Thawing Hazards and Their Developing States along the Qinghai-Tibet Engineering Corridor

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ABSTRACT

The thawing hazards (e.g. thaw slumping, thermokarst pond, thawing settlement, and thawing groove, etc) were widely distributed in permafrost regions along the Qinghai-Tibet Engineering Corridor. Under the combined influences of the human activities and climatic warming, they have current been rapidly developing in failure scale. The total length of the corridor with the thaw slumping was already up to about 45km, the accumulated water area increased about ten times from 2007 to 2009, the section with the thawing settlement has accounted for about 56% of the whole length of the Qinghai-Tibet Highway, and thawing groove subsided about 7 to 8 cm/a.

RÉSUMÉ

Au long du corridor des travaux de Qinghai-Tibet se sont présentées des catastrophes fondues dans les régions de permafrost telles que le glissement fondu de terrain, le thermokarst fondu, la subsidence fondue, l’auge fondue, etc. Influencées à la fois par les activités et l’élévation climatique globale, ces catastrophes fondues s’aggravent en échelon de ravagement. Actuellement, la longueur totale du corridor avec les catastrophes fondues a déjà atteint 45 km ; la région de l’eau accumulée a augmenté de près de dix fois de 2007 à 2009 ; la section avec la subsidence fondue a déjà occupé 56% de la longueur totale de la Route Qinghai-Tibet ; et la subsidence de l’auge fondue a une vitesse de 7-8cm par an.

1 INTRODUCTION

The Qinghai-Tibet Engineering Corridor (QTEC) from Golmud, Qinghai Province in the north, to Lhasa, Tibet Autonomous Regions in the south, encompasses a naturally-occurring north–south corridor in the hinterland of the Qinghai–Tibet Plateau (QTP) (Figure 1). The total length is about 1120 km, of which approximately 80% of the length exceeds 4,000 m in elevation while a portion of it, about 50 km, exceeds 5,000 m. Three major generally east-west trending mountain ranges, the Kunlun Mountains, Fenghuoshan Mountains, and Tanggula Mountains, and three major rivers, Chumar River, Tuotuo River, and Tongtian River cross the corridor. The high corridor has been affected by tropical east wind and subtropical west wind from the troposphere and east wind from the stratosphere in summer and by west wind from the troposphere, polar west wind, and west wind from the stratosphere in winter. It has a typical paramos continental climate. The mean annual air temperature (MAAT) is below -4 ºC, the extreme lowest temperature is up to -30ºC in winter, the extreme highest temperature is approximately 25ºC in summer, and precipitation is concentrated in the period from May to August and is about 50 to 400 mm.

The high elevation, periglacial processes, and cold and arid continental climates have influenced, or to a certain extent, determined the configuration and distribution of the permafrost environments along the QTEC. The length which is impacted by permafrost is about 550km and the total length is subject to seasonally frozen ground (Zhou et al. 2000). The permafrost is featured by rich ice and high ground temperature; of which the section of permafrost with volume ice content higher than 20 % is 221 km long, with mean annual ground temperature (MAGT) higher than -1.0 ºC (warm permafrost) of 221 km, and with the warm and ice-rich permafrost of 124 km (Liu et al. 2000, Wu et al. 2004). The max thickness of permafrost is approximately 120m and the min is 10 m.

The permafrost, especial the permafrost with the rich ice and high ground temperature is a kind of the foundational materials that is sensitive to the changes of temperature (e.g. disturbance of anthropogenic activities and global warming). During the past 50 years, many linear structures such as the QTH, the Qinghai-Tibet Railway (QTR), etc. were constructed, and the design of a new express highway from Xi'ning to Lhasa is already under way with the beginning of construction anticipated within a few years. These steadily increasing human activities can result in permafrost warming. In addition, there is the impact from a projected climate warming, estimated by Xu (2004) to be as much as a 4℃ increase in the MAAT, with a corresponding 10% increase in the annual precipitation, by the year 2100. More conservative estimates suggest a probable warming in the MAAT of about 1.1℃ by 2040 (Jin et al., 2000). Under the combined influences of steadily increasing human activities and persistent climatic warming, permafrost has been degrading at a rapid rate, and extensive accelerated degradation has resulted in a large number of the thawing hazards. Therefore, this paper reports some typical thawing hazards induced by combined influences and their developing states.

