Computers and Geotechnics 100 (2018) 144–157

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Dynamic response and pile-soil interaction of a heavy-haul railway embankment slope reinforced by micro-piles

Jie Dong[a,*], Zhi-Hui Wu[a], Xin Li[a], Hong-Yun Chen[a,b]

[a] College of Civil Engineering, Hebei Institute of Architecture and Civil Engineering, Hebei, Zhangjiakou, China
[b] China Railway Design Corporation, Tianjin, China

ARTICLE INFO

Keywords:
Micro-piles
Heavy-haul railway
Dynamic characteristics
Field test
Model experiment
Numerical simulation

ABSTRACT

We investigated the dynamic characteristics and pile-soil interaction of a heavy-haul embankment reinforced by micro-piles. First, the vibration of a heavy-haul railway under a C80 train was tested. Based on the acceleration test, the dynamic response characteristics were further studied using a model test and 3D numerical simulation, which were verified via comparison with the field test. Finally, by integrating the model test and numerical simulation results, the influence of the pile length, pile diameter and pile spacing on the dynamic behavior of the embankment was analyzed, and the vibration-attenuation characteristics and dynamic soil-arching effect were discussed.

1. Introduction

Heavy-haul railways are widely used in many countries. With the continuous growth of railway service time and the rising axle load of trains, increasing numbers of embankment settlements must be maintained. Due to the advantages of convenient construction, minimal disturbance and low cost, micro-piles have been widely used as embankment reinforcements. Because of the effects of the large loads of heavy-haul trains, the mechanism of pile-soil interaction is relatively complex. At present, scholars are focusing on studying the dynamic response of pile-supported embankments [1,2] and the dynamic behavior of piles under earthquake loads [3]. In this study, because the micro-piles are placed in the shoulder (thus affecting primarily the lateral deformation of the embankment rather than the compressive deformation of the foundation), the dynamic characteristics are the focus, as these characteristics are considerably different from those of pile-supported embankments. To date, little research has been performed on heavy-haul railway embankments reinforced by micro-piles placed vertically in the shoulder under the operation of heavy-haul trains. It is of particular significance to accurately evaluate the dynamic characteristics and determine the critical control factors of deformation for existing heavy-haul railway embankments reinforced by micro-piles.

Multiple theories have been developed for analyzing the mechanical behavior in this context. In early development, the mechanical response of a single pile subjected to lateral loads was investigated [4–6]. With further research, the nonlinear behavior of laterally loaded pile groups was analyzed based on the semi-analytical or Winkler elastic method [7–10]. Later, the finite element (FE), Winkler and analytical layer-element methods were proposed to calculate the dynamic response of piles under dynamic loading [11–13]. Because a pile-supported system can effectively control the settlement of a railway embankment, researchers have developed multiple solutions for the analysis of pile-supported embankments [1,14]. Zhang et al. [2] proposed a semi-analytical solution to assess the performance of a pile-supported embankment and found that the differential settlement of the embankment can be reduced by increasing the pile stiffness or reducing the pile spacing. These approximate solutions help us understand the basic mechanical response of reinforced piles. In addition, numerical simulation is a computationally efficient method to analyze the static or dynamic response of a reinforced-pile system. Investigators have used numerical models to obtain the mechanical response of a single pile and group piles under lateral loading by considering the effects of material nonlinearities and various reinforcement conditions [15–18]. For example, Taha et al. [19] implemented FE analysis to simulate the dynamic performance of a pile-reinforced system. Gu et al. [20] investigated the mechanism of piled-raft foundation settlement caused by cyclic train loading. Based on the full three-dimensional analyses, the study of reinforced embankments supported on floating piles considering pile-soil interaction was carried out by Bhasi et al.[21]. Sadek and Alsaleh et al. [3,22] performed a 3D FE analysis on the influence of soil plasticity on the seismic response of micro-piles. Li and Bian [23] investigated the dynamic performance of the track-embankment-ground system under a high-speed train load using a simulation

* Corresponding author at: College of Civil Engineering, Hebei Institute of Architecture and Civil Engineering, No. 13 Chaoyang West Street, Zhangjiakou 075000, China.
E-mail address: dongjie1003@hebiace.edu.cn (J. Dong).

https://doi.org/10.1016/j.compgeo.2018.04.005
Received 11 September 2017; Received in revised form 26 February 2018; Accepted 3 April 2018

approach.

Although multiple methods are available for analyzing the mechanics and dynamic response of piles, little validation work has been performed using a model or field test. Eekelen et al. performed 3D laboratory model tests to analyze the load distribution, deformation, and strains [24]. Elsaied, Manna and Ozden et al. [25–27] conducted experiments on small-scale piles to study the lateral load-carrying capacity and dynamic nonlinear response. Field test are useful for objectively determining the dynamic characteristics of a pile reinforcement system. Bhowmik [28] and Capatti [29] investigated the dynamic nonlinear behavior of micro-piles under a horizontal load. Based on field test data, the mechanical properties of a pile-supported embankment were analyzed and evaluated by Chen and Zhou et al. [30,31].

