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Soil moisture, ground temperatures, and deformation of a high-speed railway embankment in Northeast China

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ABSTRACT

Embankment deformation is a key consideration in high speed railway construction. Frost heave due to temperature and moisture variation is critical to consider in areas of seasonally frozen ground. This paper examined ground temperatures, frost heave, and moisture content in 2013–2014 at two sites along the embankment of the Harbin-Dalian Passenger Dedicated Line (HDPDL) railway. The railway is in seasonally-frozen ground of Jilin Province, China. The embankment at one site (K977) was built on the undisturbed ground surface while the other was in a cut section (K1004). Displacement measurements over one year indicated that frost heave of 14 mm at K977 and 25 mm at K1004 occurred in ballast during the freezing season. During the annual freeze-thaw period, soil moisture content varied drastically in the upper 0.6 m. The frost depth and freezing index were strongly and positively correlated during the freezing season. Soil moisture content was regarded as the primary control on the amount of frost heave, while frost depth was secondary. Furthermore, water vapor diffusion may have been an important contributor to the formation of near-surface ice. At K1004 site, the maximum recorded deformation was large and exceeded the 15 mm Chinese standard for maximum allowable heave. This suggested that high ground water level increased the amount of frost heave.

1. Introduction

China is the third largest country in the world, and distances between capital cities are commonly great. For example, the distance between Shanghai and Beijing is >1000 km. Therefore, high speed rail is one of the most important transportation methods for passengers and freight in China. Train speeds on high speed railways are increasing, and as a result, the permissible deformation of the track subgrade is decreasing. Seasonally frozen ground covers about 50% of Earth's landmass, and permafrost underlies an additional 20%, proportions similar to the distribution in China (Qiu et al., 1994). In cold regions, all infrastructures are subject to potentially-damaging freeze-thaw cycles. Frost heave is a key problem affecting the stability and lifespan of engineered structures. Taber (1929) first investigated frost heave, and the topic has since been the subject of many indoor freezing tests and numerical simulations (Everett, 1961; Miller, 1972; Gilpin, 1980; Konrad and Morgenstern, 1981; Konrad and Lemieux, 2005; Akagawa, 1988; Rempel et al., 2004). Although the frost heaving process is still being widely studied, two main mechanisms have been identified and generally accepted: (1) frost heave due to in-situ pore water, and (2) frost heave due to water migration. Water, frost-susceptible soil, and freezing temperatures are three conditions required for frost heave. To prevent frost heave at least one of these conditions must be minimized or eliminated.

The HDPDL is the first high-speed railway in cold regions with a design speed of 350 km/h. The entire railway line is located on seasonally frozen ground that experiences long and cold winters. The maximum allowable embankment deformation is only 15 mm over a length of 200 m. Although several measures were used to limit deformation (insulation layers, an anti-frost filling layer, an advanced drainage system), frost heave has still been observed along the HDPDL embankment (Shi et al., 2014; Liu et al., 2016). A number of previous laboratory experiments and numerical simulations have been undertaken to investigate and explain this phenomenon (Wang et al., 2015; Sheng et al., 2014). These studies provided sophisticated illustrations that helped define the frost heaving process, but lacked long-term field observations, and particularly soil moisture content measurements. Therefore, it is critical to investigate soil temperature and moisture variation during freeze-thaw cycles in the HDPDL embankment.

Liu et al. (2012) investigated thermal conditions in the HDPDL embankment, and found that temperature variations differed along parts of the roadbed and foundation under seasonal freeze-thaw cycles. Furthermore, the frozen depth in the embankment was deeper in sections over undisturbed natural ground than at locations with cuts (Liu et al., 2016). We included soil moisture data in this paper to help better

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understanding frost heave behavior along the HDPDL. This paper presents continuous measurements of ground temperature, soil moisture, and frost heave deformation in a winter-spring period, and discusses the influences of temperature and soil moisture on the magnitude of frost heave, which controls the smoothness of the embankment and tracks.

2. Site conditions and monitoring methods

2.1. Monitored site conditions

The HDPDL embankment was constructed in 2008–2012. Two embankment measurement sites were installed at K977 and K1004 of the railway mileage, near Changchun city, the capital of Jilin Province (Fig. 1). The embankment at the K977 site is above the natural ground surface, while the embankment at the K1004 site is in a cut section. The entire railway is located in seasonally frozen ground (Fig. 1). The depth of seasonal freezing in undisturbed ground increases from <1.0 m to near 2.0 m from Dalian to Changchun. The mean annual air temperature is about 5 °C, and the mean annual precipitation is 604 mm at the Changchun meteorological station (Gao et al., 2010). Most precipitation occurs in summer, and the maximum mean monthly precipitation occurs in July (104 mm). In early winter, the region receives little precipitation, but snowfall increases over the freezing season and reaches a maximum depth of about 20 cm (Liu et al., 2016). Continuous ground temperatures measured during the 2012–2013 freeze-thaw period indicated that the maximum depth of freezing was 3 m along the whole embankment (Liu et al., 2016). The embankment is about 240 km long and covered by non-ballast tracks. The embankment height is 3.5 m, and the upper layer is well-graded gravel mixed within cement (Fig. 2). The fill materials of the 2.3 m thick middle layer are A/B group fills (high quality and good filling materials in the China railway construction code). The A group fill materials consist of crushed rock with <15% fines content, while the B group materials have fines fractions of 15–30%. To minimize potential frost heave, a 1-meter-thick layer of non-normal A/B fillings with <5% fines content was used. The fill of the lower part of the embankment consists of A/B/C materials, which are arranged in three layers of well-graded crushed stone sandwiching two layers of sand. The surface of the embankment is covered by CRTS-I (China Railway Track Slab-I) track plate. The foundation soil is yellow clay, reinforced by 20 m long CFG-piles (Cement Fly-ash Gravel-piles) (Liu et al., 2012).

