Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Field experiment on train-induced embankment vibration responses in seasonally-frozen regions of Daqing, China*

Xian-zhang LING†[1,2], Li-na WANG[1,2], Feng ZHANG[1,2], Shi-jun CHEN[1,2], Zhan-yuan ZHU[1,2,3]

([1]*School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China*)

([2]*Institute of Subgrade and Protection Engineering, Harbin Institute of Technology, Harbin 150090, China*)

([3]*Information and Engineering Technology College, Sichuan Agricultural University, Ya'an 625014, China*)

†E-mail: xianzhang_ling@263.net

Received Oct. 29, 2009; Revision accepted Apr. 8, 2010; Crosschecked June 3, 2010

Abstract: The seasonal-frozen layer may have an influence on embankment motion from train-induced vibrations. Based on the field monitoring in a seasonally-frozen region of northeastern China, the effects of the frozen layer on the embankment responses to train-induced vibration were investigated in winter and summer via acceleration time histories and acceleration frequency spectrums. The results show that: (1) Compared to unfrozen soil conditions, the amplitudes of longitudinal and vertical vibrations at the points near the rail were increased, different influences of freight versus high-speed trains are the most evident. (2) With greater distance from the rail, the dominant frequency ranges of embankment with both frozen and unfrozen layers narrowed and shifted to low frequency bands. (3) The predominant frequency of embankment vibration with frozen soil layers shifted to higher frequencies with the increased train speed, although there was little change with unfrozen condition. Layer condition (frozen versus unfrozen) and distance to rail both play important roles in investigating the embankment vibration characteristics and rail transit field monitoring to improve the criterion of the rail construction in seasonally-frozen regions.

Key words: Embankment vibration, Spectrum characteristics, Time histories, Field monitoring, Seasonally-frozen region
doi:10.1631/jzus.A0900657 **Document code:** A **CLC number:** U21

1 Introduction

In China, over two thirds of arterial railway lines are distributed in seasonally-frozen regions. Significant attention has been paid to the effects of seasonally-frozen layers on vibration characteristics of the embankment, induced by passing trains. The importance of this matter lies in the increasing disorders of embankments induced by passing train, and also the development of passenger trains with higher speeds, as well as heavier freight trains.

As one of the basic means of investigating ground vibration response induced by passing trains, field monitoring has been thoroughly considered in unfrozen regions. Mehdi (2004) indicated that the vibrations attenuated with distance from the track centerline and the rate of attenuation of vibration with distance was lower in freight trains than non-freight trains. Xia *et al*. (2005) examined both passengers and freight trains, and analyzed the effects of train type and speed on ground vibration velocity. They pointed out that ground vibration increased with the increase of train load and speed. Ju *et al*. (2007) suggested that the vibration responses in the vertical and horizontal directions were quite large at the dominant frequencies and train speed had obvious influence on the vibration at the dominant frequencies. Galvín and Domínguez (2009) analyzed the acceleration and the

* Project supported by the National Natural Science Foundation of China (Nos. 50678055 and 50538030), the State Key Laboratory of Frozen Soil Engineering Open Found of China (No. SKLFSE200402), the Doctor Subject Special Scientific Found of China (Nos. 20070213076 and 20092302110053), and the Key Project of Technological Research and Development Programs of the Ministry of Railways (No. 2009G010-E), China

velocity time histories, the velocity frequency contents of the ground vibration induced by two types of trains traveling at different speeds. They found that dominant frequency move towards higher frequencies as train speed increases. Ju and Lin (2008) and Ju *et al*. (2009) proposed a field experiment to study the dynamic characteristics of ground vibrations induced by moving vehicles, including the mass rapid transit system and high-speed train railway. The experimental results showed that the vibration at the dominant frequencies of the trainload is very large (Li *et al*., 2007). Moreover, field experiments have verified numerical models for investigating the vibration characteristics induced by trains. Takemiya (2003) presented experimental validation of a numerical model for the prediction of ground vibrations induced by high-speed train X-2000 at Ledsgard, Sweden. Auersch (2005) developed an integrated model using a combined finite element method/boundary element method model for soil and track to calculate the dynamic responses of ground induced by passing trains. The model had been proven by experiments in several respects. Lombaert *et al.* (2006) presented field measurements to validate simulation model for the computation of ground vibration. The dynamic interaction among the train, the track, and the soil was considered in their model. Galvín and Domínguez (2007a; 2007b) developed a fully 3D model for the analysis of the soil motion and effects of high-speed train passage on nearby surface and underground structures. The model has been validated with experiment records. Lombaert and Degrande (2009) presented a numerical model for the prediction of railway-induced vibrations and this has been validated by field measurements. Both measured and predicted free-field vibrations show a moderate increase with the increase of train speed.

In frozen regions, field monitoring of embankment vibration characteristics induced by train have also been considered. Liu *et al*. (2004) investigated the propagation properties of vibrations induced by trains in a field experiment in Reshui Coal Mining located on the southern slope of the Qilian Mountain, Qinghai Province, China. They found that vibration acceleration was amplified at a certain distance from the track, though the trend of the attenuation curve was to decrease with the distance from the track to the measured point. Ling *et al*. (2010), according to the field experiment at the Beiluhe permafrost testing section along the Qinghai-Tibet railway in China, analyzed the acceleration time histories and the corresponding frequency spectra of embankment. The results suggested that the train speed and sleeper spacing had effect on dominant frequencies of the embankment vibration. They also indicated that vibration embankment of permafrost region increased with both the train load and passing speed. Ling *et al*. (2009a) studied the vibration and attenuation characteristics of embankment induced by different trains at a seasonally-frozen region of Daqing in time domain. They pointed out that the vertical and longitudinal vibrations were amplified in the freezing period while attenuated in thawing period.

