Arctic, Antarctic, and Alpine Research, Vol. 39, No. 4, 2007, pp. 682–687

Responses of Permafrost on the Qinghai-Tibet Plateau, China, to Climate Change and Engineering Construction

Qingbai Wu†*
*Xianfu Dong**
Yongzhi Liu and*
*Huijun Jin**

*State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environment and Engineering Institute, Chinese Academy of Sciences, Lanzhou 730000, China
†Corresponding author: qbwu@ns.lzb.ac.cn

Abstract

Monitoring of permafrost along the Qinghai-Tibet (Xizang) Highway shows that there is a large difference in the response of permafrost to climate change and to engineering construction. The change in cold (<-1.5°C) permafrost is greater than that in warm (≥-1.5°C) permafrost under the effect of climate change, while the cold permafrost is less sensitive to the disturbances from engineering activities. However, warm permafrost is very sensitive to both climate warming and the impacts from engineering construction. This is because engineering construction has more immediate and direct impacts on the thermal and moisture regimes of underlying permafrost, and consequently greater influence than climate change during the first few years after engineering construction. Assuming constant annual rates of warming, the surface of cold permafrost would approach the warming due to engineering construction in 50 yr, while it would take about 20 yr in areas with warm permafrost. At a depth of 6 m, the temperature rise under engineered surfaces would be reached within 20 and 5–8 yr in cold and warm permafrost, respectively. Therefore, the warming immediately following disturbances of engineering construction would occur naturally in a few years under warm permafrost, but it would take decades for cold permafrost to have the similar thermal effects. Therefore, climate change will have more direct and immediate impacts on the thermal regime of warm permafrost and on the stability and reliability of engineering infrastructures above warm permafrost.

Introduction

The response of permafrost to climate change and engineering construction is vitally important for studying the interactions between climate and permafrost, and between engineering infrastructure and permafrost, and to understand terrestrial and hydrological process in cold regions (Koster, 1993; Nelson et al., 1993; Zhang and Stamnes, 1998). Under global climate warming scenarios, permafrost is projected to undergo great change (Wu and Tong, 1995; Zhao and Wang, 1996; Li and Cheng, 1997). Permafrost change under a disturbed surface will be greater than under natural surfaces. The effect of global climate change on permafrost is less than that of engineering activity on it. According to drilling data from the 1980s and 1990s, the northern and southern limits of the Qinghai-Tibet Plateau permafrost have not changed substantially under natural conditions, with only minor changes in the thickness and temperatures of the permafrost. However, under asphalt pavement, permafrost has undergone great changes. Not only has the depth of the permafrost table changed significantly, permafrost also has degraded, resulting in a 5- to 8-km southward retreat of northern boundary and a 9- to 12-km northward retreat of the southern boundary. The permafrost table deepens greatly under an asphalt pavement (Wang and Mi, 1993; Wu and Tong, 1995).

Climate change and engineering construction are both expected to thicken the active layer and raise permafrost temperature. However, the responses of permafrost to climate change and to engineering construction differ substantially on the Qinghai-Tibet Plateau due to local variations in topography, geology, hydrology, vegetation, and soils, which is of interest to geotechnical engineers and scientists. Formerly, it was believed that cold (<-1.5°C) permafrost is more thermally stable and subsequently less sensitive to climate change and engineering activity than warm (≥-1.5°C) permafrost (Cheng, 1984; Tong and Wu 1996; Wang et al., 1996; Ding, 1998). However, monitoring of permafrost temperatures under the influences of a changing climate and the disturbances from the construction and operation of the Qinghai-Tibet Highway necessitate the reconsideration of this conclusion. The observations show that the rates of increase in permafrost surface temperatures (temperature at the permafrost table) and in permafrost temperature are substantially greater for areas with cold permafrost than areas with warm permafrost under a changing climate. Climate changes, however, have greater impacts on the thermal regimes of cold permafrost than engineering activities.

Much research on permafrost along the Qinghai-Tibet Highway are focused on either climate change or engineering activity (Yu et al., 2002; Wu et al., 2003; Wu and Liu, 2004). There are very few comparisons of the effects of climate change and engineering activities on the thermal regimes of permafrost. Seven field sites were installed along the Qinghai-Tibet Highway from Xidatan to Tanggula Pass in 1995 in order to monitor the responses of permafrost and active layer processes to climate changes and engineering construction and operations, and to find the important factors for consideration in engineering designs at different locations and at different timescales.

