Soil Dynamics and Earthquake Engineering 88 (2016) 33–44

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Vibration characterization of fully-closed high speed railway subgrade through frequency: Sweeping test

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ARTICLE INFO

Article history:
Received 15 December 2015
Received in revised form
23 March 2016
Accepted 19 May 2016

Keywords:
Sugrade
Field test
Dynamic stress
Expansive soil
High speed railway

ABSTRACT

This paper presents the vibration characteristics of a new type fully-closed railway subgrade (FCRS) through field frequency – sweeping test. The FCRS, which uses semi-grid modified cement-based compound material as waterproof layer, is designed to solve serious subgrade damage problems induced by expansive soil. Dynamic stress sensors and accelerometers were installed at various locations in FCRS to monitor dynamic response. The results show that the attenuation regularities of dynamic stress and acceleration along subgrade depth were significantly affected by excitation frequency and semi-grid waterproof layer. The pronounced frequency of FCRS investigated in this paper was gently influenced by its layer system, and gradually changed from 20 Hz to 22 Hz as depth increased.

1. Introduction

YUN-GUI high-speed railway is one of the most important parts of the Pan – Asia railway network in China. It connects two capital cities of Guangxi Zhuang autonomous region and YunNan province, with a total length of 710 km and design speed of 200~250 km/h. It is also the longest high-speed railway in the word that founded on expansive soil. The most annoying characteristic of expansive soil is considerable swelling and shrinkage volume change as moisture content varies [1–3]. Due to seasonal climate change, moisture in the expansive soil varies periodically, resulting in periodic swelling and shrinkage of the soil. Cyclic swell–shrink movements, especially differential volume changes in expansive soil may induce considerable distresses and severe damages to overlying railways [4], such as subgrade sinking, rail inhomogeneous uplift, mud pumping [5], etc. For high-speed railways that allow trains to run at speeds higher than 200 km/h have very small / differential settlement tolerance in its service period. Therefore, the difficulty of design and construction of YUN-GUI high-speed railway is extremely increased. Within recent decades, numerous methods have been proposed to minimize or diminish the volume change through adding certain additives such as lime [6], fly-ash [7], cement [8] or polymers [9]. Most of these methods are available when used to improve expansive soil foundation of buildings which are insensitive to small deformation and having a relative small or limited foundation geometry size. However, railway line is a long strip like construction that extends for tens, hundreds or even thousands of kilometers, physico–mechanical properties of expansive soil significantly different along the line, thus, it is really difficult to ensure the treating quality by these adding additives methods. Take the existing "Nan-Kun" railway which was constructed during the period of 1990–1997 for instance, over one hundred kilometers of this line is laid on expansive soil, despite the adding additives methods were used to improve expansive soil, lots of subgrade bed damages are still occurring.

The generation mechanisms of railway subgrade diseases in expansive area have been thoroughly studied by field investigation, experiments and analytical works. On these basis, a new type of fully-closed railway subgrade with a semi-rigid waterproof layer was developed, which is suitable for expansive soil section of YUN-GUI high-speed railway. However, it is well known that the vibration level of railway subgrade is closely associated with subgrade layer system and trains travel speeds [10–12], in particularly, when the excitation frequency induced by the running train approaches the resonance frequency of subgrade, extremely high vibrations may occur, and the train may derail [13].

Vibrations may significantly accelerate micro-structure damage of subgrade soil and increase the total subgrade accumulation deformation. Therefore, it is important to study the dynamic

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http://dx.doi.org/10.1016/j.soildyn.2016.05.011
0267-7261/

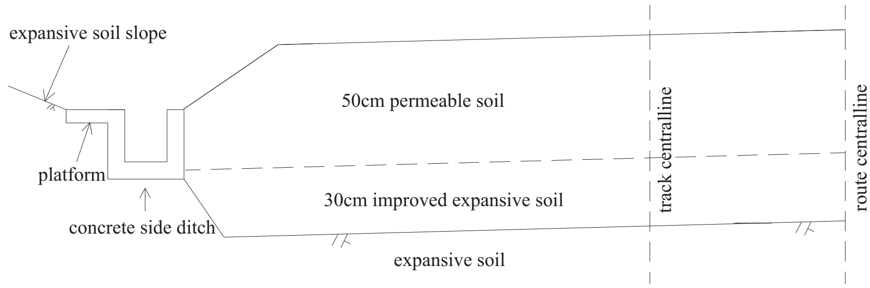

Fig. 1. Cutting section of subgrade bed in expansive soil of the existing "Nan-Kun" railway.

response of this new type railway sbubgrade under different excitation frequency which represents the effects caused by different train speeds.

