shaped gap) around the tunnel–soil interface. Such expressions allow the rapid estimation of ground deformations by using a simple soil parameter (i.e., the Poisson's ratio), and their applicability has been successfully verified through comparison with a number of case histories.

While empirical and analytical methods provide a simple and practical means of estimating tunnelling-induced ground movements, numerical analyses (generally based on FEM or FDM) provide the most powerful tool for carrying out such predictions because of their ability to consider such factors as ground heterogeneity, soil nonlinearity, advanced soil models, 3D effects, complex tunnel geometries, the interaction with surrounding structures, and the tunnel construction method and sequence. In addition, numerical analyses allow for consideration of the near-field ground response around the tunnel (say in the region within one tunnel diameter) where the effect of factors, such as plastic strain, stress–path dependence, consolidation or the excavation method, becomes prominent. However, even though favourable comparisons with measured ground movements have been reported (e.g., Lee et al., 1994; Surjadinata et al., 2006), finite element models are often known to overpredict the width and to underpredict the gradient of the settlement trough (e.g., Chen et al., 1999; Pound, 2003). To obtain better predictions, it is often necessary to use advanced soil models and to carefully select the corresponding model parameters. Moreover, the designer should bear in mind the complexity and high computational costs involved, particularly if non-linear soil behaviour and 3D effects have to be taken into account.

1.2. Analysis of pile response

The second step of the procedure is usually carried out via a continuum-based or Winkler spring analysis of the piles subjected to the vertical and lateral tunnelling-induced soil movements evaluated using any of the methods described above. Current analysis methods are mainly restricted to purely elastic analyses or to single isolated piles (e.g., Chen et al., 1999; Xu and Poulos, 2001; Kitiyodom et al., 2005). It is indeed generally assumed that the effects of group interaction are beneficial to the pile response as compared to single isolated piles, i.e., group effects lead to a reduction in the deformations, forces, and moments induced in the piles.

2. PGROUPN analysis

The proposed analysis is based on the two-step approach described above and is carried out with PGROUPN (Basile, 2003, 2010), a computer program for pile-group analysis which is commonly adopted in pile design through the software Repute (Geocentrix Ltd., 2012). The main feature of the program lies in its capability to provide a 3D non-linear boundary element