The current study deals with the vibration characteristics of embankment by analyzing the acceleration response in time and frequency domains, based on the field experiment on a seasonally-frozen region of Daqing in winter (frozen state) and summer (unfrozen state). In the following sections, the monitoring scheme is introduced to understand the background of experiment site and the experiment method, and then acceleration time histories and acceleration spectrums of embankment vibration induced by different trains under the unfrozen and frozen conditions are analyzed. Finally, some practical conclusions are provided to further understand the vibration and dynamic stability of embankment in seasonally-frozen regions.

2 Monitoring scheme

The field experiment was situated at K124+118 in Harbin-Daqing Railway Line, where two parallel railway lines cross the experiment profile (Fig. 1). The Daqing area, a typical seasonally-frozen site, is located in the northeast of China. The highest temperature in summer is 37 °C, and the lowest temperature in winter reaches −35 °C. Meanwhile, the maximum frozen boundary and the groundwater level are at about 1.8–2.0 m below ground surface. According to field investigation, the embankment is composed of four layers (Fig. 2). The vibration responses of the embankment induced by passing trains are monitored in the profile in winter and summer.

Fig. 1 Pictures of field monitoring
(a) Experiment site; (b) Accelerometers; (c) Passing train; (d) Installation of accelerometers; (e) Data acquisition systems

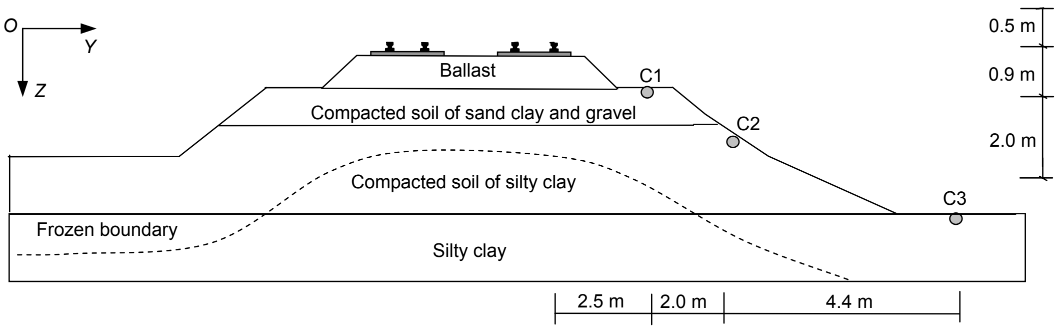

Fig. 2 Section view of monitoring section and layout of monitoring points

In this study, the *X*-direction is the train's direction, the *Y*-direction is perpendicular to the train direction, and the *Z*-direction is the direction of gravity. Fig. 2 illustrates the arrangement of measurement points, located at a lateral distance to the rail of 2.5, 4.5, and 8.9 m, respectively. Three accelerometers were presented at each point to measure the vibration in three directions.

The accelerometers of 891-2, with an acceleration resolution factor of 1×10^{-5}, were designed and produced by the Institute of Engineering Mechanics, China Earthquake Administration. The signal acquisition and analysis system INV306 was developed by the Eastern Institute of Vibration and Noise Technology in China. The detailed vehicle information was acquired from the monitoring train station.

3 Results and analysis

To investigate the effects of the seasonally- frozen layer on the vibration characteristics of the embankment, the following recorded data are presented and analyzed: the acceleration time histories and the frequency contents, resulting from the passing three type trains (the slow-speed passenger train N45, the high-speed passenger train T507, and freight train) at three selected positions at various distances from the rail.

3.1 Acceleration response in time domain

The two characteristic accelerations, i.e., the maximum absolute acceleration $|a_i|_{max}$, the average absolute acceleration $|a_i|_{ave}$, are introduced and defined as follows:

$$|a_i|_{\max} = \max\{|a_{ij}|\},\ i = X, Y, Z,\ j = 1, 2, \cdots, N, \quad (1)$$

$$|a_i|_{\text{ave}} = \sum_{j=1}^{N} |a_{ij}|/N, \quad (2)$$

where a_{ij} is the jth acceleration record in the i direction, N is the total acquisition amount of acceleration record at one point. According to Eqs. (1) and (2), the acceleration eigenvalues of embankment vibration induced by the passing train at different distances to the rail (D) in winter and summer are calculated and listed in Tables 1 and 2.

