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Numerical analysis of ground motion characteristics in permafrost regions along the Qinghai-Tibet Railway

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ABSTRACT

Due to the vulnerability of permafrost environment to climate changes, permafrost in the Qinghai-Tibet Plateau (QTP) is experiencing thickening of the active layer and warming ground temperatures that together have a significant influence on the ground motion characteristics. A series of in situ wave velocity tests were carried out in permafrost regions along the Qinghai-Tibet Railway (QTR) and the characteristics of shear wave velocity of frozen soil were summarized. Then, the ground motion responses in permafrost regions were simulated, and the impact of permafrost change on the seismic site response was discussed. Moreover, the dynamic response of the traditional embankment at the Beiluhe site in permafrost regions was studied. The changes of ground motion parameters were significantly impacted and showed reproducible changes with different active layer thicknesses and permafrost thicknesses. The ground motion amplification coefficients increased with the increase of active layer thickness, and the amplification coefficients were greater in a warm season than that in a cold season. Furthermore, the active layer thickness had little influence on the characteristic site period, and the variation of the characteristic site period with the permafrost thickness showed the logarithmic variation characteristic. Compared with the soil profile away from the center of the railway subgrade, the acceleration under the embankment showed a significant increase due to the overlying subgrade embankment. The increase in amplitude was about 29%, which illustrated that the deformation of the soil under the embankment became greater and may be more prone to damage during the seismic loading.

1. Introduction

The Qinghai-Tibet Plateau (QTP) is the highest and one of the most extensive plateaus in the world. With a high elevation, low latitude mountain environment, the QTP has the largest extent, about $1.3 \times 10^6\,km^2$, of mountain permafrost on earth. Permafrost covers about 53% of the total area of the plateau (Cheng, 1984; Jin et al., 2006). Moreover, the QTP is one of the most tectonically and seismically active regions, where a total of 33 Ms 6.0–6.9 earthquakes and 3 Ms 7.0–8.5 earthquakes have occurred since 1980 (Wang et al., 2009; Deng et al., 2014). Field investigations after these earthquakes revealed that earthquake ruptures, fractures, liquefaction, seismic subsidence, and collapses formed in areas underlain by permafrost. The Ms 8.1 Central Kunlun earthquake of 14 November 2001 produced a 400-kilometer-long surface rupture zone, with as much as 16.3 m of left-lateral strike-slip along the active Kunlun fault in northern Tibet (Lin et al., 2002). These earthquakes produced widespread damages to the infrastructure and construction projects in permafrost regions. Therefore, it is critical to study earthquake disaster mitigation and prevention in the permafrost regions on the QTP.

The warm permafrost is quite sensitive to temperature changes, because the physical, chemical and engineering properties change at these temperatures. Moreover, these characteristics are also influenced by the ice content, which varies with temperature changes (Xu et al., 2001; Li et al., 2008). Due to the vulnerability of permafrost environment and ongoing climate changes, permafrost on the QTP is experiencing thickening of the active layer and warming ground temperatures. These changes have a significant influence on the ground motion characteristics (Mu et al., 2012; Li et al., 2006). At present, study of ground motion characteristics in permafrost regions is in the exploratory stage, and the prevention of seismic disaster is a great challenge, as well as the earthquake site zonation. It is, therefore, important to study the characteristics of ground motion and the influence of active layer and permafrost on the parameters that control ground motion in permafrost regions on the QTP.

The study of the ground motion effects is an issue of growing recent interest. Many resources have been invested to understand these phenomena, especially the seismic ground motion characteristics. Firstly,

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the seismic data was recorded to understand and estimate the local site effects. Ernesto et al. (1993) used data from low intensity 1989 and 1990 events to make a preliminary evaluation of site amplification. The site amplification characteristics have been identified by Kumar et al. (2006) from the frequency bands of significant amplification observed in the spectral ratios of the horizontal to the vertical component records. Furthermore, Hassani et al. (2011) used the generalized inversion of the S-wave amplitude spectra from the strong-motion network data in East-Central Iran to estimate simultaneously source parameters, site response and the S-wave attenuation. In permafrost areas of China, the ground motion effects observed after earthquakes has attracted the interest of the research community. There are some examples in the literature, such as Xu et al. (2003), who calculated the earthquake response spectra of the permafrost sites with different temperature and different overlay thicknesses. Wang et al. (2004) studied the influences of temperature on the seismic displacement, velocity, acceleration and response spectra of permafrost. Yan et al. (2005) analyzed the stochastic earthquake responses of the permafrost sites along the Qinghai-Tibet Railway, by applying the random vibration theory and the finite element method. Qi et al. (2006) discussed the influence of the seasonal frozen layer on the ground motion features in seasonally frozen regions. In previous researches on the characteristics of ground motion in permafrost regions, the change of the active layer and the influence of permafrost thickness have not considered.

In this paper, field wave velocity tests were carried out in permafrost regions and the elementary characteristics of the wave velocities of the permafrost soils were obtained. Then using the results from dynamic triaxial tests, the characteristics of ground motion at permafrost sites were analyzed using the equivalent linearization method. The influence of both the active layer thickness and the permafrost thickness were determined. Finally, the two-dimensional non-linear dynamic time history analysis was used to validate the results of ground motion calculations, and to evaluate the influence of the embankment on seismic ground motion.

