Cold Regions Science and Technology 121 (2016) 214–225

Contents lists available at ScienceDirect

Cold Regions Science and Technology

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

Stress and deformation characteristics of transmission tower foundations in permafrost regions along the Qinghai–Tibet Power Transmission Line

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ARTICLE INFO

Article history:
Received 28 September 2014
Received in revised form 2 June 2015
Accepted 9 June 2015
Available online 19 June 2015

Keywords:
Qinghai–Tibetan Plateau
Stress
Tower foundation
Frost heave force
Transmission line
Permafrost

ABSTRACT

A transmission tower foundation embedded in frozen soil is subject to both the wind-induced uplift and frost heave forces. The frost heave results in an upward force acting on the foundation, while additional stress induced by the structure load may compress the underlying soils. The freezing- and thawing-induced deformations tend to cause further structural loads and lead to instability problems within the structure. To evaluate the engineering risk and ensure the safety of the Qinghai–Tibet Power Transmission Line (QTPTL) system, stress sensors were installed at the bases of two test tower foundations to investigate the stress state of the tower foundations. Using data on air and ground temperatures, and the deformation of tower foundations, we analyzed the stress variation, and the causes were discussed here. The results showed that the stresses at the bases of tower foundations had a close relationship with air and ground temperatures. The cooling of the underlying soils led to the occurrence of frost heave, which pushed the foundations upward and caused a significant stress bulb under the bases of tower foundations. Seasonal variations in the contact stress depended on the seasonal freezing and thawing of foundation soil. The contact stress increased with the cooling of the underlying soils and decreased with the warming of the underlying soils. The results also showed that the contact stress was free of the wind influence, i.e., the wind-induced uplift force was minor for the contact stress. To fully understand the influences of freezing and thawing on the stress state of tower foundations, a thermal–elasto-plastic finite element model for the tower foundation–soil system was established, and the stresses and deformations of a tower foundation subject to frost heave and thaw settlement were simulated. The results showed that the frost heave force induced by soil freezing potentially threatens the safety and normal operation of the QTPTL. Thaw settlement may lead to harmful deformation of tower foundations if global warming is considered in the numerical model. The remedial measure with thermosyphons only can reduce the settlement of the foundation and will increase the frost jacking risk of the foundation.

1. Introduction

The Qinghai–Tibet Power Transmission Line (QTPTL) runs across 1038 km of permafrost and seasonally frozen ground in the interior of the Qinghai–Tibetan Plateau. The mean annual air temperature of permafrost and seasonally frozen ground along the QTPTL varies between −3 °C and −7 °C and the minimum air temperature is lower than −37 °C in short durations. The active layer is subjected to annual freeze–thaw cycles and its thickness varies between 2 and 3 m. Thus, substantial heave force is expected due to the existence of extensive frost-susceptible soils and cold climate. Moreover, the wind-induced uplift force is another load for the transmission towers and can reach more than 1500 kN. Warm and ice-rich permafrost is widespread in permafrost regions of the Qinghai–Tibetan Plateau. The warming and subsequent thawing of ice-rich permafrost tend to result in serious engineering and environmental consequences. If not well designed or built, the tower foundations may be jacked up in the freezing periods and subside in the thawing periods, which would result in expensive maintenance costs and significantly threatens the safety and operation of the transmission lines. In arctic and sub-arctic regions, intense frost-induced heaving has considerably deteriorated the condition of numerous power network objects and significantly threatens the construction and operation of transmission lines (e.g., Cheng et al., 2009; Jiang and Liu, 2006; Lyazgin et al., 2004). Seasonal frost heave or thaw settlement deformation can impact the mechanical state of the foundations, while the stress state of tower foundations and surrounding soils has a close relationship with foundation failures. Therefore, it is important to understand how the stress changes in order to reduce tower foundation damage.

Previous studies of foundations in cold regions have been focused on the adfreeze bond strength and frost heave force (e.g., Johnson and Esch, 1985; Penner, 1974; Tong and Guan, 1985). Since the 1930s, measurements of the adfreeze strength between piles and frozen ground have been undertaken (Ladanyi and Foriero, 1998; Penner and Gold, 1971; Penner and Irwin, 1969; Perameswaran, 1978; Sadovsikiy and Sanger,

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http://dx.doi.org/10.1016/j.coldregions.2015.06.007
0165-232X/

1973; Saitykov, 1944; Trow, 1955). Many studies focused on the bearing capacity and uplift performance of piles in frozen soil in recent decades (Aksenov and Kistanov, 2008; Selvadurai and Hu, 1996; R. Wang et al., 2005; X. Wang et al., 2005; Zhang et al., 2008). To further understand the frozen soil–foundation interactions, researchers have used the finite element method and model testing to determine the distributive features of stress and deformation. Wu et al. (2010) proposed a nonlinear elasto-plastic finite element model for a pipeline-soil system and calculated the mechanical performance of the oil pipeline subject to differential frost heave in permafrost regions. Xu et al. (2010) investigated the stress and strain of a buried pipeline and surrounding soils by a model test, and analyzed the ambient temperature of the pipeline foundation, the displacement and axial strain, and the stress in the pipeline induced by frost heave and thaw settlement. However, the stress and deformation characteristics of tower foundations have received little attention and there has been limited effort towards the understanding of the mechanical behavior of foundations.