Relatively few attempts [14,20,24,32,33] have been made to study the acting mechanical mechanisms and dynamic mechanical behavior of embankments. The dynamic response of a pile-reinforced embankment under heavy-haul train operation is a complex phenomenon, and experimental verification of the dynamic response of such embankments is scant. Thus, it is necessary to study the characteristics of an existing railway reinforced by micro-piles using a model test. Relative to ordinary train loads and seismic loads, the heavy-haul train load has the characteristics of low frequency, high amplitude and long duration, and embankment settlement problems during operation are more prominent. Moreover, the dynamic response characteristics of a heavy-haul railway embankment reinforced by micro-piles placed vertically in the shoulder are significantly different from those of pile-supported embankments. Therefore, it is necessary to explore the dynamic characteristics of a heavy-haul railway embankment and to further elucidate the mechanism of pile-soil interaction, which is of great significance to establishing rigorous guidance for micro-pile design and construction. Combining a field test, numerical simulation and a model test, the present investigation aims to study the dynamic behavior of an embankment reinforced by micro-piles, including the dynamic earth pressure, the displacement of the embankment, the bending moment and the vibration acceleration characteristics. Through systematic experiments and numerical simulation, the dynamic response characteristics of an embankment reinforced by micro-piles are obtained.

2. Field test

In China, the Shuohuang Railway is the second-largest channel for transporting western coal to eastern ports. To meet the coal demand associated with rapid economic development, both the number of trains and the train axle weight continue to increase. The original railway embankments suffer from settlement and lateral deformation, and the thickness of the ballast pavement is also growing. Indeed, embankment failures, landslides, uneven settlements and similar events are becoming much more common than in the past [34]. The degradation of the Shuohuang Railway embankment is shown in Fig. 1.

To further control embankment deformation and ensure railway operation, reinforcement measures are being implemented while trains continue to operate. Many scholars around the world are studying the failure mechanism of embankment slopes and the reinforcement of embankments. Ciotlaus et al. [35] presented a study of the slope stability of railway embankments subjected to increasing axle loads. Considering the vertical loads acting on the top of the slopes, Zhou et al. [36] studied slope stability by evaluating the failure mechanism. To improve the bearing capacity and stability of an embankment, many methods are used to enhance embankment performance, such as geotextile reinforcement and prefabricated vertical drains (PVD) [37,38], polyester (PET) and polypropylene (PP) geotextiles [39] and geocell reinforcement [40]. Furthermore, Li et al. [41] investigated the combined effects of the viscoelastic behavior of geosynthetic reinforcement and foundation soils on the performance of reinforced embankments. More recently, soil-cement deep mixing (DM) columns combined with geosynthetic basal reinforcement are accepted to construct road and railway embankments over soft foundations [42]. The slope stability of stone column-supported embankments [43,44] and the behavior of soft ground reinforced by floating stone columns [45] are also under study. Meanwhile, Esmaeili et al. [46] performed laboratory and numerical investigations of a tied back-to-back system for stabilizing high railway embankments. To prevent disruption of the normal operation of the railway and considering the reinforcement effect, the Shuohuang Railway Company has adopted a more practical plan to use micro-piles mounted vertically in the shoulder to reinforce embankments. Because heavy-haul C80 trains aggravate embankment settlement to a greater degree than C70 and C64K trains, knowledge of the vibration acceleration close to the heavy-haul train line is necessary to apply the appropriate vibrational load in the model test and numerical simulation.

A typical embankment subsidence section of the Shuohuang railway located in the Yuanping area of Shanxi Province is selected as the test object, with a loess layer thickness of 12–33 m, which is distributed on the sand and gravel layer. For the field test, seven measuring points are arranged along the vertical rail of the heavy-haul train line, as shown in Fig. 2.

Three measuring points are located on a sleeper, the shoulder and the embankment footing, respectively, and the other four measuring points are 10 m, 20 m, 40 m and 60 m from the embankment footing. The accelerations were measured using a B&K automatic acquisition system made in Denmark. Photographs of the field test are shown in Fig. 3.

The vibration intensity of the ground during heavy-haul train operation varies. The vertical vibration level (VL_Z) is selected as the evaluation standard, i.e. the vertical vibration acceleration level (unit: dB) is obtained correcting the different frequency weighted factors specified in the ISO2631/1-1997. The formula is as follows:

$$VL_z = 20\lg(a'_{rms}/a_0) \tag{1}$$

$$a'_{rms} = \sqrt{\frac{1}{T}\int_0^T a_w^2(t)dt} \tag{2}$$

where a_0 is the reference acceleration of $1 \times 10^{-6}/\mathrm{s}^2$; a_w is the vibration acceleration obtained by correcting different frequency weighted factors; and T is the average time of vibration measurement.

The 1/3 octave spectrum analysis is performed on the collected vibration acceleration discrete signals to obtain the vibration acceleration corresponding to each center frequency, and each center frequency is then multiplied by the corresponding weighted factor to obtain the weighted acceleration discretization signal. Finally, an inverse transform analysis is performed on the corresponding 1/3 octave spectrum to obtain the required vibration acceleration signal value. According to the above equation, the vertical (Z-direction) acceleration vibration level can be obtained.

The accelerations of a C80 train and a C64K train running at different speeds were recorded. The test results indicate that at the embankment footing, the vibration level generated by a C80 train at a speed of 65 km/h is 86.5 dB, and that generated by a C64K train at a speed of 66 km/h is 86 dB; 20 m from the sleeper, the vibration levels are 85.3 dB and 84.7 dB for the C80 and C64K trains, respectively. The vibration levels of the other points are shown in Fig. 4. These results show that a larger vibration amplitude is associated with the C80 heavy-haul train. Thus, based on the measured excitation source input, the present study focuses on the dynamic response of the embankment reinforced by micro-piles under the operation of a C80 train.

3. Model experiment

3.1. Model test overview

The model test box consists of a steel plate, 15 mm thick tempered glass, a vibration-isolation sponge, an adjustable bracket, a dynamic force-transmission rod, and a 30 cm × 5 cm × 0.3 cm force-