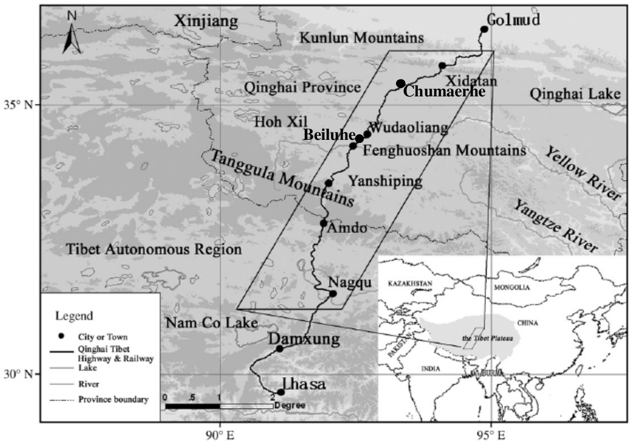

Figure1 Location of the studied segment of the Qinghai–Tibet Engineering Corridor on the Qinghai–Tibet Plateau (Revised from Jin et al., 2008a).

2 THAWING HAZARDS

Thawing hazards are developed as result of thawing of ice-rich permafrost or melting of massive ground ice (Brown and Grave, 1979; Hinzman *et al.*, 1997; Niu *et al.*, 2008). Normally the occurrence of active thawing hazards indicates that permafrost is unstable and warming. According to the field observations, the hazards caused by thawing are mainly classified into four kinds, including thaw slumping, thermokarst ponding, thaw settlement, and thawing groove.

2.1Thaw Slumping and Its Developing States

The thaw slumping is commonly caused by slope toe disturbance in ice-rich permafrost regions. They are mainly located in the Hoh Xil Hill Region, Beiluhe Basin, and southern slope of Fenghuoshan Mountain along the QTH (Figure 1), and the total length is about 45km because of the early construction of the QTH and the asphalt surface rebuilding in 1980s, which were different as the subsequent reconstruction projects or the construction of the QTR, ignored the protection of the permafrost environment. The embankment filling came directly from both sides within 50 to100 m range away from the roadway. These cutting for construction material not only have seriously damaged large area of vegetation, but also have induced the formation and development of thaw slumping in sloping regions (Figure 2). Once the turf layer is damaged, the slumping process rapidly develops in the first few years, and in a few years, it may be spread from the root to top of the hillside.

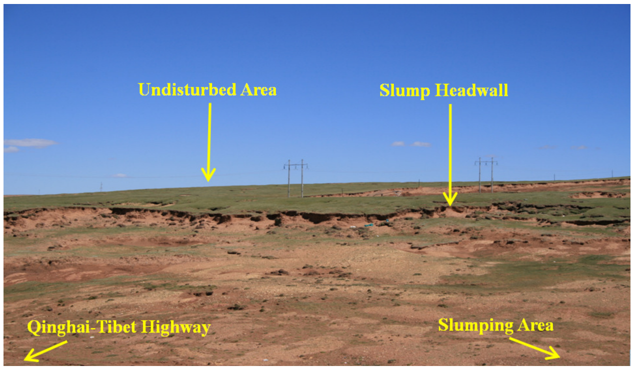

Figure 2 Thaw slumping developed at the Hoh Xil Hill Region along the QTH and QTR. This slumping zone is about 30km length and $10^6 m^2$ of area. During the past nearly decade years, it has been retreating at about 1.2m/a rate due to the permafrost degradation. The surface in slumping area is bare soil and many cracks have developed within 10 m in slumping headwall.