Study Area and Methods

Permafrost is present in most areas above 4100 m elevation along the Qinghai-Tibet Highway. On the Qinghai-Tibet Plateau,

1523-0430/07 $7.00

TABLE 1

Information on permafrost monitoring sites along the Qinghai-Tibet Highway.

Location	Site no.	Latitude (N)	Longitude (E)	Elevation (m)	MAAT (°C)	MAGT (°C)	Active layer thickness (m)	Permafrost thickness (m)
Kunlun Mountains	1	35°37′58″	94°04′18″	4770	−5.0 to −7.0	−2.6 to −3.2	1.5 to 2.8	60 to 120
Kunlun Mountains	2	35°27′12″	94°04′13″	4759				
Kunlun Mountains	3	35°36′15″	94°03′10″	4733				
HMS 66	4	35°30′50″	93°44′05″	4552	−4.5 to −5.0	−0.5 to −1.0	2.0 to 3.5	25 to 40
Chumaerhe High Plain	5	35°23′49″	93°32′01″	4482	−4.5 to −5.0	−0.5 to −1.0	2.0 to 3.5	25 to 40
Wudaoliang	6	35°13′48″	93°05′06″	4610	−4.5 to −5.5	−0.9 to −1.2	2.5 to 3.0	40 to 90
Hoh'xil Mountains	7	35°07′36″	93°02′12″	4707	−5.5 to −6.5	−1.2 to −1.8	1.5 to 3.5	30 to 100
Fenghuo Mountain	8	34°41′24″	92°53′30″	4938	−5.0 to −7.0	−1.5 to −3.0	0.8 to 2.5	50 to 120

Notes: MAAT is mean annual air temperature, MAGT is mean annual ground temperature. Site No. 3 has no monitoring borehole under natural surface.

the effect of elevation on permafrost distribution is stronger than that of latitude (Cheng and Wang, 1982; Cheng, 1984). Generally, mean annual ground temperatures (MAGT) decrease with increasing elevations at rates of 8 to 9°C km^{-1}. The MAGTs rise 1°C and the lower limit of permafrost rises 100 to 110 m per degree of latitude (Tong and Li, 1982). Elevation is the controlling factor for the distribution and characteristics of permafrost on the Qinghai-Tibet Plateau. The MAGTs vary from −0.1 to −4.5°C, decreasing with increasing elevation and latitude. Permafrost thickness is from several meters to more than 100 m (Li, 1982). The permafrost table ranges from 0.8 to 3.8 m depth. Permafrost along the Qinghai-Tibet Highway has lower thermal gradients of about 46°C km^{-1}, compared with that in unfrozen soil under permafrost of about 61°C km^{-1} (Wang and Li, 1983; Guo, 1985).

In order to investigate the response of permafrost to climate change along the Qinghai-Tibet Highway, seven monitoring sites were installed along the Qinghai-Tibet Highway according to the local MAGTs and sensitivity of the permafrost to climate change and engineering activity. The basic data for each site is shown in Tables 1 and 2.

At each monitoring site, thermistor cables were installed under the natural surface, the road shoulder, and centerline. Permafrost temperature and freeze-thaw processes under natural and engineering effects were monitored on 5th and 20th day of each month. The monitoring began in 1995 and lasted for 6 yr for sites 1, 2, 3, and 5 and it continues to the present for sites 4, 7, and 8.

Permafrost Change under the Effect of Climate Change

The permafrost table deepened in all seven monitored natural surface sites from 1996 to 2001 (Table 2), at mean rates that ranged from 3.6 to 9.2 cm yr^{-1}. The permafrost table shows some minor interannual variations under natural surfaces (Table 2). Table 3 gives the variations of mean annual permafrost surface temperature at seven sites from 1996 to 2001. The mean annual rates of changes in the permafrost surface temperature are about 0.06 to 0.10°C yr^{-1} for cold permafrost and about 0.01 to 0.04°C yr^{-1} for warm permafrost. The mean annual temperature at 6 m depth of rose about 0.04 to 0.06°C yr^{-1} for cold permafrost, and about 0.02 to 0.03°C yr^{-1} for warm permafrost (Table 4). The rate of change of cold permafrost is obviously larger than that of warm permafrost, whether considering permafrost surface temperature or permafrost temperature at 6 m depth.

