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Characteristics and controlling factors of frost heave in high-speed railway subgrade, Northwest China

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ABSTRACT

Frost-heave of the subgrade significantly influences the stability of transportation infrastructure. In particular, small amounts of frost heave in coarse-grained subgrade fill may pose challenges to the safe operation of high-speed railway lines in cold regions. In this study, frost heave, ground temperatures, and soil moisture contents were examined at 15 test sections along Lanzhou-Xinjiang high-speed railway (LXHR), and the factors controlling the observed heave are discussed. The development of frost heave in three subgrade layers (0–0.5, 0.5–1.5, and 1.5–2.7 m depth) was examined at each section over two freezing seasons (October 2015 to September 2017). The frost depth in the subgrade reached 220–400 cm, significantly deeper than in surrounding natural ground. The frost penetrated 2.3 m of A/B group fill, a special fill material for high-speed railways. The frost heave in some sections is greater than the allowable total deformation limit of 19 mm. Most of the total frost heave (40–50%) occurred in the 50 cm thick subgrade surface layer. Residual deformation developed over the two years, which has likely resulted in increased porosity and decreased compaction and strength. Frost heaving is mainly controlled by supplies of water from the surface, from below, and laterally from adjacent ground, and the fines content of the material. The data presented provide valuable information on the construction and performance of high-speed railways in regions with seasonally-frozen ground.

1. Introduction

Soil that experiences temperatures below 0 °C may be classified into (1) short-term frozen soil, frozen for hours to a half month, (2) seasonally-frozen soil, frozen for a half month to months, and (3) permafrost, frozen for at least two consecutive years (Zhou et al., 2000). In general, short-term frozen soil causes little or no damage to infrastructure, while seasonally-frozen soil and permafrost may seriously affect the stability of engineered structures. Engineering studies on seasonally-frozen soil focus mainly on methods to limit frost heave, e.g., by controlling fine particle content, controlling soil moisture content, and lowering the groundwater table (Kubo and Sakaue, 1986; Dai et al., 1994; Nurmikolu, 2005; Nurmikolu and Kolisoja, 2008; Jiang et al., 2007; Xu et al., 2010a, 2010b; Du, 2015). In contrast, permafrost engineering research commonly focuses on anti-thawing methods to actively cool the subgrade (Cheng, 2005; Jin et al., 2005; Yue et al., 2007; Niu et al., 2015).

In China, seasonally-frozen soil and permafrost affects 54 and 25% of the land area, respectively, and is broadly distributed in northern China (Zhang et al., 1999, see Fig.1). With increasing development in Northwest China, the need for effective infrastructure construction in cold regions is critical. This is highlighted by the rapid expansion of the high-speed railway system in the region. The total length of high-speed railway will reach 30,000 km by 2020, with 75% built within short-term or seasonally-frozen soil regions (China Government, 2016).

The fill used in high-speed railway subgrade is generally coarse-grained, mixed with a smaller fraction of fine-grained material to limit the frost heave ratio to < 3.5% (Xu et al., 2010a, 2010b). The low unfrozen water content and resulting discontinuous liquid water distribution in such coarse-grained material limits ice lens formation that results in frost heave (Sheng et al., 2013, 2014a). Common engineering practice ignores the small amount of heave that may occur in coarse-grained material, as it does not usually influence the safe operation of the infrastructure. However, the deformation tolerance for high-speed railway subgrade is very low (< 19 mm), so even a small amount of frost heave can be problematic, especially in regions where the depth of freezing is significant. Consequently, frost-heave deformation monitoring must be carried out on most high-speed railways in northern China early in their operational life to ensure safe driving conditions, such as on the Harbin to Dalian Passenger Dedicated Line (HDHR) (Liu

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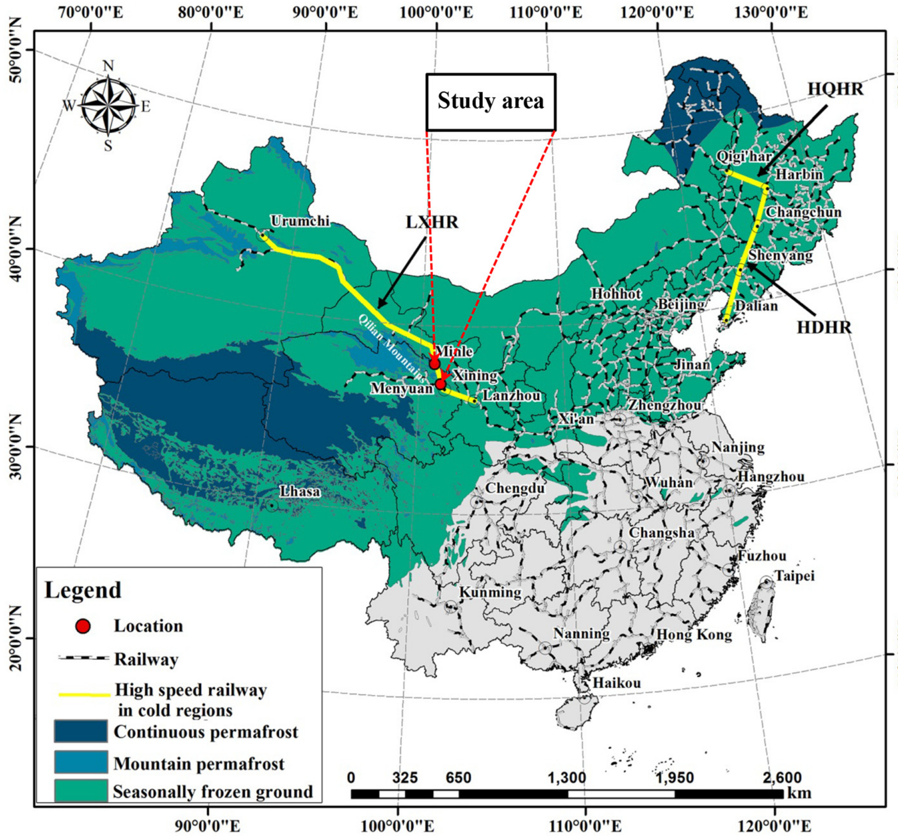