In order to investigate the development of thaw slumps, we studied a case located on the west slope of the QTH at K3035 mileage in Beiluhe Basin. This thaw slump formed in the period of the reconstruction of QTH in 1990 to 1992. The vegetation, which covered massive ground-ice with thickness about 2 to 4 m, was destroyed for cutting for embankment. The failure showed as detachment of the active layer, consisted of sand and silty clay. After years of repetitions of the thawing-collapse-slide, the current 110-meter-long and 72-meter-wide landslide area was formed. In 2002, two boreholes (one drilled in undisturbed area, and another was in failed area) were drilled and the equipment were installed to monitor the retrogressive process of the landslide area and ground temperature changes. Drilling results show that the thickness of ground-ice in undisturbed area was 4.0m, while it was only 1.7m in failed area. It was obvious that about 2.3m-thickness ground-ice has been melted with the ongoing slumping process. In addition, the observational results of ground temperatures show the depth of permafrost table was 2.0m in the undisturbed area, with 15 to 20% of it was covered by vegetation, while it was 2.3m in failed area that the surface was exposed. The temperatures in undisturbed area were lower than those in the failed areas. The maximum difference of ground temperature appeared at a depth of 2 m, where ground temperature in the undisturbed area was -3.38 ºC, while it was -1.88ºC in the failed area. Such a situation was same to the tundra thaw slumps studied by Kokelj et al. (2009) in Mackenzie Delta Region, Northwest Territories, Canada. The slumping headwall retrogressed 5 m in 2002 and nearly 3 m in 2003. The failure in fact occurred mainly from July to October. According to the data from recent 3 years, the current collapse-extending velocity was 2 to 5 m/a. Although the velocity slows down, there spread many fissures behind the wall and there is no evidence that the failure would stop soon (Niu et al., 2005).

2.2 Thermokarst Pond and Its Developing States

The occurrence of the thermokarst ponds can result from an external natural disturbance, such as the forest fire or climatic warming (e.g. Burn and Smith, 1990; Yoshikawa and Hinzman, 2003). However, on the Qinghai-Tibet Plateau (QTP), infrastructure construction, such as the QTH, the Oil Products Pipeline, and Fibre-Optic Cables, etc. left many small pits on the surface due to digging or the passage of heavy equipment. These pits subsequently filled with water and developed into thermokarst ponds after undergoing long-term slumping and collapse.

Thermokarst ponds (including water pits) are widely located in the Chumarhe High Plateau, Wudaoliang Basin (a special part of Hoh Xil Hill Region), and Beiluhe Basin (Figure 1 and 3). A detailed statistical data in 2007 showed that approximately 69 thermokarst ponds and 234 water pits were developed at both sides of roadway of QTH from Xidatan Basin to Hoh Xil Hill region, and their areas were about 1.5×10^4 m^2 and 1.0×10^4 m^2, respectively (Niu et al., 2008). The current survey in September 2009 showed the surface water areas (including thermokarst ponds and water pits) from Xidatan Basin to Beiluhe Basin have already been up to 3.5×10^5 m^2, and exceeding about ten times because of the disturbance from the current improvement project which started in 2008.

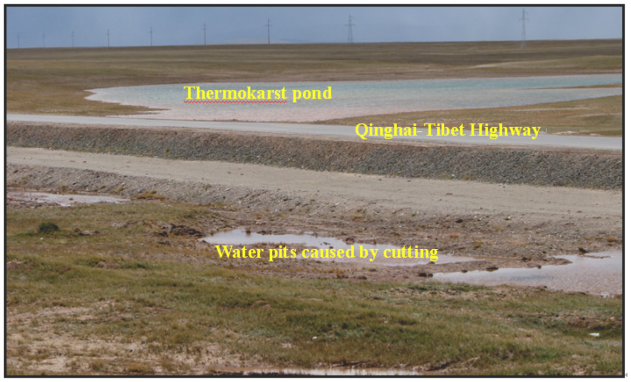

Figure 3 Thermokarst pond and small water pits developed at Chumarhe High Plateau along the QTH. These, sporadic or string-like distributed, are existed in the section of bottomland or intermountain basin with ice-saturated permafrost or massive ground-ice. The water depth is about 0.5 to 3.0 m, and the areas rang from less than $100m^2$ to about $60,000m^2$.