2. Shear wave velocities and kinetic parameters of frozen soil

2.1. Shear wave velocities of frozen soil

Different types of rocks and soils have different elastic wave propagation properties, and these directly influence the dynamic responses of a geological region. In an infinite elastic medium, the shear wave velocity V_s and the compression wave velocity V_p can be determined:

$$V_p = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \qquad V_s = \sqrt{\frac{E}{2\rho(1+\mu)}} = \sqrt{\frac{G}{\rho}} \tag{1}$$

where E is Young modulus, G is shear modulus, ρ is the density and μ is the Poisson's ratio.

The wave velocities, especially the shear wave velocity, have an important impact on calculating the seismic response. In permafrost regions, the wave velocity variations due to temperatures and ice contents at different locations were observed. Based on the in situ wave velocity tests, the characteristics of shear-wave velocity distribution of shallow ground in permafrost regions were obtained. Fig. 1 illustrated the variations of shear wave velocity with depth of the typical boreholes at the permafrost test sites. It was observed that shear wave velocity increased near the upper limit of the permafrost and the V_s of the frozen soil could reach 700 m/s at 12 m depth. Fig. 2 illustrated the ground temperature profiles of the typical boreholes in permafrost regions. It could be found that the temperature had an important influence on the shear wave velocity distribution.

The active layer depths currently range from1 to 4 m along the QTR (Ma et al., 2008; Zhao et al., 2010). The freezing and thawing of active layer varied with the seasonal air temperature variation, while the stratigraphic layers beneath the active layer remaining frozen were less affected by air temperature variation. Moreover, except for the measured data, the velocity data in this regions was collected and a statistical comparison with typical soils down to 10 m, i.e. silty clay, mudstone and fine sandy soil, was shown in Table 1. The velocities at different locations varied not only with the lithology but also with ground temperature. Ground with lower temperatures had higher velocities.

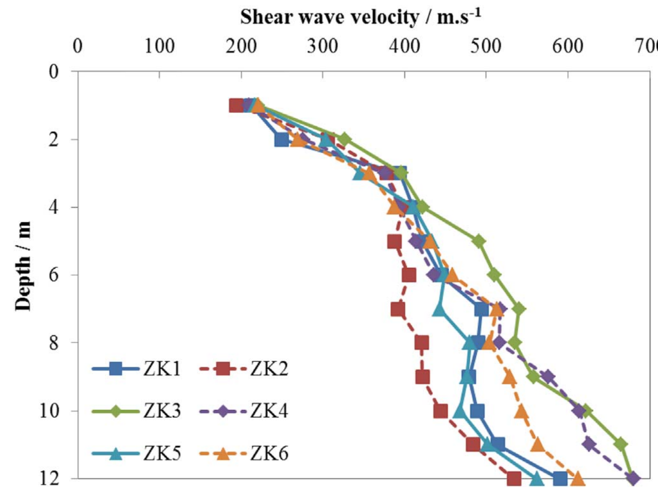

Fig. 1. The variations of shear wave velocity with depth of the typical boreholes.

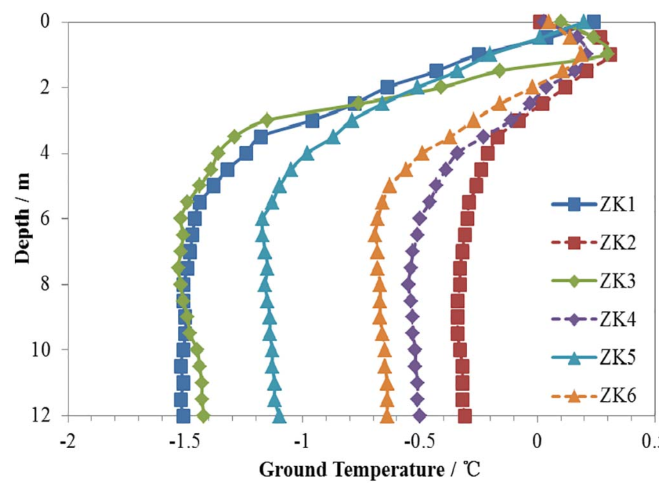

Fig. 2. Ground temperature profiles of the typical boreholes in permafrost regions.

Table 1
Wave velocity in-situ tests in the Qinghai-Tibetan Plateau.

Lithology	Depth (m)	Soil state	V_s/m/s
Silty clay	0–4	Unfrozen	140–240
		Frozen	210–430
	4–10	Frozen	395–540
Fine sandy soil	0–4	Unfrozen	120–263
		Frozen	204–400
	4–10	Frozen	251–456
Mudstone	0–4	Unfrozen	216–328
		Frozen	296–532
	4–10	Frozen	545–869

2.2. Kinetic parameters of frozen soils

The kinetic parameters, including the shear modulus and damping ratios, change under different shear strain amplitude. The kinetic parameters of frozen soils were obtained using the dynamic triaxial