Permafrost Change under Engineered Surfaces

The mean annual permafrost surface temperature of warm permafrost under asphalt rose 0.08 to 0.14°C yr^{-1}, compared to a rise of 0.01 to 0.03°C yr^{-1} for cold permafrost (Table 5). In accordance with the change of mean permafrost surface temperature, the depth to the permafrost table increased at a rate of 11 to 31 cm yr^{-1} for warm permafrost and 1 to 4.6 cm yr^{-1} for cold permafrost (Table 6). Permafrost temperature changes at 6 m depth accords with the change in permafrost surface temperature and permafrost table depth. The mean annual temperature at 6 m depth under asphalt rose faster for warm permafrost (0.11°C yr^{-1}) than for cold permafrost (0.02–0.05°C yr^{-1}) (Table 7). The effect of engineering activity on permafrost change is greater than the influence of climate change.

Discussion

The effect of climate change is larger than the effect of engineering activity for cold permafrost, but the effect of climate change is smaller than the effect of engineering activity for warm permafrost. Actually, permafrost change beneath engineered

TABLE 2

Permafrost table depth under natural surfaces, 1996–2001.

Location	Site no.	Permafrost table depth (m) 1996	Permafrost table depth (m) 2001	Mean annual increase (cm yr^{-1})
Kunlun Mountains	1	1.09	1.50	8.2
Kunlun Mountains	2	1.22	1.40	3.6
Fenghuoshan Mts.	8	1.26	1.60	6.8
Wudaoliang	6	2.53	2.75	4.4
Hoh'xil Mountains	7	1.64	2.00	7.2
HMS 66	4	1.94	2.40	9.2
Chumaerhe High Plain	5	3.24	3.50	5.2

TABLE 3

Permafrost surface temperature under natural surfaces, 1996–2001.

Location	Site no.	Permafrost surface temperature (°C) 1996	Permafrost surface temperature (°C) 2001	Mean annual increase (°C yr^{-1})
Kunlun Mountains	1	−3.05	−2.68	0.07
Kunlun Mountains	2	−3.08	−2.78	0.06
Fenghuoshan Mts.	8	−3.73	−3.36	0.07
Wudaoliang	6	−1.82	−1.75	0.01
Hoh'xil Mountains	7	−2.14	−1.63	0.10
HMS 66	4	−0.82	−0.63	0.04
Chumaerhe High Plain	5	−0.43	−0.30	0.03

TABLE 4

Permafrost temperature at 6 m depth under natural surfaces, 1996–2001.

Location	Site no.	Permafrost temperature (°C) 1996	Permafrost temperature (°C) 2001	Mean annual increase (°C yr^{-1})
Kunlun Mountains	1	−3.19	−2.90	0.06
Kunlun Mountains	2	−3.06	−2.77	0.06
Fenghuoshan Mts.	8	−3.67	−3.48	0.04
Wudaoliang	6	−1.63	−1.50	0.03
Hoh'xil Mountains	7	−2.01	−1.69	0.06
HMS 66	4	−0.91	−0.83	0.02
Chumaerhe High Plain	5	−0.56	−0.40	0.03

embankments, for either cold permafrost or warm permafrost, is affected by both climate change and engineering activity so that permafrost changes beneath the embankment should be larger than that under the effect of climate change all the time. However, the monitoring results show that cold permafrost change beneath asphalt pavement is lower than cold permafrost change beneath natural surfaces. This is because of the difference in the permafrost response to the thermal disturbance of engineering construction and climate change.

Response of permafrost to climate change is a slow process; long-term effects of climate change produce a slower change of permafrost. However, response of permafrost to engineering activity is quick; the short-term effect of engineering activity produces a large change in permafrost. Over the short term, the much larger influence of engineering on permafrost dwarfs possibly the impacts of climate change. Figure 1 shows permafrost surface temperature change for cold and warm permafrost under the effect of climate change and engineering activity. The mean permafrost surface temperature in warm permafrost is about 0.5°C greater under asphalt than natural surfaces, and in cold permafrost is about 2.9°C greater under asphalt than natural surfaces (Fig. 1). Given the rates shown in Table 3, it will take at least 50 yr for climate change to raise permafrost surface temperatures under natural surfaces to the temperatures under asphalt for cold permafrost and 20 yr for warm permafrost. Figure 2 shows permafrost temperature change at 6 m for cold and warm permafrost under the effect of climate change and engineering activity. Figure 2 indicates that engineering activity can produce mean permafrost temperature at increase at 6 m depth of 0.50 to 1.5°C. Present climate change rates will produce this great a change at 6 m depth in 20 yr for cold permafrost, but only 5 to 8 yr for warm permafrost.

