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Characteristics of dynamic response of the active layer beneath embankment in permafrost regions along the Qinghai–Tibet Railroad

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ABSTRACT

Dynamic response characteristics and stability of embankment are of primary importance for railroad operation in permafrost regions. The strong motion tests are carried out on a traditional sand gravel embankment at the Beilu River segment along the Qinghai–Tibet Railroad, and the acceleration waveforms at the shoulder and the slope toe of the embankment, when passenger train and freight train pass, are collected through strong motion tests. There is an obvious attenuation effect during the waveform transfer process from the shoulder to slope toe, and the natural frequency of the embankment is between 30–40Hz. Based on the tests in situ, the nonlinear dynamic finite element analysis is applied for numerical simulations on dynamic response of the traditional sand gravel embankment to train load, and the influences of underlying active layer on the dynamic response of the embankment at different seasons are analyzed. The results show that the vibration attenuation of the train load is obvious at different seasons, which presents a linear decrease tendency in summertime, but a nonlinear decrease tendency in wintertime. Both of the two decrease tendencies mainly occur within the soil layer above the permafrost table, but the attenuation effect in summertime, when the active layer is thawed, is slightly greater than that in wintertime when the active layer is frozen. Soil deformation induced by train vibrations occurs mainly above the permafrost table in summertime, but in wintertime, it mainly occurs above the natural surface. Meanwhile, the amount of deformation at the same location in summertime is far more than that in wintertime.

1. Introduction

The Qinghai–Tibet Railroad (QTR), as the world's highest and longest plateau railroad, is 1142 km in length, of which 546.41 km are traverse large areas of continuous permafrost regions (Zhang., 2000). Due to the vulnerability of permafrost environment and ongoing climate change, problems associated with the permafrost become key issues to the stability of the railroad embankment. In permafrost regions, one of the most important principles in the railroad construction is protecting the permafrost from warming and thawing (Cheng and Ma, 2006; Ma et al., 2002; Niu et al., 2003). For this purpose, positively protective engineering measures were taken in the construction of the railroad (Ma et al., 2009). The observation data of ground temperature and embankment deformation in permafrost regions showed that the protective effect on protecting the permafrost was obvious (Ma et al., 2011; Mu et al., 2010, 2012). However,during the operation of the railroad, some diseases occurred at some sections in permafrost regions, which already affected train speed and threaten the railroad safe operation (Cheng, 2002; Wu et al., 2003). Therefore, study on the dynamic response characteristics and the stability of embankment under train load is very important for a railway's long-term reliable operation.

The dynamic stability of the railway embankment has been researched in many previous studies. For example, based on the elastoplastic constitutive model, Kutara (1980) studied the accumulative deformation of soil under traffic loads using the finite element method, but the transfer mechanism of actual traffic load and the effect of the cyclic load were not considered; A method is developed for determining the parameters of the predictive model presented by Li and Selig (1996, 1998) for subgrade cumulative strain, which takes into account the influence of the number of load cycles, stress state, soil type and physical state; Li et al. (2007) studied the ground vibrations induced by high-speed train passing on viaduct, and the influences of different train speed and the damping ratio of soil on ground vibration were analyzed; Li et al. (2006) and Dong et al. (2008, 2010) discussed the distribution of subgrade dynamic deviatory stress and studied the cumulative deformation under repeated moving loads on high-speed railways, the simulation results were in good agreement with the field measured data; Gao et al. (2011) researched the three-dimensional responses of the track and the ground based on Biot's wave propagation equations. Researches above didn't involve analyses of the dynamic transfer

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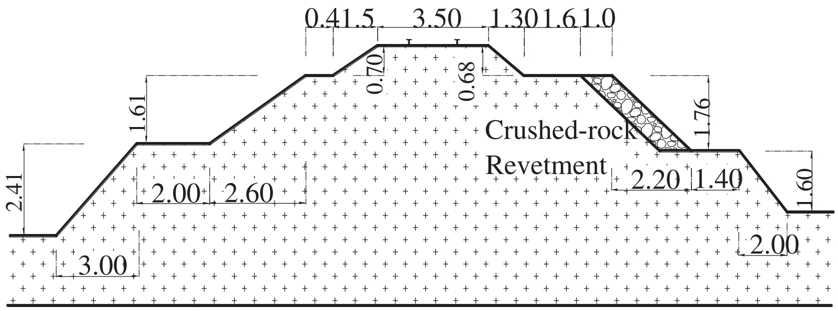

Fig. 1. The profile of the testing embankment DK1142 + 480 (unit:m).

characteristics of the train load and had less contribution to dynamic safety evaluation of engineering. Wu et al. (2011) discussed the vibration response of the embankment in permafrost regions along the Qinghai–Tibet Railroad, but the influences of seasonally freezing/thawing of active layer on dynamic response of embankment were not considered.