Fig. 3 shows time histories in the longitudinal vibration observed at different points located at various distances from the rail under frozen and

Table 1 Comparison of the average absolute acceleration induced by trains for different seasons (m/s²)

Condition	Train type	Speed (km/h)	C1 (D=2.5 m)			C2 (D=4.5 m)			C3 (D=8.9 m)		
			$\|a_x\|_{ave}$	$\|a_y\|_{ave}$	$\|a_z\|_{ave}$	$\|a_x\|_{ave}$	$\|a_y\|_{ave}$	$\|a_z\|_{ave}$	$\|a_x\|_{ave}$	$\|a_y\|_{ave}$	$\|a_z\|_{ave}$
Winter (frozen)	Slow-speed train N45	68	0.081	0.038	0.117	0.053	0.027	0.045	0.014	0.017	0.018
	High-speed train T507	140	0.105	0.045	0.149	0.070	0.035	0.067	0.014	0.017	0.027
	Freight train	59	0.112	0.053	0.190	0.074	0.033	0.063	0.013	0.016	0.026
Summer (unfrozen)	Slow-speed train N45	69	0.042	0.040	0.076	0.035	0.041	0.039	0.012	0.016	0.013
	High-speed train T507	140	0.097	0.077	0.132	0.074	0.078	0.062	0.026	0.038	0.031
	Freight train	58	0.070	0.067	0.108	0.055	0.060	0.058	0.022	0.028	0.023

Table 2 Comparison of the maximum absolute acceleration induced by trains for different seasons (m/s²)

Condition	Train type	Speed (km/h)	C1 (D=2.5 m)			C2 (D=4.5 m)			C3 (D=8.9 m)		
			$\|a_x\|_{max}$	$\|a_y\|_{max}$	$\|a_z\|_{max}$	$\|a_x\|_{max}$	$\|a_y\|_{max}$	$\|a_z\|_{max}$	$\|a_x\|_{max}$	$\|a_y\|_{max}$	$\|a_z\|_{max}$
Winter (frozen)	Slow-speed train N45	68	1.103	0.800	1.551	0.643	0.268	0.508	0.083	0.127	0.111
	High-speed train T507	140	1.426	0.753	1.720	0.786	0.285	0.614	0.071	0.130	0.142
	Freight train	59	2.555	0.878	2.606	1.237	0.398	0.664	0.111	0.151	0.197
Summer (unfrozen)	Slow-speed train N45	69	0.514	0.442	0.724	0.329	0.323	0.303	0.088	0.178	0.098
	High-speed train T507	140	0.817	0.967	1.077	0.559	0.534	0.413	0.159	0.301	0.191
	Freight train	58	1.030	0.841	1.508	0.487	0.534	0.666	0.148	0.258	0.201

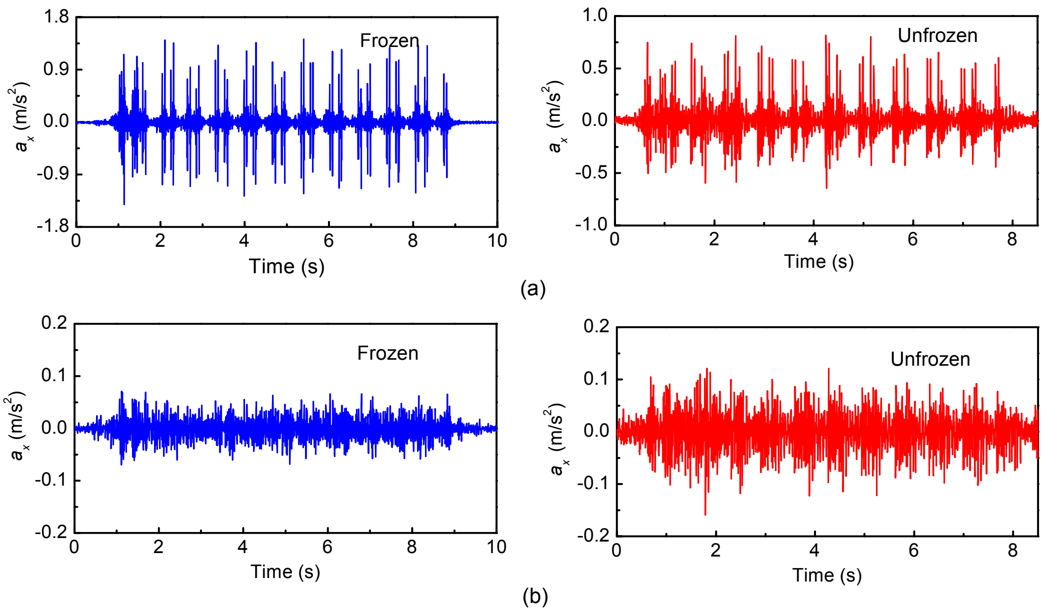

Fig. 3 Acceleration time histories in longitudinal acceleration induced by T507 at different points under frozen and unfrozen soil conditions. (a) D=2.5 m; (b) D=8.9 m

unfrozen conditions. In the time response curves corresponding to a position at a distance of 2.5 m to the rail, one can clearly identify the passing of each of the axles supporting the train (Fig. 3a). At this measured point, the maximum absolute acceleration in summer is approximately 0.817 m/s^2, about 57.3% of the amplitude recorded in winter. This is mainly attributed to the variations of soil structure and dynamical behaviors (Ling *et al*., 2009b) in winter. The frozen layer enhances the soil stiffness and decreases the soil damping, which consequently increases the response to the embankment motion in longitudinal direction. The vibration response recorded at the point far from rail, for example 8.9 m (Fig. 3b), shows attenuation according to geometrical damping and internal damping of the soil. At a distance of 8.9 m from the rail, the measured maximum absolute accelerations in winter and summer are approximately 0.071 and 0.159 m/s^2, respectively.