The thermokarst pond constitutes a major heat source, giving rise to anomalous heat flow and temperature difference between the ground layer beneath pond bottom (Ling and Zhang, 2003). In March 2006, a typical 2 m deep thermokarst pond (informally named BLH-A Pond) was studied in the Beiluhe Basin on the Qinghai-Tibet Plateau. Shore retrogression, water temperatures, and ground temperatures beneath and around the pond were monitored.

The observational results show that the thaw depth at shore edge was about 0.7 m greater than that in the adjacent terrain. The ground temperatures in the undisturbed area were lower than those beneath the pond. As far as the MAGT is concerned, it was -1.06 ºC in the undisturbed area, 4.5ºC beneath the pond center bottom, and -0.17 ºC in inshore. Overall, the high degree of disturbance associated with the thermokarst pond is shown by mean annual ground temperatures beneath it that are more than 5ºC higher than in the surrounding terrain at the same depth. Measured results from monitoring profiles showed that almost all the shore happened different collapsing retrogression from August 2007 to October 2009. The collapsing ranges were all more than 0.5 m, and the maximum value was about 2.8 m. There were many cracks and collapse blocks within 10 m away from the shore edge. These cracks are gradually widening and developing greatly in warm seasons. The blocks cut by the cracks incline toward the pond, and collapse into the water when the bottom ice-rich frozen soil thawed or the massive ice melted.

The permafrost environments have been severely disturbed around the thermokarst ponds, as evidenced by widespread rising of ground temperatures, much more rapidly than in the undisturbed areas. The depth of the permafrost table is steadily increasing due to the ground warming. In the worst case scenario, such as beneath the thermokarst ponds with over 2.0m water depth, the permafrost has completely thawed (Lin et al., 2010).

2.3 Thawing Settlement and Its Developing States

The engineering construction, especially the QTH and QTR, has disturbed the thermal equilibrium state between the air and the ground surface, causing the temperature rising in permafrost. The presence of talik beneath the roadbed and the subgrade settlement are evident response. During the past 30 years, the observational results to the QTH indicate that the taliks (perennial thaw layer) between the bottom of the seasonally frozen layers and the top of permafrost table has formed beneath the subgrade and accounted for about 56% of the whole QTH permafrost sections (First Highway Design and Research Institute, 2001). These sections are generally located in the Xidatan Basin, Chumarhe High Plateau, and Beiluhe Basin etc, with mean annual ground temperature (MAGT) generally greater than -1.5℃ (warm permafrost) and the relatively lower elevations. The formation of the taliks signifies the degradation and thawing of the permafrost and also makes to form a “thawed channel” below the roadbed (Wang, 1993; Jin et al., 2008b). Most of the taliks have free water throughout the year and can cause much more thaw settlement, resulting in damages of the roadways, especially when heavy trucks pass in warm seasons. According to the survey in 1990 showed that the failed sections where severely affected serving accounted for about 32% of the total length of the QTH in the permafrost areas (Wang and Mi, 1993), and about 80 to 85% roadbed failures have been induced by permafrost thawing settlement (Cheng, 2003).

During the past decade years, the taliks thickness has increased about 30 to 50 cm (Wang et al., 1993; Wu et al. 2005; Jin et al., 2006, 2008). The development of talik would lead to the increase of seasonally frozen depth, the decline of permafrost table, and increasing of the MAGT below the roadbed. Some stable or quasi-stable permafrost areas have been extending into the unstable or the extremely unstable permafrost areas. Numerical simulation results showed the sections with taliks will maybe extend to all the QTH sections in the permafrost areas if the permafrost degradation will be accelerated ceaselessly during the next 50 to 100 years (Wang et al., 2003). At that time, some low-temperature permafrost areas, such as Kunlun Mountain, Fenghuoshan Mountain, and Tanggula Mountain etc, will develop into severe damages sections.

