Engineering Geology 230 (2017) 95–103

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Causes of pile foundation failure in permafrost regions: The case study of a dry bridge of the Qinghai-Tibet Railway

Yanhui You[a], Jinchang Wang[b], Qingbai Wu[a], Qihao Yu[a,*], Xicai Pan[c], Xinbin Wang[a], Lei Guo[a]

[a] State Key Laboratory of Frozen Soils Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China

[b] Qinghai-Tibet Railway Company, China

[c] State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing, China

ARTICLE INFO

Keywords:
Pile foundations
Permafrost degradation
Sub-permafrost groundwater
Pile settlement
Geophysical investigation

ABSTRACT

Pile foundations are widely used to support dry bridges crossing large extents of warm and ice-rich permafrost zones along the Qinghai-Tibet Railway (QTR). The performance of these pile foundations are related to permafrost conditions surrounding the piles. However, the impacts of permafrost degradation on the stability of pile foundations have been rarely investigated. In this study, permafrost degradation has been assessed around several pile foundations in the Tanggula Mountain area along the QTR 15 years after the first field investigation in 2001 for the construction of the QTR. This assessment is mainly based on drilling, geophysical surveys, and monitoring of the settlements affecting the pile foundations. The permafrost in contact with the piles has significantly thinned after the piles were casted-in-place and put into service about 8 years ago. Moreover, the thickness of residual permafrost is less than the embedment length for some piles and, therefore, the adfreeze bond between the piles and permafrost has significantly decreased. In addition, artesian sub-permafrost groundwater has been observed around the middle-lower and below the piles. Due to this sub-permafrost aquifer, the end bearing capacity of the piles and the friction between the piles and thawed soils have also probably decreased. The applied load on the piles is now supported by the residual permafrost resulting in large settlements of the piles. The thaw consolidation and settlement of degrading permafrost have also potentially contributed to the total settlement. According to the investigation presented herein, the occurrence of sub-permafrost aquifer which was induced by permafrost degradation is the primary cause of pile settlements. The failure mechanisms of the piles as revealed by this assessment are useful for the design and maintenance of piles in warm and ice-rich permafrost regions. Moreover, the use of geophysical methods for investigating pile foundation failure due to permafrost degradation has proved effective.

1. Introduction

The Qinghai-Tibet Railway (QTR) crosses large extents of warm and ice-rich permafrost regions in the Qinghai-Tibet Plateau (QTP) (Zhang et al., 2008). Several roadbed-cooling methods have been used to mitigate potential geohazards due to permafrost degradation along the QTR (Cheng, 2005; Cheng et al., 2008; Ma et al., 2009). For instance, pile foundations are widely used for a total length of 125 km of dry bridges to cross ice-rich and extremely unstable permafrost sections along the QTR (Cheng et al., 2009). Although the pile foundations have good mechanical stability and low disturbance on permafrost during installation, permafrost change can still influence their stability.

The bearing capacity of piles embedded in permafrost mainly comes from the adfreeze forces between the pile surface and permafrost. The end bearing of piles usually accounts for a small fraction of their total bearing capacity, unless the pile end is embedded in ice-free bedrock or thaw-stable granular materials (Andersland and Ladanyi, 2004). The adfreeze strength depends on permafrost temperature, soil type, ice content, surface roughness of piles (Ladanyi and Guichaoua, 1985; Weaver and Morgenstern, 1981), and salinity of pore water in permafrost (Biggar and Sego, 1993a,b).

The permafrost temperature is of great concern in designing pile foundations. For warm permafrost with ground temperature above − 1 °C, Weaver and Morgenstern (1981) have proposed to design piles based on the properties of unfrozen ground if permafrost is thaw-stable. In case of thaw-unstable permafrost, the frozen ground has to be prethawed and compacted or to be cooled at temperature below − 1 °C. Similar approaches were applied for the piles along the QTR and the

* Corresponding author.
E-mail address: yuqh@lzb.ac.cn (Q. Yu).

http://dx.doi.org/10.1016/j.enggeo.2017.10.004
Received 27 April 2017; Received in revised form 5 October 2017; Accepted 5 October 2017
Available online 07 October 2017

design of piles in very unstable permafrost regions with ground temperature above −0.5 °C were based on the properties of unfrozen ground. According to this design principle, the embedment lengths of piles can be calculated and the settlements can be assessed to compare with the tolerable limits under service loads (Andersland and Ladanyi, 2004). The thermal state of permafrost is also taken into account when the piles are casted in-place, as the permafrost around the piles can warm or thaw due to the thermal disturbance of pre-drilling and concrete hydration heat. The temperature increase or permafrost thawing can reduce the adfreeze forces between the piles shaft and permafrost, and increase the creep rates of adjacent permafrost. The loading time depends on the feedbacks of the adjacent soils, which influence the design approaches of pile foundation for railway construction (Wang et al., 2005).

The stability of pile foundation can be also affected by the increase in permafrost temperature (Nixon, 1990) during the service life of piles. For instance, the freeze-thaw cycles of ground around piles are often intensified due to the high thermal conductivity of metal and concrete used to build piles (Duan and Naterer, 2009; Li et al., 2016). This frequently results in frost heave or thaw settlement of piles for power lines. Unlike the piles of power lines, the piles supporting dry bridges along the QTR are shaded by the bridges reducing the solar radiation on the ground surface (Cheng, 2005). As a result, the dry bridges are beneficial for lowering the ground temperature underneath the dry bridges of the QTR (Xia et al., 2014).