Fig. 4 provides the measured time histories in the lateral acceleration at different measured points located at varying distances from the rail under frozen and unfrozen conditions. Measurements taken at the position 2.5 m from rail (Fig. 4a) indicate the maximum vibration acceleration in winter approximately 0.753 m/s^2, about 78% of the amplitude in summer. This is because the vibration behavior is changed during freezing process, which leads to the restraint of lateral vibration by deeply frozen soil layer. The maximum accelerations under frozen and unfrozen conditions observed at a position located 8.9 m from the rail (Fig. 4b) are approximately 0.130 and 0.301 m/s^2, respectively.

Fig. 5 shows acceleration time histories in the vertical direction observed at various distances from the rail under frozen and unfrozen conditions. When the distance to the rail is 2.5 m, the maximum absolute accelerations in winter and summer are approximately 1.720 and 1.077 m/s^2, respectively. This suggests that the amplitude of vibration in vertical direction is increased because of the seasonally-frozen layer. When the distance to the track is 8.9 m, the maximum vertical absolute accelerations in winter and summer are approximately 0.142 and 0.191 m/s^2.

As shown in Figs. 3–5, for the position located 2.5 m from the rail, the decreasing order of vibration amplitude in winter is vertical direction, longitudinal direction and lateral direction; however, the maximum vibration of vertical direction in summer is the greatest and that of the longitudinal direction is the least. At a point of 8.9 m from rail, the maximum absolute acceleration in the longitudinal direction is the lowest in winter, while the greatest in the lateral direction in summer. The figures also show that the attenuation rate in longitudinal direction under frozen soil conditions is the highest, but vertical vibration

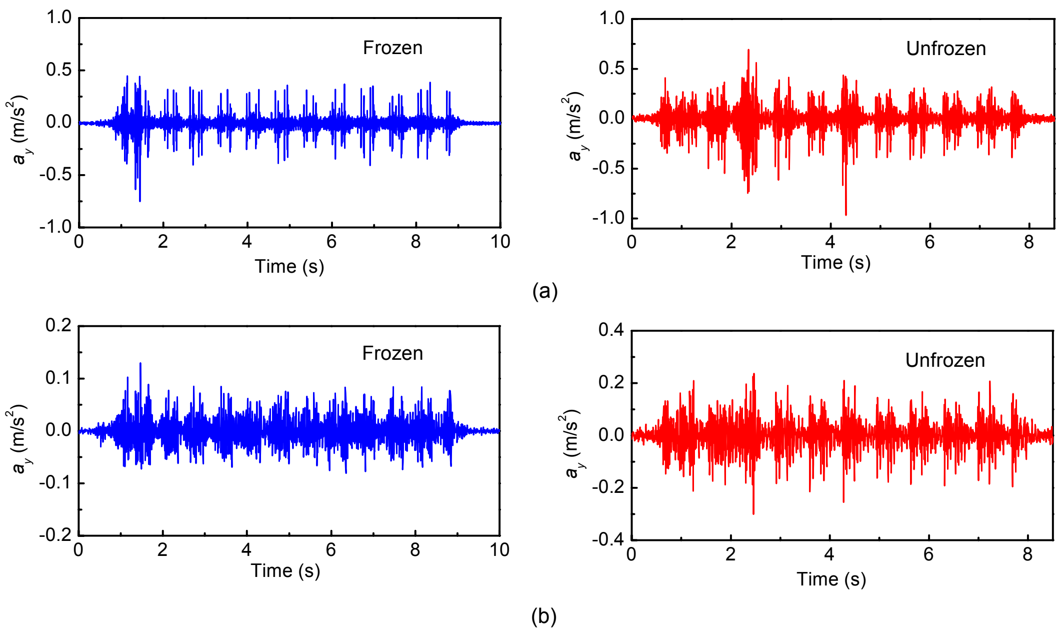

Fig. 4 Acceleration time histories in lateral acceleration induced by T507 at different points under frozen and unfrozen soil conditions. (a) *D*=2.5 m; (b) *D*=8.9 m

attenuates most quickly than other directions for unfrozen soil conditions. The differences in vibration characteristics and attenuation laws are owing to the changes of stiffness and damping of the top layer when it is frozen.

Acceleration time histories of high-speed train, slow-speed train, and freight train at embankment point C1 in the vertical direction under frozen and unfrozen conditions are shown in Fig. 5a and Fig. 6. The maximum absolute accelerations of vertical vibration for frozen soil induced by slow-speed passenger train, high-speed passenger train and freight train are 1.551, 1.720 and 2.606 m/s^2, respectively, about 2.14, 1.60 and 1.73 times, respectively, than those observed in unfrozen soil conditions. It can be seen that embankment vibration becomes more