The dynamic response of embankment in permafrost regions is a complex process and the actual vibration of the train is the key issue in the related studies. In previous researches on the characteristics of embankment deformation under the train load, the train load was always regarded as the equivalent half-wave sine load, and the dynamic response of the embankment was analyzed under the equivalent load. However, the calculated result was in short of reliable test data, especially the real vibration data. In this paper, a traditional sand gravel embankment at the Beilu River segment along the QTR is selected, and a series of real time strong motion tests are carried out. From the tests, the acceleration waveforms when the train passes are collected, the attenuation characteristic of the vibration and the natural frequency of the embankment are obtained as well. Based on these tests in situ, the nonlinear dynamic finite element analysis is applied for a dynamic response numerical calculation on traditional sand gravel embankment. The dynamic transfer characteristic and the deformation of the traditional sand gravel embankment are simulated, and influence of the active layer on embankment dynamic response at different season is analyzed as well.

2. Profile of Beilu river segment

The Beilu River test segment of the Qinghai–Tibet Railroad belongs to the landforms of alluvium and diluvium high plains, located between the Hoh Xil mountains and Fenghuoshan Group. This segment is in the arid climate region of Qinghai–Tibet Plateau, the freezing period of which can reach up to eight months, from September to the following April. According to the meteorological data, the annual average temperature of this area is −5.2 °C, the extreme maximum temperature is 23.2 °C, and the extreme minimum temperature is −37.7 °C. Thick ice layer underground near the permafrost table along the whole test section is abundant, and the temporal and spatial variations of thermal regimes of the permafrost exist in the site. The mean annual ground temperature of permafrost ranges from −3.0 °C to −0 °C. So from the point of engineering geology view, the test segment belongs to the unfavorable and bad engineering geological section.

The natural permafrost table of the segment is between −2 m and −3.0 m, while the mean annual ground temperature is between −1.41 and −1.68 °C (Sun et al., 2008; Wu et al., 2013). On the background of permafrost degradation in Qinghai–Tibet Plateau, the effect of traffic engineering would intensify the tendency. With the purpose of protecting the permafrost effectively and maintaining the stability of embankment in the permafrost areas, positively protective engineering measures were taken in constructing the railroad. Especially at the Beilu River segment, different embankments are presented, such as crushed/blocked rock embankment, ventilated embankment, thermal insulation material, thermosyphon, embankment with crushed-rock slope protection, reasonable height embankment, shadow shield embankment, assembled culvert, etc (Cheng and Ma, 2006).

Table 1
The lithology, moisture content and density test results of DK1142 + 480.

Hole position	Depth(m)	Lithology	Moisture content %	Density g/cm^3
DK1142 + 480	0.5	Silty sand	26.3	1.6
Natural pore	1.3	Silty clay	20.0	1.8
	2.2	Silty clay	81.4	1.9
	9.7	Marlite	15.2	2.1

3. Strong motion test and testing segment

The vibration sensors and strong motion recorders are used to measure the vibration phenomena and effects, which can reflect the movement process of the earthquakes and seismic responses of the structures. The strong motion observation method is applied in the Beilu River test segment of the Qinghai–Tibet Railroad, to monitor the vibration transfer process and make a scientific and reasonable evaluation of the characteristic of the vibration. On this basis, the characteristics of embankment deformation and vibration response are studied.

The real time strong motion tests were carried out at the typical structure embankment along the QTR in the warm season in 2009, such as traditional sand gravel embankment, ventilated embankment, crushed/blocked rock embankment, etc (Chen et al., 2011). The test results show that there was an obvious attenuation effect during the transfer process at different embankments. In this paper, by taking the test at the traditional sand gravel embankment as an example, we give a brief introduction to the application of the strong motion

Fig. 2. The strong motion observation instrument.