TABLE 5

Permafrost surface temperature under asphalt pavement, 1996–2001.

Location	Site no.	Permafrost surface temperature (°C) 1996	Permafrost surface temperature (°C) 2001	Mean annual increase (°C yr^{-1})
Kunlun Mts.	1	−0.26	−0.20	0.01
Kunlun Mts.	2	−0.32	−0.17	0.03
Fenghuoshan Mts.	8	−0.67	−0.53	0.03
Hoh'xil Mts.	7	−0.20	0.20	0.08
HMS 66	4	−0.49	0.22	0.14
Chumaerhe High Plain	6	−0.14	0.42	0.11

TABLE 6

Permafrost table depth under asphalt pavement, 1996–2001.

Location	Site no.	Permafrost table depth (m) 1996	Permafrost table depth (m) 2001	Mean annual increase (cm yr^{-1})
Kunlun Mts.	1	2.19	2.42	4.6
Kunlun Mts.	2	2.70	2.88	3.6
Fenghuoshan Mts.	8	3.55	3.60	1.0
Hoh'xil Mts.	7	4.00	4.56	11.2
HMS 66	4	6.41	7.50	21.8
Chumaerhe High Plain	5	6.00	7.56	31.2

The effect of engineering thermal disturbance is only to raise the permafrost temperature for cold permafrost. For warm permafrost, energy is also used to thaw ground ice near the permafrost table. Cold permafrost beneath embankments with asphalt pavement produced a larger change in the first years after engineering construction compared to warm permafrost so that the change of cold permafrost beneath embankment with asphalt pavement is comparatively insensitive to climate change. Because of close relationships of permafrost with climate change and engineering activity, engineering designers must consider the effect of climate change and engineering activities on permafrost from the early stages of engineering construction for the areas with warm permafrost. However, engineering designers should not consider the effect of climate change until permafrost change is more than the change under the engineering state for the areas with cold permafrost.

Recent Climate Change

Temperature change of cold permafrost is greater than those of warm permafrost under the effect of climate change. There are only two meteorological stations, Wudaoliang and Tuotuohe Riverside, in permafrost regions on the Qinghai-Tibet Plateau. Wudaoliang Meteorological Station is located in a cold permafrost region and Tuotuohe Riverside Meteorological Station is located in a warm permafrost region. The change of air temperature at the Wudaoliang Station seems to be greater than at Tuotuohe Riverside Station (Figs. 3, 4). The mean annual air temperature (MAAT) at the Wudaoliang Station rose 0.7°C from about −5.9°C in the 1960s to about −5.2°C in the 1990s. The MAAT at the Tuotuohe Riverside Station rose 0.5°C from about −4.4°C in the 1960s, to about −3.9°C in the 1990s. Mean annual surface temperature (MAST) in the 1960s was about −2.0°C, and about −0.7°C in the 1990s, indicating an about 1.3°C rise of surface temperature during the past 40 yr at the Wudaoliang

TABLE 7

Permafrost temperature at 6 m depth under asphalt pavement, 1996–2001.

Location	Site no.	Permafrost temperature (°C) 1996	Permafrost temperature (°C) 2001	Mean annual increase (°C yr^{-1})
Kunlun Mts.	1	−1.52	−1.40	0.02
Kunlun Mts.	2	−1.46	−1.31	0.03
Fenghuoshan Mts.	8	−1.61	−1.35	0.05
Hoh'xil Mts.	7	−0.77	−0.62	0.03
HMS 66	4	−0.056	0.50	0.11
Chumaerhe High Plain	5	−0.14	0.41	0.11