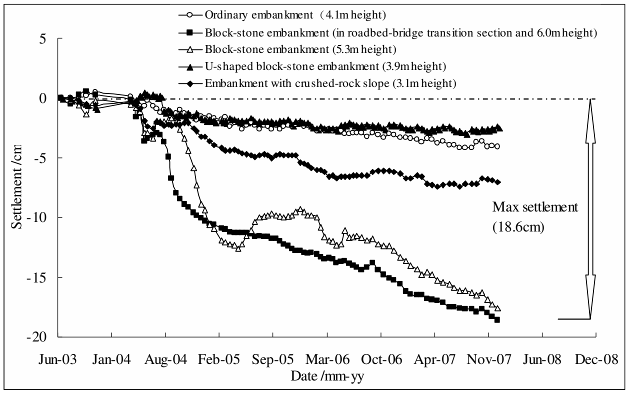

Figure 4 Time-settlement curves of the five embankments in Chumaerhe test sections along the QTR

The same results were also from the observation to the QTR. In 2007 to 2009, 56 sections subgrade settlement along the QTR were surveyed. The results indicate that the average settlement value was 17.8 cm in road shoulder; it was 13 to 15 cm when the embankment height is less than 5 m, and the settlement increased to 17 to 23 cm when the height is more than 5 m. In order to reveal the development trend and deformation features of subgrade settlement, a long-term field observation site in Chumaerhe High Plain (DK1043+000-DK1067+000) was started in July 2003. Figure 4 shows that the maximum settlement occurred in the block-stone embankment (in roadbed-bridge transition section) with 6.0 m of embankment height reached 18.6 cm, and the minimum settlement was only about 3 cm. However, the settlement value always creased (curve decline) during the observation period. These results indicate that the settlement could continue to develop under the influence of the global warming and the degradation process of permafrost. Thaw settlement has also been characterized along other corridors such as the Norman Wells Pipeline corridor in the Mackenzie Valley NWT Canada (Burgess and Smith, 2003; Smith et al., 2008; Smith and Riseborough, 2010). Thawing beneath the right-of-way (ROW) and associated thaw settlement in response to vegetation clearing, surface disturbance, pipeline construction and operation is still continuing, and in ice-rich terrain, increases in thaw depth have been accompanied by settlement of the ground surface.

2.4 Thawing Groove and Its Developing States

On the QTP, thawing grooves are common landscapes in permafrost regions, where ice-rich permafrost exists. It is normally caused by linear cutting or even ground surface disturbance by truck or car driving in wet land. Figure 5 shows a thawing groove developed along the QTR at mileage K980 south to the Kunlun Mountain. The embankment was constructed in 2003 and the slopes were covered with crushed stone in 2006. On the west side a 1.5-meter-high water barrier and drainage ditch were constructed in 2003. But in 2006, as surface water was gathered between the barrier and the embankment, the barrier was removed and the ditch was covered. According to our investigation in 2007, a 180-meter-long thawing groove along the former ditch was developed with a depth of 20 cm in July (Figure 5 (a)) and then subsided to 40 cm in September (Figure 5 (b)). Because of the settlement in the groove, many parallel fissures developed along the both sides of the groove. The nearest fissure was 3.5 m far from the embankment. In November 2007, a monitoring program providing ground temperature and deformation data was established. The geological data from boreholes show that the strata here consisted of 10-meter-thick fine sand with gravels and the underlying silty clay. The permafrost table was 1.5 m in depth and the permafrost was ice-rich or ice-saturated.