2.2. Measurement methods

The data measurement system included ground temperature, soil moisture, and displacement sensors attached to a data logging and transmission system. The temperature probes were designed and assembled in the State Key Laboratory of Frozen Soil Engineering (SKLFSE), and the sensors have an accuracy of 0.02 °C. The TDR-3 soil moisture sensor (Jinzhou Sunshine Meteorological Science and Technology co., LTD, China) has an accuracy of 2% within a moisture content range of 0–50%. The displacement sensors (Hunan Galaxy Sensing Technology co., LTD, China) have an accuracy of 1 mm. The temperature probes were installed vertically with sensors at 11 different depths (Fig. 2). The sensor spacing below the subgrade surface was 0.25–0.5 m. The moisture sensors were distributed between depths of 0.15 and 3 m (Fig. 2). Finally, the frost heave sensors were installed to monitor the deformation of frost heave within 0.5 m, 1.5 m and 2.7 m of the surface. All sensors were connected to a central data logger at each site. The data analyzed in this paper was recorded from November 1, 2013 to December 1, 2014. The data was transmitted offsite, and the measurement equipment was inspected regularly during maintenance operations.

3. Results

3.1. Surface temperature and frost heave

The embankment surface temperature and displacement measurements for the two sites are shown in Fig. 3. The embankment at the K977 site was built above undisturbed ground. The embankment surface temperature at the site dropped below 0 °C on November 10 (Fig. 3a). At this time, frost heaving began, though it decreased and then remained stable after 4 days as the surface temperature increased. After November 25 the surface temperature did not rise to 0 °C until February 28. Between November 25 and December 12, the recorded displacements from the three sensors installed at 0.5, 1.5, and 2.7 m were the same, indicating that the rapid heaving during this time occurred between the surface and 0.5 m depth. Seventy-eight percent of the total 14 mm of heave recorded by the two deeper sensors occurred during this short period. The maximum frost heave displacement was recorded on December 25 and then remained stable until the beginning of thawing on March 16. As thawing progressed, the displacement decreased rapidly to about 2 mm within 9 days, then remained stable over the entire thaw season. In summary, displacement from frost

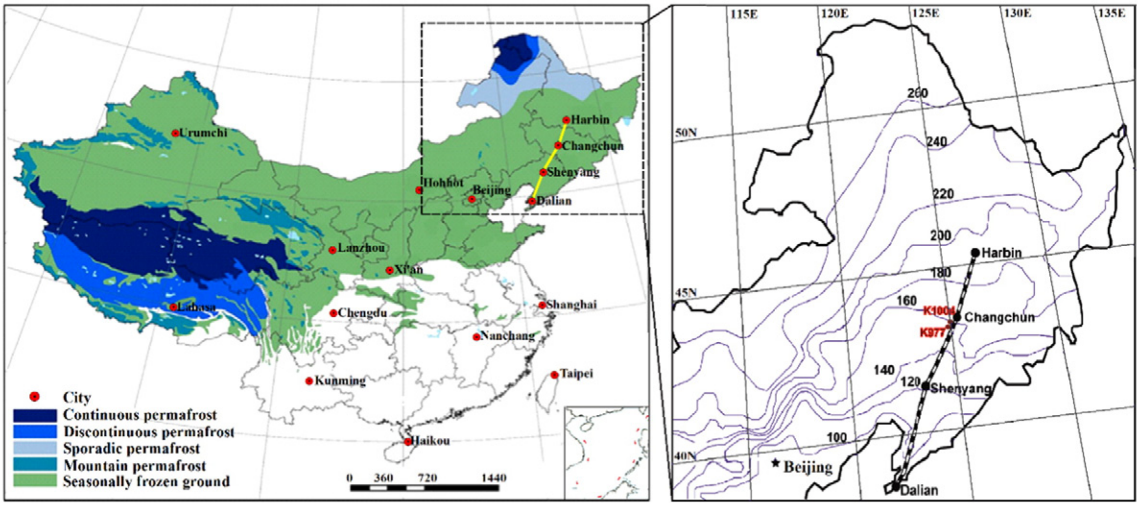

Fig. 1. Location of the study region and ground thermal zones in China (left), and the two measurement sites (K1004 and K977) along the HDPDL with contours of the depth of freezing (cm) in North-east China (right).