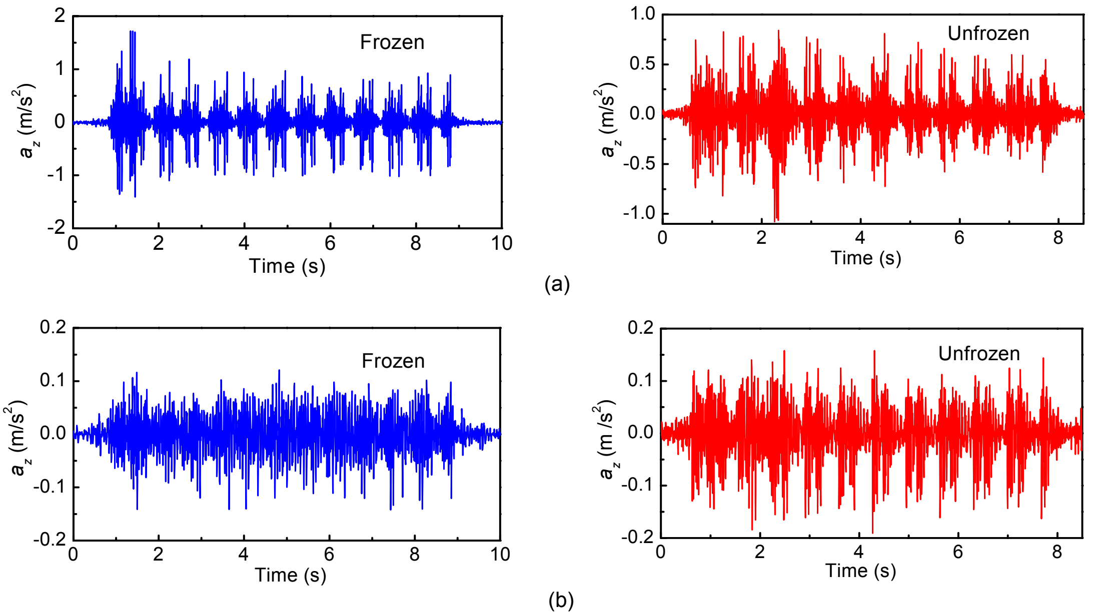

Fig. 5 Acceleration time histories in vertical acceleration induced by T507 at different points under frozen and unfrozen soil conditions. (a) *D*=2.5 m; (b) *D*=8.9 m

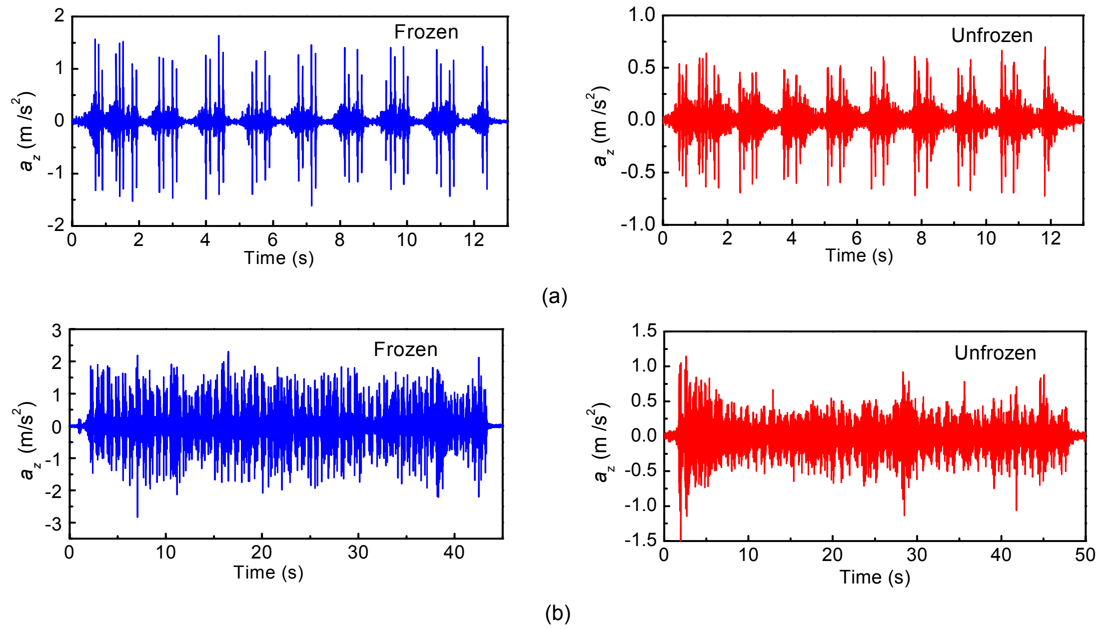

Fig. 6 Comparison of vertical vibration accelerations induced by different type trains under frozen and unfrozen soil conditions at point C1. (a) Slow-speed passenger train; (b) Freight train

intense with the increase of train speed. The main reason is that the dynamic stress between the train and the rail increases with the increase of train speed, leading to the increase in vibration intensity, and thus, the maximum acceleration increases (Chen *et al.*, 2007). Though the speed of the freight train is lower than that of the passenger train, the vertical vibration induced by freight train is greater than that induced by the passenger train. The above results show that the train load has more notable effects on vertical vibration of the embankment than train speed.

Fig. 5a and Fig. 6 also show that the vertical vibration responses induced by different types of trains are all amplified due to seasonally-frozen soil. Dynamic magnification factors, expressed as the vibration amplitude under frozen condition divided by the amplitude under unfrozen condition, are the greatest for the freight train and the least for the high-speed train. Thus, the effect of train load on vibration is amplified due to the seasonally-frozen layer. The reason is that an ice matrix formed during the freezing process greatly enhances the stiffness of soils, leading to an increase in the elastic modulus of frozen soils (Qi *et al.*, 2006; Yang *et al.*, 2008). These changes inevitably affect the interaction mechanism of vehicle-track-embankment systems.

