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Mechanical behaviour of piled-raft foundations subjected to high-speed train loading

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Abstract

In this paper, settlement of piled-raft foundation for high-speed train is considered systematically. It is observed in a case study that the railway settled significantly due to the cyclic train loading after a one-month trial operation. As traditional methods such as empirical methods or numerical simulation based on primitive constitutive models are unable to properly interpret the settlement mechanism, a sophisticated model-based numerical simulation, using a soil-water coupled finite element (FE)-finite difference (FD) hybrid algorithm, is conducted to investigate the mechanism of the settlement of the piled-raft foundation and excess pore water pressure (EPWP) of soft soils caused by the cyclic train loading. In order to demonstrate the performance of this numerical simulation, the calculated results are compared with the data recorded in the one-month trial operation and the reliability of the proposed numerical method is confirmed. The newly proposed numerical method is also used to predict the long-term settlement and the change in the EPWP during a one-year period. The predicted results suggest that without proper treatment, more serious settlement would have occurred, which is unacceptable in engineering terms.

Keywords: High-speed train; Piled-raft foundation; Long-term settlement; Soil–water coupled finite element method (FEM); Soil–pile interaction

1. Introduction

In recent years, with the development of the social economy and the high rate of population growth, the urbanization process has been accelerating and more people are migrating to large cities. Transportation has become a major obstacle to urban development. High-speed trains, a convenient and efficient means of mass transportation, has become one of the fastest growing sectors in the mass transportation system. The operating speed of high-speed trains can reach more than 300 km/h, which produces a large vibration loading on the tracks and foundations. Economic activity in China is mostly concentrated in the southeast coastal areas, e.g., the Yangtze River Delta, where soft ground is the norm and the subgrade soils are mostly 'Shanghai soils', which are characterized by a high water content, high compressibility and low shear strength. It is known that not only the construction of the railway lines, but also the traffic loading may generate considerable settlement and seriously affect the normal operation of the railway, and sometimes even result in accidents. Therefore, the development of a method to accurately predict the long-term settlement of soft soils under traffic loading is an important research topic.

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Researchers have been focusing on various aspects of the settlement problems associated with soft soils and traffic loading. Hyodo et al. (1996) conducted a dynamic analysis to investigate the settlement of an embankment road constructed on soft clay under traffic loading. Kutara et al. (1980) estimated deformation due to traffic loading in a one-dimensional consolidation theory, using the concept of equivalent static loading to simplify the settlement analysis. Fujikawa et al. (1996) proposed a simplified method to estimate the settlement of a low embankment road due to traffic loading, and verified its validity based on a field investigation. Monismith et al. (1975) proposed an exponential formula to describe the relationship between the plastic strain of soil and the amount of cyclic loading in undrained cyclic tests. This calculation model is simple, but the physical meaning of the parameters is not clear, and because data range is quite large, it is difficult to determine the values consistently. Li and Selig (1996) introduced soil strength parameters and proposed an improved method for determining these parameters, taking the soil type and its physical state into consideration. The method was also used to analyze some engineering examples related to the settlement of soft soil due to traffic loading. By taking the influence of initial deviatoric stress into consideration, Chai and Miura (2002) proposed a model to improve the shortcoming of the method suggested by Li and Selig (1996): it could not be applied to muddy soil. In addition, based on the experimental results, Zhou et al. (1996) proposed a residual deformation model for soft clay to determine the long-term and short-term settlement under cyclic loading. Jiang and chen (2001) analyzed the one-dimensional settlement features of clayey soil subjected to various loading waveforms through cyclic tests. Huang et al. (2006) discussed the accumulative deformation behaviour of saturated soft clay in undrained cyclic triaxial tests under different loading conditions.

In general, the settlement of soft soils due to traffic loading can be divided into two parts: a settlement induced by plastic deformation of the soils subjected to undrained cyclic loading, and acumulative consolidation settlement induced by the dissipation of EPWP after the loading. Though the empirical methods mentioned above provide a rough estimation of the long-term settlements, they are usually not so accurate and are very limited in its application. A numerical analysis based on a sophisticated constitutive model for soft soils is therefore required.

In recent years, remarkable developments in the research into constitutive models for overconsolidated and structured clays have been achieved. For example, Whittle and Kavvadas (1994), Nakai and Hinokio (2004), Mita et al. (2004) and Yao et al. (2009) have developed models for overconsolidated soils; Asaoka et al. (1998), Rouainia and Muir Wood (2000), Liu and Carter (2002), Kimoto and Oka (2005), and Yin et al. (2011) have proposed models for structured soils or naturally deposited soils. Since most of these models for structured soils have a feature that involves an inner yielding surface, similar to the concept of a bounding surface (Dafalias et al., 1975) or a subloading surface (Hashiguchi and Ueno, 1977) within a normally yielding surface, they can also describe overconsolidated clays. Zhang et al. (2007, 2010, 2011) proposed a constitutive model referred to as the 'Cyclic Mobility Model' for both sandy and clayey soils, in which the concepts of superloading (Asaoka et al. 1998), and subloading (Hashiguchi and Ueno, 1977), together with a newly proposed stress-induced anisotropy, are adopted to describe the influence of the structure, the density and the stress-induced anisotropy in an unified way. Subsequently, because intermediate principal stress has a large influence on the mechanical behaviour of soils (Ye et al., 2012, 2013), Ye et al. (2012) modified the Cyclic Mobility Model to enable it to describe soils under general three-dimensional stress conditions. Based on the modified model, Ye et al. (2007) conducted a series of numerical analyses using an FEM code, DBLEAVES, (Ye, 2007, 2011) to simulate shaking-table tests on a saturated sandy soil with a repeated liquefaction-consolidation process. Bao et al. (2012) also conducted numerical tests on the seismic enhancement effect on existing group-pile foundations with a partial-ground improvement method to find out the optimum pattern of ground improvement around existing pile foundations. The applicability of this approach for evaluating the seismic behaviour of pile foundations was verified with shaking table tests. In addition, as reported in the works by Jin et al. (2010), Xia et al. (2010), Bao et al. (2012), Morikawa et al. (2013), and Bao et al. (2014), DBLEAVES is capable of solving many geotechnical engineering problems relating to static/dynamic loading under different boundary and drainage conditions for earth structures, retaining walls, and soil-structure interactions of group-pile foundations.

In this paper, the mechanical behaviour of piled-raft foundations subjected to high-speed train loading, including the settlement of the foundation and EPWP of the subgrade soils, is the main focus and is discussed in detail. This is a typical problem relating to the interaction between soils and piled-raft foundations and should be considered in soil-water coupling schemes. The mechanical behaviour of the foundation and the subgrade soils should be considered not only during train loading but also in the process of postconsolidation. Therefore, it is necessary to conduct a series of dynamic and static analyses in a unified, sequential way to simulate the real life situation. For this reason, the FEM analysis should be based on a constitutive model, like the Cyclic Mobility Model, which can accurately describe the soils subjected to different loadings, dynamic or static, under different drained conditions, in a unified way. The case study of the high-speed train is discussed with the above-mentioned numerical method, and its reliability is validated by field observation.

2. Problem description

2.1. Background and description of a case study

Shanghai soils are typical soft sedimentary soils with a high water content, high permeability, high compressibility and low shear strength, as illustrated in Table 1. Significant settlement of the subgrade soils of the railway due to cyclic train loading could occur if the railway foundation is not properly designed and constructed. The cyclic train loading acts initially on the tracks and then transfers through the sleepers and the slab to the foundation and subgrade soils. Its magnitude is dependent