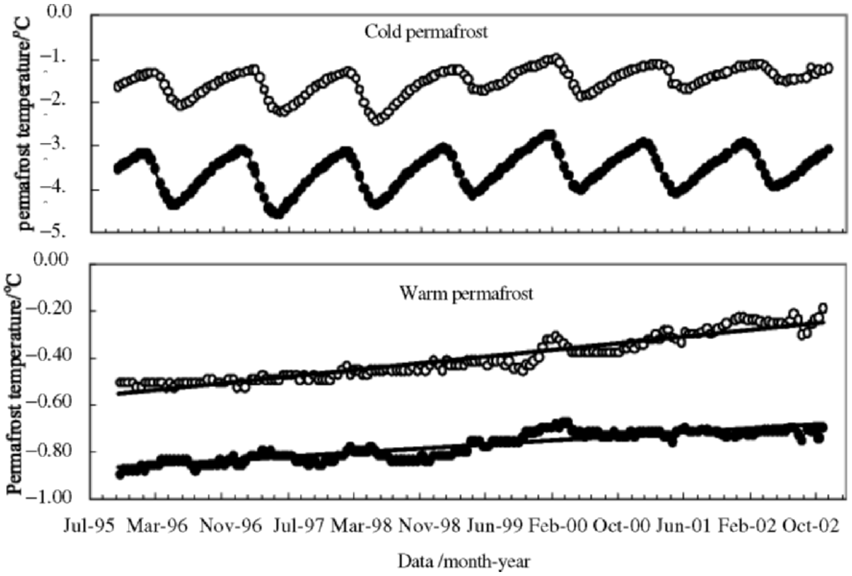

FIGURE 1. Permafrost surface temperature under the natural and engineered (asphalt) surfaces. Solid points are under natural surface and open points are under the central roadbed.

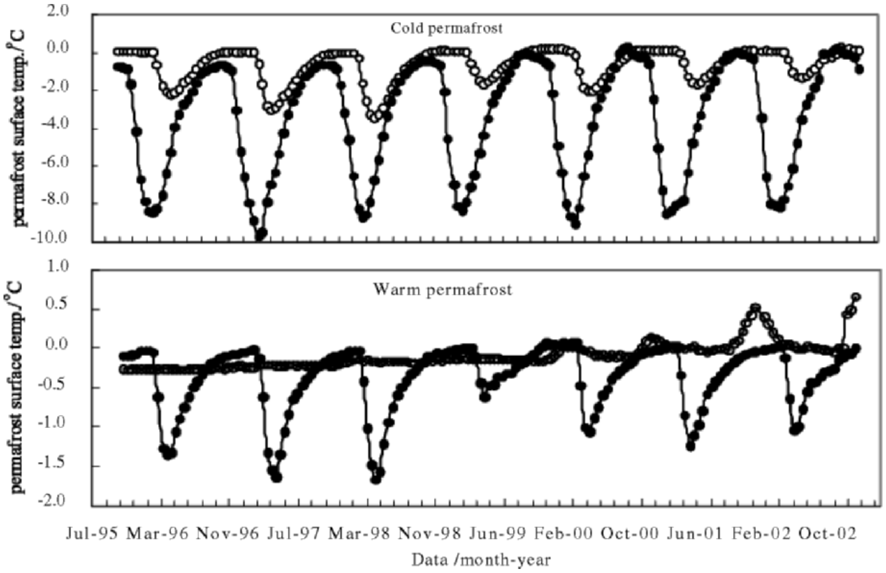

FIGURE 2. Permafrost temperature change at 6 m depth under the natural and engineered (asphalt) surfaces. Solid points are under natural surface and open points are under the central roadbed.

Meteorological Station. The MAST in the 1960s was about −0.78°C, and about −0.26°C in the 1990s, indicating a rise of about 0.52°C during the past 40 yr at the Tuotuohe Riverside. The change of the MASTs is about 0.8°C higher than that of the MAATs at the Wudaoliang Station. The amplitude of the changes at the Tuotuohe Riverside is smaller than that at the Wudaoliang Station. It seems that the climatic warming in the mountainous areas is more significant than that in the river valleys on the Qinghai-Tibet Plateau.

Conclusions

The changes in cold permafrost are larger than that in warm permafrost on the Qinghai-Tibet Plateau under a warming climate.