3.2 Acceleration response in frequency domain

Fig. 7 shows the vertical acceleration frequency spectrums induced by the high-speed train at different distances from the rail under frozen and unfrozen soil conditions. All acceleration amplitudes of embankment vibration attenuate with the increase of distance from the rail for frozen and unfrozen soils, likely because of the filter effect and damping of soil. At the point C1, located 2.5 m from the rail (Fig. 7a), vertical vibration in winter and summer concentrates at 30 to 100 Hz and 10 to 100 Hz, respectively. This indicates

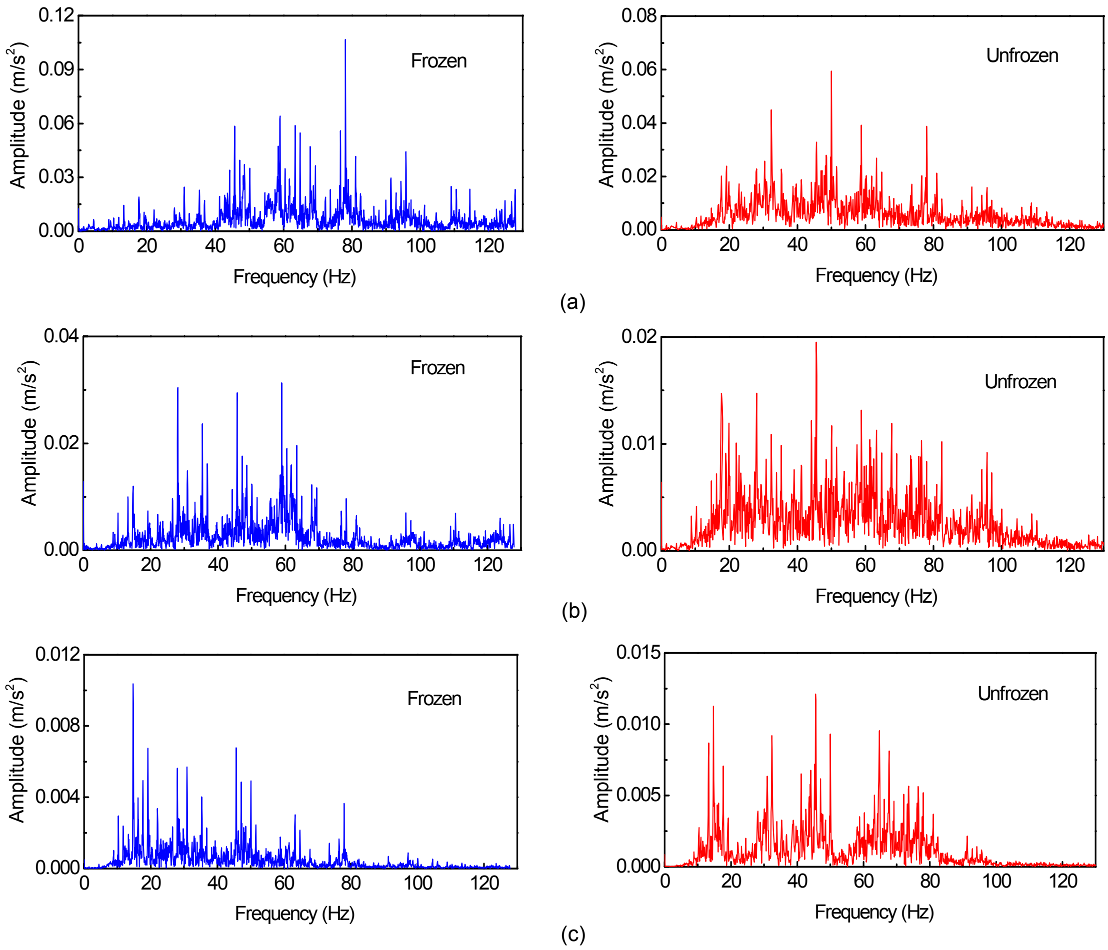

Fig. 7 Frequency curves of embankment vertical acceleration induced by high-speed passenger train T507 at different points under frozen and unfrozen soil condition. (a) *D*=2.5 m; (b) *D*=4.5 m; (c) *D*=8.9 m

that the predominant frequency band in summer is broader. There are many adjacent peaks, and the vibration amplitude in winter is maximal at 78.1 Hz, other peaks occurring at 58.8 and 45.7 Hz. Under unfrozen soil conditions, the first, second and third predominant frequencies are 50.0, 32.3 and 58.8 Hz, respectively. The vibrations associated with intermediate and high frequencies are all more promptly attenuated than low frequency components with the increase of distance from the rail, under frozen and unfrozen soil conditions. When the vibration reaches the point C2 (Fig. 7b), the dominant frequency bands of vibration in winter and summer range from 20 to 80 Hz and 10 to 100 Hz, respectively.

For the furthest point C3 (Fig. 7c) in winter, the first, second and third predominant frequencies are 14.7, 45.6 and 30.9 Hz, respectively. The first, second and third predominant frequencies in summer, however, are 46, 14.7 and 64.8 Hz, respectively. When the vibration eventually reaches point C3, for frozen soil conditions, the dominant frequency band ranges from 10 to 70 Hz and the intermediate and high frequencies are close to zero; however, the dominant frequency band ranges from 10 to 84 Hz under unfrozen soil conditions.