Fig. 1. Distribution of frozen soil and the location of Lanzhou-Xingjiang High-speed Railway (LXHR) in China.

Table 1
Location and general site conditions of the 15 test sections.

No.	Mileage	Location	Subgrade type	Height/m	Monitoring items
1	DK323 + 100	southwest	Embankment	+0.9	FD
2	DK325 + 900	slope of	Cutting	−0.5	GT, FD, SM
3	DK326 + 203	Qilian	Embankment	+2.0	FD
4	DK327 + 293	Mountain	Embankment	+4.9	GT, FD, SM
5	DK369 + 230	northeast	Cutting	−1.3	GT, FD, SM
6	DK371 + 190	slope of	Embankment	+0.4	GT, FD, SM
7	DK373 + 140	Qilian	Embankment	+2.6	FD
8	DK380 + 530	Mountain	Embankment	+2.8	FD
9	DK382 + 125		Embankment	+2.1	FD
10	DK383 + 000		Embankment	+1.1	GT, FD, SM
11	DK383 + 345		High Embankment	+7.3	GT, FD, SM
12	DK384 + 330		Embankment	+3.8	FD
13	DK391 + 940		Embankment	+4.1	GT, FD, SM
14	DK392 + 790		Embankment	+3.9	GT, FD, SM
15	DK406 + 930		Half cutting and half filling	−3.9 to +0.4	FD

Note: FD, frost-heave deformation, GT, ground temperature, and SM, soil moisture.

et al., 2012, 2016; Niu et al., 2016), and the Harbin to Qiqihaer Passenger Dedicated Line (HQHR) (Wu et al., 2013).

Lanzhou-Xinjiang High-speed Railway (LXHR) is the first high-speed railway built and operated in northwest China (Fig. 1). The line passes through the cold and high elevation environment of Qilian Mountains. Moist soil conditions in the region, caused by autumn precipitation and melt runoff in early winter provides conditions favourable for frost heaving of the subgrade. The purpose of this study is to 1) report the frost-heave characteristics of the subgrade during two freezing seasons, 2) examine the factors influencing the measured frost heave, and 3) discuss several questions related to the frost-heaving mechanisms based on observations of ground temperatures and soil moisture contents at 15 test sections with different subgrade heights.

2. Engineering background and climate conditions

2.1. Lanzhou-Xinjiang high-speed railway (LXHR)

Lanzhou-Xinjiang High-speed Railway (LXHR) started to build in April 2010, and has operated since December 2014. The total length from Lanzhou city to Urumchi city is ~1066 km (Fig.1). The railway was designed for speeds of 200–250 km/h. About 110 km of the line crosses terrain over 3000 m in elevation, including Qilian Mountain. The subgrade is ~600 km in length, excluding bridges and tunnels, and the subgrade surface is covered by high strength concrete (Ballastless track). The width of the roadbed surface is ~13.6 m.

2.2. Test sections and geological conditions

Fifteen test sections were identified for monitoring based on initial surveys of frost heaving of the subgrade in 2012–2014. The test sections are located at high elevation near Qilian Mountain (Fig.1). Frost-heave deformation (FD), soil moisture contents (SM), and ground temperatures (GT) were measured at the test sections (Table 1). Sections No. 1–4 are on the southwest slope of Qilian Mountain (nearby Menyuan), where the line crosses mountainous terrain with elevations of 3200–3300 m. The ground is covered by Quaternary (Holocene) pluvial silt and silty clay, or upper Pleistocene pluvial and gravelly strata. The uppermost ground layer is silt 0.3–1.0 m thick, underlain by ~1.3–20 m thick gravelly soil (Fig. 2A). Sections No. 5–15 are on the northeast slope of Qilian Mountain (nearby Minle), where the line passes an inclined alluvial and flood plain at elevations between 3200 and 2400 m. Most of the ground surface is covered by loose Quaternary sediments.