Apart from the thermal effects of piles and bridges, the climate warming can also result in significant permafrost degradation such as the thickening of the active layer and permafrost thinning (Wu and Zhang, 2010; Wu et al., 2012). Moreover, according to Wang et al. (2006), the adfreeze forces mobilized on pile surface can decrease, the end bearing capacity of piles is more solicited as the permafrost thickness is decreasing, and the total bearing capacity of the pile foundation can be significantly reduced. Local factors, such as high geothermal anomalies and groundwater flow in active fault zones, can thin or thaw permafrost and lead to migrating pingos which might damage the pile foundations of dry bridges (Wu et al., 2004, 2005). Furthermore, the bridge shade can cause a non-uniform solar radiation over ground surface, lead to different ground temperature around the piles, and affect the long-term performance of piles (Xia et al., 2014).

In this context, even if the pile foundations used along the QTR provide effective means to ensure the railway stability (Cheng et al., 2008), some geohazards have been observed along the QTR. For instance, very small average settlement of pile foundations of about 2 mm and maximum values of about 5 mm were monitored during the initial few years after QTR construction (Cheng et al., 2009). However, some pile foundations have failed in the Tanggula Mountains area but the causes of failures are still not well understood. In the present study, these causes of these failures have been assessed using drilling, geophysical surveys, and monitoring of settlement of pile foundations. The aims of this study are: 1) to investigate the permafrost changes around the pile foundations, 2) to monitor the settlement of pile foundations, and 3) to assess the influence of permafrost changes on the settlement of pile foundations.

2. Study site

The study site is located in Tanggula Mountains area along the QTR (Fig. 1). The length of the studied dry bridge is about 600 m. Several piles were casted-in-place to support this dry bridge. Only a shallow seasonal river in the north can flow underneath the bridge (Fig. 1b). The river water is less than 30 cm in depth and less than 1.5 m in width, and is about 60 m away from the dry bridge. Swamping wetland has also formed at the toe of the slope south of the foundations.

The design of pile foundations of the dry bridge was based not only on the temperature of permafrost during the construction period and but also on the potential increase in permafrost temperature due to climate warming. According to the investigation prior to the QTR construction in 2001, the permafrost adjacent to the dry bridge was warm and extremely unstable. Considering these extremely unstable permafrost conditions, the piles were designed to carry the loads even if the permafrost is thawing in the future.

According to an automatic weather station about 40 km away from the study site, the mean annual air temperature (MAAT) varied from −6.0 to −6.5 °C, and the mean annual rainfall from 250 to 300 mm from 1998 through 2006 (Wu and Zhang, 2008). The permafrost conditions along the QTR and Qinghai-Tibet Highway (QTH) have been studied. The permafrost distribution is generally continuous but tectonic or lake taliks can occasionally occur (Jin et al., 2008b). The thicknesses of permafrost range from several meters to more than 100 m. Due to local environmental conditions such as groundwater flow and geothermal anomalies along active faults, permafrost can be absent (Jin et al., 2008a; Wu et al., 2010).

Group of four piles was designed to support each of the bridge pier (Fig. 1c). The piles were 20 m in lengths and were about 1.2 m in diameters. Slightly oversized holes were drilled for the installation of cast-in-place piles. The designed allowable settlement of the piles and the differential settlement between the adjacent piles over the service life of the studied dry bridge are 80 and 40 mm respectively. Installation of the piles was completed before 2006. Ten adjacent foundations numbered from #1 to #10 were investigated in this study (Fig. 2). As a ground icing was observed at a distance of about 30 m south of the pile foundation #6 in January 2010, indicating artesian groundwater conditions, thermosyphons were installed to a depth of 20 m around the pile foundations #4 to #9 in 2010 to cool down permafrost. This mitigation method of permafrost degradation is beneficial for increasing the adfreeze forces between the pile surface and permafrost.

3. Field investigation

3.1. Drilling campaigns

Three boreholes B01-1 to B01-3 were drilled in 2001 down to a depth of 31 m around the pile foundations before the construction of the QTR (Fig. 2a). These boreholes were located along the central axis of the foundations to investigate the permafrost conditions in this section. The lithology, permafrost base, and ice content were assessed by analyzing the drill cores. This information was used for the design of pile foundations.

Additional boreholes were drilled in 2010, about five years after the construction of the pile foundations, to investigate the permafrost change (Fig. 2a). Gravimetric water contents on drill cores were measured. In order to reduce the thermal disturbance of permafrost during the drilling, the boreholes at both sides of the foundations were located about 5 to 7 m away from the foundations. In total, 14 boreholes were drilled at depths from 15 to 40 m which are slightly larger than the embedment length of the piles. Moreover, several boreholes were drilled at depths larger than 30 m to identify the permafrost base. If artesian sub-permafrost groundwater conditions were found, the boreholes were then backfilled to stop the outflow. Boreholes were also located in both shady and sunny sides of the foundations to characterize the permafrost differences.

A steel pipe was driven in the borehole B7-NW before its backfilling in 2010. A cable with thermistor sensors was installed in this steel pipe to measure the ground temperature from the surface down to a depth of 20 m during a field trip in January 2015.

3.2. Geophysical surveys

As previously mentioned, no borehole was drilled close to the piles to avoid any thermal disturbance of permafrost. To overcome the lack of information on permafrost conditions close to the piles, a geophysical investigation was undertaken in this study. Ground Penetrating Radar