Comparing the predominant frequency ranges of embankment with frozen and unfrozen soils for three measured points, they all transfer to a low frequency band with the increase of distance from the rail. The figures show that the first predominant frequency of embankment vibration alternatively changes in the frequency band with the increase of distance from the rail. The main reason is that the subgrade vibration has several dominant frequency bands where the vibratory energies are almost identical, and the amplitudes of all the bands decrease at different rates while the vibration propagates underground, so that the dominant frequency band appears alternately among the bands. The tie spacing action rate is

$$f_1=v/d_1, \tag{3}$$

where v and d_1 represent the train speed and normal tie spacing. The normal tie spacing of the testing section is 0.6 m. When the high-speed train is passing by, the value of f_1 equals 64.8 Hz. The action rate of shifting axle load is

$$f_2=v/d_2, \tag{4}$$

where d_2 represents the inflexible wheelbase. The inflexible wheelbase of the high-speed train is 2.5 m, when substituting the parameter to Eq. (4), the value of f_2 is calculated as 15.55 Hz. Thus, embankment vibration response near the rail (C1) is mainly affected by the sleeper, as well as vehicle speed, tie spacing and embankment condition. For the points far from the rail, the embankment vibration is largely influenced by vehicle speed, trailer inflexible wheelbase, etc.

Fig. 8 shows the vertical vibration spectrums of embankment induced by different speed trains in frozen and unfrozen soil layers. The frequency spectrums of the measurements taken for both train speeds are quasi-discrete and characterized by axle and bogie passing frequencies, as well as sleeper passing frequency. It can be seen from Fig. 8 that frequency peaks move towards higher frequencies as train speed increases. But, for unfrozen condition, the predominant frequency changes little with an increase in train speed.

4 Conclusions

In this study, the effects of seasonally-frozen soil on embankment vibration were obtained in terms of time histories and frequency spectrums. The following conclusions can be made:

1. The attenuation law of different directions is changed due to frozen soil. The decreasing order of attenuation rate is longitudinal>vertical>lateral direction under frozen condition, and the greatest and lowest attenuation rate is in the vertical and lateral directions, respectively, under unfrozen soil conditions.

2. Seasonally-frozen soil can affect vibration characteristics. Compared to unfrozen soil conditions, the amplitudes of longitudinal and vertical vibrations at points near the rail, under frozen soil conditions, are amplified, and magnification factors are the greatest for freight trains and the least for the high-speed passenger trains, showing that the effect of train load on vibration is amplified due to the seasonally-frozen layer.

3. Embankment vibration increases with the increase of train speed and train load, and the train load has more effects on embankment vibration than the

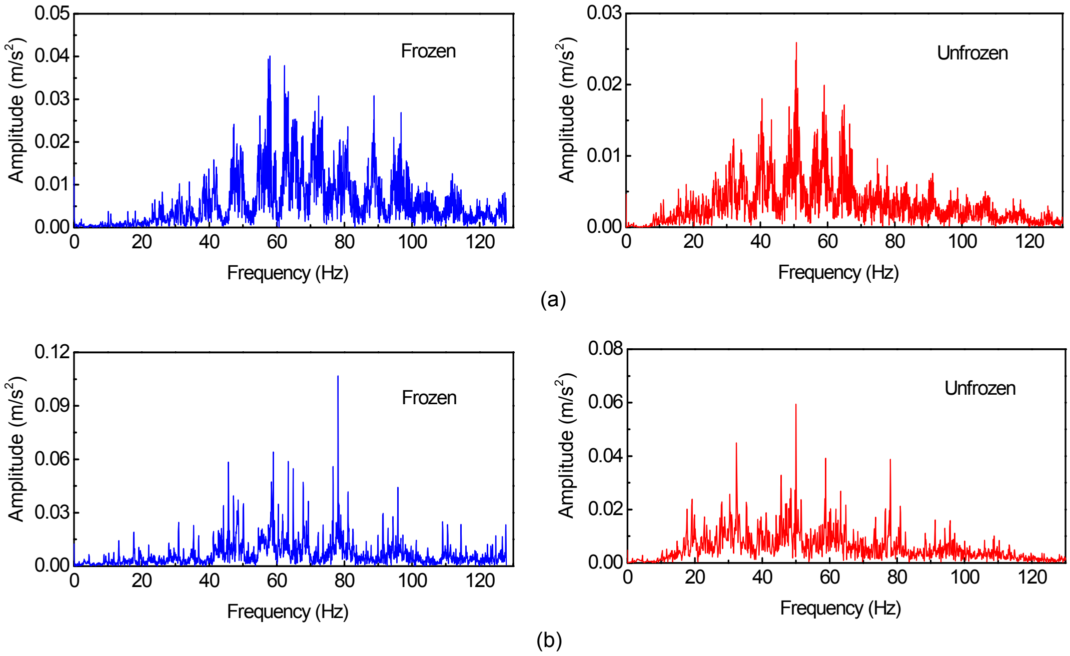

Fig. 8 Frequency spectrums of embankment vertical acceleration induced by different speed passenger trains under frozen and unfrozen soil conditions at point C1. (a) Slow-speed passenger train; (b) High-speed passenger train

train speed. Moreover, dynamic magnification factors are the greatest for the freight train and the least for the high-speed passenger train.

4. The vibrations associated with intermediate and high frequencies are more promptly attenuated than low frequency components and the predominant frequency range of embankment with frozen and unfrozen soils all shift to low frequency band with the increase of distance from the rail.

5. The predominant frequencies of embankment vibration with frozen soil layer shifts to high frequencies with the increase in the train speed, while changing little for unfrozen conditions.

Acknowledgements

The authors would like to express thanks to S. L., MA and Z. Y., SUN of the Institute of Engineering Mechanics, China Earthquake Administration for assistance in carrying out field experiments.