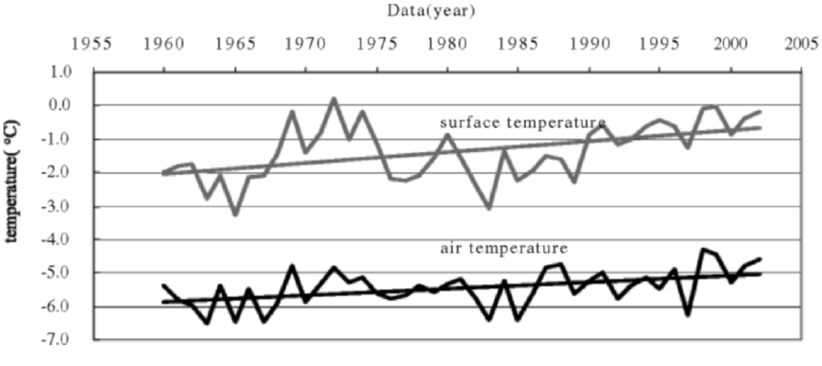

FIGURE 3. MAAT (mean annual air temperature) and MAST (mean annual surface temperature) at the Wudaoliang Meteorological Station on the Qinghai-Tibet Plateau over the past 40 yr.

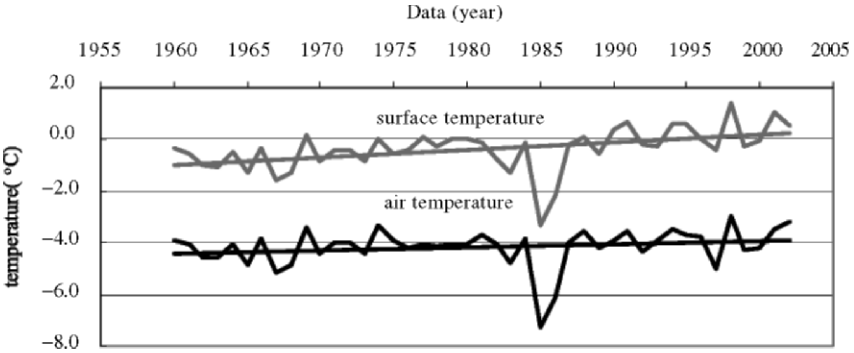

FIGURE 4. MAAT and MAST at the Tuotuohe Riverside Meteorological Station on the Qinghai-Tibet Plateau over the past 40 yr.

The mean annual increase in permafrost table depth is about 3.6 to 8.2 cm yr^{-1} for cold permafrost and about 4.4 to 9.2 cm yr^{-1} for warm permafrost under natural surfaces. The rate of mean annual permafrost surface temperature rise is about 0.06 to 0.10°C yr^{-1} for cold permafrost and about 0.01 to 0.04°C yr^{-1} for warm permafrost. The rate of change in the mean annual permafrost temperature at 6 m depth is about 0.04 to 0.06°C yr^{-1} for cold permafrost and about 0.02 to 0.03°C yr^{-1} for warm permafrost.

The change in warm permafrost is greater than cold permafrost under asphalt surfaces. The rate of the rise in the mean annual permafrost surface temperature is 0.08 to 0.14°C yr^{-1} for warm permafrost and 0.01 to 0.03°C yr^{-1} for cold permafrost. The mean annual increment of the permafrost table is 11 to 31 cm yr^{-1} for warm permafrost and 1 to 4.6 cm yr^{-1} for cold permafrost. The rate of the rise in the mean annual permafrost temperature at 6 m depth is 0.11°C yr^{-1} for warm permafrost and 0.02 to 0.05°C yr^{-1} for cold permafrost.

The response of permafrost to climate change and engineering activity differs significantly. The change of cold permafrost is larger than that of warm permafrost under the effect of climate change and is smaller than that of warm permafrost under the effect of engineering activity. Over time, the impacts of engineering activity on cold permafrost dwarfs that resulted from the climate change.

This research makes an important revelation for considering climate change for engineering construction in cold regions. Warm permafrost under engineered surfaces experiences the combined impacts of climate change and engineering several years after construction. On the other hand, cold permafrost under engineered surfaces would need to wait about 30 to 50 yr to undergo the combined influence of the climate change and engineering activity.

Acknowledgments

This research is funded by the Outstanding Youth Foundation Project, the National Natural Science Foundation of China (Grant No. 40625004) and "973" National Social Development Research Program (2002CB412704), and the Chinese Academy of Sciences "100 Talents" Project "Stability of Linear Engineering Foundations in Warm Permafrost Regions under a Warming Climate." The authors would like to thank Assistant Professor Suzanne Prestrud Anderson, Institute of Arctic and Alpine Research and Department of Geography, University of Colorado at Boulder, for editing our article.