In fact, many analytical methods, numerical methods and field tests have been presented in literatures to investigate the ground vibrations induced by high-speed train. For instances, A.P. Filippov [14] modeled the train-subsoil system as a moving load over a beam laid on elastic half-space, and the critical train speed obtained approximately equals to Rayleigh wave velocity. Labra [15] improved A.P. Filipov's model by considering axial stress in the beam, and found that the critical velocity was decreasing with increasing axial stress. Krylov [16] and Sheng et al. [17] established continuous models to analyze dynamic behavior of the train-rail-embankment system in the frequency domain by using Fourier transform in space and time domain. With the progress of computer capacity, numerical methods became a paramount important way to analysis the train-rail-embankment system response while high-speed trains passing [18–20]. Authors such as N. Hamdan et al. [21] employed a combined finite element–thin layer model to analyze the reduction effectiveness of different shape wave barriers in ground wave propagation in the frequency domain, and the complex geometries of barriers were dealt by unstructured triangular mesh grids. Kouroussis et al. [22] mixed multi-body model of railway vehicle and finite element model of track together through wheel/rail contact forces, and found that the pitch motion of bogies and car-bodies had non-ignorable influence on ground vibration. D. Connolly et al. [23] used a 3D numerical model to investigate the role of embankment stiffness in the transmission of vibration.

Despite this, there is still a common disadvantage of all these theoretical and numerical findings, these methods are all based on different kinds of modeling assumptions which could not fully reflect the real working conditions of high speed railway. Thus, it is of great importance to carry out field dynamic tests to study the ground vibrations induced by high-speed railway. In fact, considerable field observations have been made by railway companies and institutes in China [24], France [25], Germany [26], Spain [27], Portugal [28], Belgium [29] and UK [30], to investigate the substantial increase in vertical movements of railway subgrade as the train speed or exciting frequency approaches the critical velocity or resonance frequency of the subgrade. These results from analytical methods, numerical methods and field test indicated that vibration characteristics of subgrade are influenced by subgrade layer system, stiffness, filling soil type, or ground geological condition, etc. [31,32].

To the authors' knowledge, the fully-closed railway subgrade structure, called FCRS for short, was used for high speed railway to across the expansive soil sections for the first time, and there is no published literature related to the field experimental analysis of the dynamic response variation under different frequency excitation regarding the FCRS. However, a complete presentation of the research process and experiments associated to this new kind of railway subgrade is beyond the scope of this paper. Thus, the aims of this paper are limited to the following: investigation of subgrade damage mechanisms of the existing "Nan-Kun" railway which was constructed on expansive soil, a brief description of FCRS, and attempts to figure out the influences of excitation frequency on dynamic parameters at different horizontal position and their distributions in vertical direction using field frequency – sweeping dynamic test.

2. Damage investigation of existing railway in expansive soil area

The construction of the existing "Nan-Kun" railway with a total length of 898 km started in December 1990, and has been exploited commercially since July 1997. Approximately 146 km of this line have to cross expansive soil area, and the annual rainfall along this line is 1105 mm/year (YunNan province) – 1540 mm/year (Guangxi Zhuang autonomous region), and almost 80% of annual rainfall are concentrated in rainy season (from May to October). Fig. 1 presents the typical layer structure of subgrade bed in expansive soil cutting section. The subgrade bed was composed of permeable soil layer with a thickness of 50 cm and an improved expansive soil layer with a thickness of 30 cm. According to China Code for Design on Subgrade of Railway [33], the permeable soil is a kind of widely used subgrade filling which requires hydraulic conductivity larger than 10^{-3} cm/s, silt and clay total content less than 10%. Expansive soil was improved by lime and fly-ash.

Around to 127 subgrade damages of the "Nan-Kun" railway in the expansive area were observed in its first year (from July 1997 to August 1998) commercially operation. Since then, subgrade that lying on expansive soil foundation became a nightmare of railway management department, the cost of maintenance and treatment for these damages was up to million dollars every year. Owing to the intensification of subgrade bed damages occurred along the railway line, a technical survey was conducted by the Ministry of Railways of China. Some representative damage pictures collected during this survey are shown in Fig. 2. Fig. 2(a) shows that ballast and permeable soil moved outward along the surface of improved expansive soil layer, note that this picture was photographed on November 11, 1998, just a year later its commercially operation. Fig. 2(b) shows that the unreinforced concrete ditch at subgrade bed side was dislocated and completely damaged. Fig. 2(c) shows a wavy rail surface and cracking damage of Lin - Feng railway station platform, this picture was photographed on April 20, 2010. As seen in Fig. 2(d), continual subsidence was another representative damage type.

The mechanism of these damages can be summarized and explained as follows:

i. For permeable soil was always saturation in rainy season due to its hydraulic conductivity couldn't match the rainfall infiltration velocity, effective stress of the permeable soil was obviously reduced when excess pore water pressure was generated by