References

Auersch, L., 2005. The excitation of ground vibration by rail traffic: Theory of vehicle-track-soil interaction and measurements on high speed lines. *Journal of Sound and Vibration*, **284**(1-2):103-132. [doi:10.1016/j.jsv.2004.06.017]

Chen, B., Chen, G.X., Zhu, D.H., Su, X.M., 2007. Experimental study of ground vibration caused by rail transit. *Journal of Disaster Prevention and Mitigation Engineering*, **27**(3):312-317 (in Chinese).

Galvín, P., Domínguez, J., 2007a. Analysis of ground motion due to moving surface loads induced by high-speed trains. *Engineering Analysis with Boundary Elements*, **31**(11):931-941. [doi:10.1016/j.enganabound.2007.03.003]

Galvín, P., Domínguez, J., 2007b. High speed train-induced ground motion and interaction with structures. *Journal of Sound and Vibration*, **307**(3-5):755-777. [doi:10.1016/j.jsv.2007.07.017]

Galvín, P., Domínguez, J., 2009. Experimental and numerical analyses of vibrations induced by high-speed trains on the Córdoba-Málaga line. *Soil Dynamics and Earthquake Engineering*, **29**(4):641-657. [doi:10.1016/j.soildyn.2008.07.001]

Ju, S.H., Lin, H.T., 2008. Experimentally investigating finite element accuracy for ground vibrations induced by high-speed trains. *Engineering Structures*, **30**(3):733-746. [doi:10.1016/j.engstruct.2007.05.019]

Ju, S.H., Lin, H.T., Chen, T.K., 2007. Studying characteristics of train-induced ground vibrations adjacent to an elevated railway by field experiments. *Journal of Geotechnical and Geoenvironmental Engineering*, **133**(10):1302-1307. [doi:10.1061/(ASCE)1090-0241(2007)133:10(1302)]

Ju, S.H., Lin, H.T., Huang, J.Y., 2009. Dominant frequencies of train-induced vibrations. *Journal of Sound and Vibration*, **319**(1-2):247-259. [doi:10.1016/j.jsv.2008.05.029]

Li, Z.Y., Gao, G.Y., Feng, S.J., Shi, G., 2007. Analysis of ground vibration induced by high-speed train. *Journal of Tongji University (Natural Science)*, **35**(7):909-914 (in

Chinese).

Ling, X.Z., Zhang, F., Zhu, Z.Y., Ding, L., Hu, Q.L., 2009a. Field experiment of embankment vibration induced by passing train in a seasonally frozen region of Daqing. *Earthquake Engineering and Engineering Vibration*, **8**(1):149-157. [doi:10.1007/s11803-009-8090-z]

Ling, X.Z., Zhu, Z.Y., Zhang, F., Chen, S.J., Wang, L.N., Gao, X., Lu, Q.R., 2009b. Dynamic elastic modulus for frozen soil from the embankment on Beiluhe basin along the Qinghai-Tibet railway. *Cold Regions Science and Technology*, **57**(1):7-12. [doi:10.1016/j.coldregions.2009.01.004]

Ling, X.Z., Chen, S.J., Zhu, Z.Y., Zhang, F., Wang, L.N., Zou, Z.Y., 2010. Field monitoring on the train-induced vibration response of track structure in Beiluhe permafrost region along Qinghai-Tibet railway in China. *Cold Regions Science and Technology*, **60**(1):75-83. [doi:10.1016/j.coldregions.2009.08.005]

Liu, J.K., Liu, F.X., Fang, J.H., 2004. Modeling and monitoring the train-induced vibration in permafrost in Reshui coal mining, Qinghai. *Journal of Glaciology and Geocryology*, **26**(2):177-181 (in Chinese).

Lombaert, G., Degrande, G., 2009. Ground-borne vibration due to static and dynamic axle loads of intercity and high-speed trains. *Journal of Sound and Vibration*, **319**(3-5):1036-1066. [doi:10.1016/j.jsv.2008.07.003]

Lombaert, G., Degrande, G., Kogut, J., François, S., 2006. The experimental validation of a numerical model for the prediction of railway induced vibrations. *Journal of Sound and Vibration*, **297**(3-5):512-535. [doi:10.1016/j.jsv.2006.03.048]

Mehdi, B., 2004. Train-induced Ground Vibration and Its Prediction. MS Thesis, Royal Institute of Technology, Stockholm, Sweden.

Qi, J.L., Ma, W., Sun, C.S., Wang, L.M., 2006. Ground motion analysis in seasonally frozen regions. *Cold Regions Science and Technology*, **44**(2):111-120. [doi:10.1016/j.coldregions.2005.09.003]

Takemiya, H., 2003. Simulation of track-ground vibration due to a high-speed train: the case of X-2000 at Ledsgard. *Journal of Sound and Vibration*, **261**(3):503-526.

Xia, H., Zhang, N., Cao, Y.M., 2005. Experimental study of train-induced vibrations of environments and buildings. *Journal of Sound and Vibration*, **280**(3-5):1017-1029. [doi:10.1016/j.jsv.2004.01.006]

Yang, Z.Y., Dutta, U., Xiong, F., Biawas, N., Benz, H., 2008. Seasonal frost effects on the dynamic behavior of a twenty-story office building. *Cold Regions Science and Technology*, **51**(1):76-84. [doi:10.1016/j.coldregions.2007.05.001]