To investigate the stresses and deformation of tower foundations in the permafrost regions along the QTPTL, the thermal regime, stress state, and deformation were monitored and simulated. The results were analyzed to understand the frost damage processes of tower foundations, as well as to make mitigative recommendations for the design and the construction of power transmission lines in cold regions.

2. On-site experimental investigations on stress and deformation of tower foundations

2.1. Site description and instrumentation

To study the stress and deformation of tower foundations in cold regions, two experimental tower foundations were constructed at Qingshui'he along the QTPTL in 2011. The elevation of the study site is 4465 masl and the average annual air temperature during the period of 2011 to 2012 at the site is −4.9 °C, with extremes of approximately 19.97 and −38.04 °C. Weather records show that the average annual wind speed is 4.8 m/s. Engineering geological investigations at the site indicate that there is ice-rich clayey soil with a thickness of 0.5 to 4 m below the permafrost table and the ice content by volume is about 50% – 80%. The mean annual ground temperature (MAGT) of the permafrost at the 490# test tower foundation is −0.5 °C and the permafrost table is 2.5 m. The MAGT of the permafrost at the 492# test tower foundation is −1.0 °C and the permafrost table is 2.8 m. The thickness of ice-rich permafrost at 490# and 492# is 2.2 m and 3.0 m, respectively. The test tower foundations are located in a warm and ice-rich permafrost zone and have low thermal stability.

The contact stresses at the soil–foundation interface are vital to understand the interaction between structural foundations and the supporting soil. To investigate the contact stress characteristics of tower foundations, three thin-film pressure sensors were installed beneath each tower foundation. To monitor ground temperatures at the test foundation section, six boreholes were drilled in the vicinity of the tower foundation soils (Fig. 1). The depths of these boreholes varied from 10 to 23 m. In each borehole, thermistors were installed at depth intervals of 0.5 m from the ground surface. The thermistors were made by the State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, and with a calibrated accuracy of ±0.05 °C. The deformation of the tower foundations was measured by a water level instrument.

To study the cooling effect of two-phase closed thermosyphons, four thermosyphons were installed around the 492# tower foundation. The length of thermosyphons was 9 m; the evaporation part was 7 m-long and was embedded in the ground. The condensation part was 2 m-long and was exposed in the air. Fig. 1 shows the sensor installation design at the test footing foundation and force analysis.

3. Results and discussions

3.1. Seasonal variation of contact stress

Fig. 2(a) shows the seasonal variation of contact stress under the 490# test tower foundation. The contact stresses of 490# showed significant variations. The absolute value of contact stress decreased gradually after October and reached approximately 0 kPa in January. Then the contact stress increased gradually to approximately 300 kPa in May, and then it remained constant during the summer. The seasonal variation of contact stress had a close relationship with the seasonal variation in air temperature near the site (Fig. 2c). The contact stress decreased significantly with the decrease in air temperature in winter and increased with the increasing air temperature. The contact stress showed a positive correlation with the seasonal variations of ground temperatures near the tower foundation (Fig. 3a). The tower foundation tended to suffer from the force induced by wind. However, our experimental results showed that the seasonal variations contact stress beneath the foundation did not appear to have a visible relationship with the wind speed near the site (Fig. 2d).

The 490# tower foundation is located in an ice-rich permafrost site with a MAGT of −0.5 °C. The ground temperatures near the base of tower foundation show significant seasonal variation. The compression of warm permafrost leads to the occurrence of settlement deformation. Our monitoring showed that settlement deformation at 490# has occurred since 2010, and total settlement amount reached 0.08 m in the past three years (Fig. 3b). As shown in Fig. 1(b), the contact stress depends on the load, frost heaving force, and adfreeze bond strength

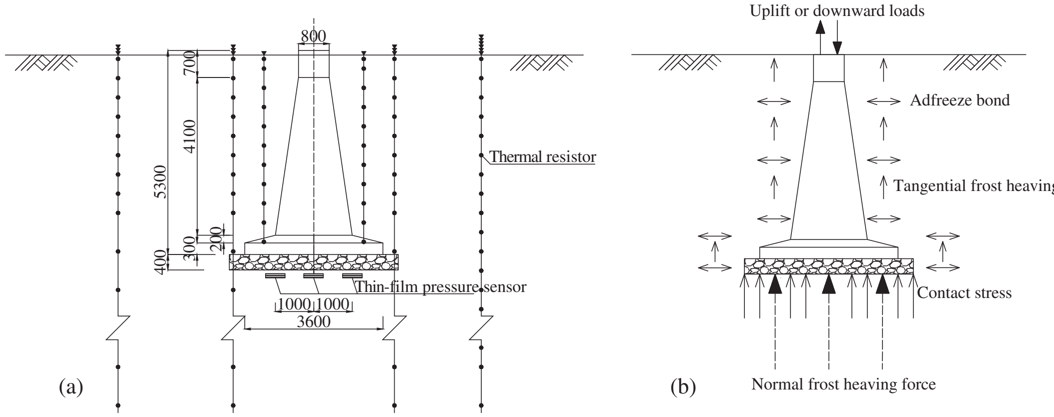

Fig. 1. Sensor installation design at the test tower foundation (a) and force analysis (b) (unit: mm).