According to the observational results from 2008 to 2009, the thawing groove obviously subsided, in which the settlement value in the groove bottom was about 15cm within two years, and more than that in both shoulders. The warm season was the main period of shoreline collapse, especially from August to October per year. The shallow layer soils (above 2.5 m) in shoulders of the thaw groove were being glided toward the groove, and the horizontal displacement in 0.5m depth was 5cm in 2008. The MAGT in thaw groove was more about 0.52℃ than that in undisturbed regions. The calculated results to heat balance between the thawing groove and embankment show that the time of absorbing heat of the thawing groove starts in mid of April, ends in beginning of November, and lasts about 233 day. The heat absorbed per unit area is about 3300kJ per year. About 70×10^3 kJ heat is transported from thaw groove to permafrost embankment per year. The thawing groove has great influenced on the stability of the nearby permafrost embankment.

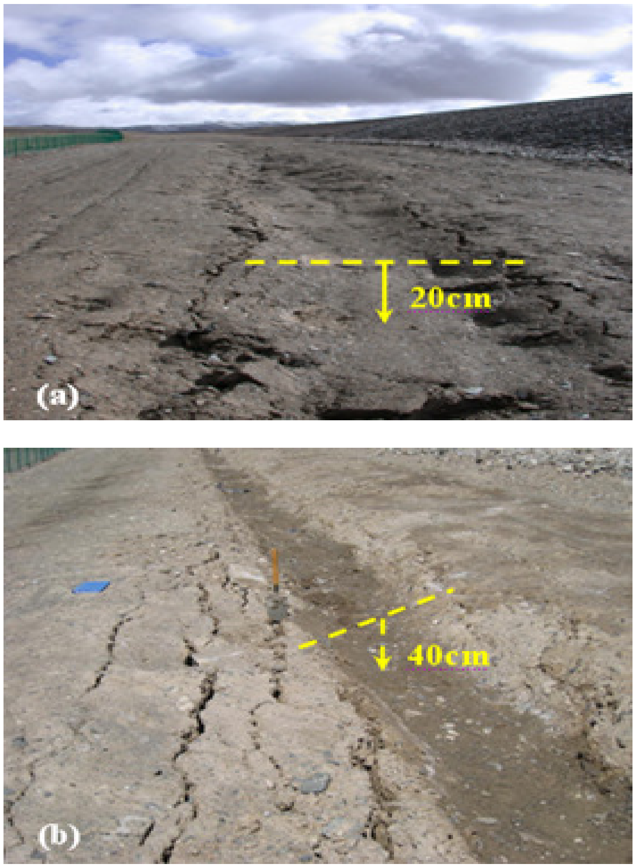

Figure 5 Thawing groove developed on the west side of K980+000. (a) Status in July, 2007; (b) Status in September, 2007.

3 CONCLUSIONS

1.The permafrost along the Qinghai-Tibet Engineering Corridor has been degrading at a rapid rate, and extensive accelerated degradation has resulted in a large number of the thawing hazards, including thaw slumping, thermokarst pond, thawing settlement, and thawing groove, etc.

2. The field observations in the recent three years (2007-2009) show that the thawing hazards have been rapidly developing in failure scale, and have severely impacted on the permafrost environment and engineering usage.

3. The current collapse-extending velocity of thaw slumping was 2 to 5 m/a, and the total length of the corridor with the thaw slumping was already up to about 45km; The maximum shore retrogression a range was close to 1.0 m/a, and the accumulated water area increased about ten times from 2007 to 2009; The thawing settlement has accounted for about 56% of the whole Qinghai-Tibet Highway permafrost sections, and the average subsidence value in Chumaerhe High Plain site was 17.8 cm in road shoulder of the QTR; The subsidence speed of thawing groove in bottom was about 7 to 8 cm/a, and the horizontal displacement in 0.5m depth was 5cm/a.

Acknowledgements

This research was supported in part by the Important Orientation Projects of the CAS (KZCX2-YW-Q03-04), the National Program on Key Basic Research Project (973 Program) (2010CB434813), the grant of the Western Project Program of the Chinese Academy of Sciences (KZCX2-XB2-10), Natural Science Foundation of China (Grant No. 40625004, 40801024) and the National Science Supporting Project of the Ministry of Science and Technology of China (2006BAC07B02).

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