References Cited

Cheng, G. D., 1984: Problems on zonation of altitudinal permafrost. *ACTA Geographic Sinica*, 39(2): 185–193. (In Chinese.)

Cheng, G. D., and Wang, S. L., 1982: On the zonation of altitudinal permafrost in China. *Journal of Glaciology and Geocryology*, 4(2): 1–17. (In Chinese.)

Ding, Y. J., 1998: Recent degradation of permafrost in China and its response to climate warming. *Proceedings of the 7th International Conference on Permafrost, Yellowknife, Canada*. Quebec: Laval University, 225–230.

Guo, D. X., 1985: The effect of geological structure on permafrost. *Geographic Sciences*, 5(2): 98–105. (In Chinese with English abstract.)

Koster, E. A., 1993: Introduction—Present global change and permafrost, within the framework of the International Geosphere-Biosphere Program. *Permafrost and Periglacial Processes*, 4: 95–98.

Nelson, F. E., Lachenbruch, A. H., Woo, M.-K., Koster, E. A., Osterkamp, T. E., Gavrilova, M. K., and Cheng, G. D., 1993: Permafrost and changing climate. *Proceedings of the 6th International Conference on Permafrost*. Wushan, Guangzhou: South China University of Technology Press, Vol. 2, 987–1005.

Li, S. D., 1982: The permafrost temperature and thickness along the Qinghai-Xizang (Tibet) Highway (Abstract). *Proceedings of the Symposium on Glaciology and Geocryology*. Geographical Society of China, Beijing: Science Press, 7–10.

Li, S. X., Cheng, G. D., and Guo, D. X., 1996: The future thermal regime of numerical simulating permafrost on the Qinghai-Tibet Plateau, China under the climate warming. *Science in China (series D)*, 39(4): 434–441.

Tong, C. J., and Wu, Q. B., 1996: The effect of climate warming on the Qinghai-Tibet Highway. *Cold Regions Science and Technology*, 24: 101–106.

Tong, B. L., and Li, S. D., 1982: Some characteristics of permafrost on Qinghai-Tibet Plateau and a few factors affecting them. *Professional Papers on Permafrost Studies of the Qinghai-Tibet Plateau*. Beijing: Beijing Science Press, 1–11. (In Chinese with English abstract.)

Wang, J. C., and Li, S. D., 1983: Analysis of geothermal conditions near the permafrost base along the Qinghai-Tibet Highway. *Professional Papers on Permafrost Studies of the Qinghai-Tibet Plateau*. Beijing: Beijing Science Press, 38–43. (In Chinese with English abstract)

Wang, S. L., and Mi, H. Z., 1993: The change of permafrost under roadbed with asphalt pavement along the Qinghai- Tibet Highway. *Journal of Glaciology and Geocryology*, 15(4): 566–574. (In Chinese with English abstract.)

Wang, S. L., Zhao, X. F., and Guo, D. X., 1996: Response of permafrost to climate change on the Qinghai-Tibet Plateau. *Journal of Glaciology and Geocryology*, 18(Supplement): 157–165. (In Chinese with English abstract.)

Wu, Q. B., and Tong, C. J., 1995: Permafrost change and stability of the Qinghai-Tibet Plateau. *Journal of Glaciology and Geocryology*, 17(4): 350–355. (In Chinese with English abstract.)

Wu, Q. B., Shi, B., and Fan, H. Y., 2003: Engineering geological characteristics and processes of permafrost along the Qinghai-Tibet Highway. *Engineering Geology*, 68(3–4): 387–396.

Wu, Q. B., and Liu, Y. Z., 2004: Ground temperature Monitoring and its recent change in Qinghai-Tibet Plateau. *Cold Regions Sciences and Technology*, 38: 85–92.

Yu, S., Zhang, J. M., Liu, Y. Z., and Wu, J. M., 2002: Thermal regime in the embankment of the Qinghai-Tibet Highway in permafrost regions. *Cold Regions Science and Technology*, 35: 35–44.

Zhang, T., and Stamnes, K., 1998: Impact of climatic factors on the active layer and permafrost at Barrow, Alaska. *Permafrost and Periglacial Processes*, 9: 229–246.

Zhao, X. F., and Wang, S. L., 1996: Recent degradation of permafrost on the Qinghai-Tibet Plateau. *Cryosphere*, 2: 7–13.

Ms accepted June 2007