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EFFECT OF SANDY SEDIMENTS PRODUCED BY THE MECHANICAL CONTROL OF SAND DEPOSITION ON THE THERMAL REGIME OF UNDERLYING PERMAFROST ALONG THE QINGHAI-TIBET RAILWAY

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ABSTRACT

To date, the mechanical control of drifting sand is the main method used for the protection of the Qinghai-Tibet Railway from damage. The thermal effect of sandy sediments which are held in place on the underlying permafrost is a key area of interest and the focus of this paper. A ground temperature investigation of the permafrost along the railway route was undertaken and results were related to the different mechanical control measures used to control moving sand which had resulted in varying sandy sediment thicknesses. The studies were conducted in the Hongliang River area of the Qinghai-Tibet Plateau from June 2010 to September 2010 using thermistor sensors. The results showed that the permafrost ground temperature and its daily variation, as well as the thawing depth of the active layer, decreased after the setting-up of sand movement controls which had resulted in the accumulation of thick sandy sediments within the outside fringe of sand-control engineering, or a covering of thin sandy sediments within the inside trackside (fringe) of sand-control engineering. Below the thick sandy sediment cover accumulated by sand-blocking fences, the average maximum temperature decreased. Average temperature decreased and the average depth of seasonal thawing (average thinning) were 3·38°C, 0·54°C and 0·48 m, respectively. Below the thin sand sediment cover accumulated by the checkerboard sand barriers, the values for the same parameters were 1·02°C, 0·21°C and 0·5 m, respectively. This study found that the mechanical control of sand does not only protect the railway from obstruction, but also facilitates permafrost stability, which in turn can help promote safety in railway operations. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: Qinghai-Tibet Railway; mechanical control of sand; sandy sediments; permafrost; thermal regime; PR China

INTRODUCTION

The Qinghai-Tibet Railway runs from Xining to Lhasa, with a total length of 1956 km. It crosses a large amount of permafrost and many deserts on the highest plateau in the area (Figure 1). After it became operational, however, permafrost protection and the control of blown sand along the railway have become major concerns (Cheng *et al*., 2008; Cheng *et al*., 2009; Cheng *et al*., 2004; Li *et al*., 2009; Niu *et al*., 2008; Sun *et al*., 2005; Wu *et al*., 2007); (Duan, 2001; Liu *et al*., 2007; Liu *et al*., 2010; Yu *et al*., 2001; Zhang *et al*., 2010a; Zhang *et al*., 2010b; Zhang *et al*., 2010c). There are a number of measures for dealing with permafrost problems during construction, those adopted have so far prevented obvious problems. However, the current blown sand damage after the setting-up of the roadbed and its auxiliary buildings are severe. To date, there are 93 sand-damaged sections with a total length of 270·5 km accounting for one-seventh of the total length of the railway. These sections are categorised according to their severity of damage: severe, moderate and slightly damaged sections with corresponding lengths of 43, 55 and 172·5 km, respectively. There are distributed mainly at the Xitie Mountain, Fushaliang, Hongliang River, Tuotuo River, Zhajiazangbu, Cuona Lake, Wulan, Keke, Gahai, Yanqiao, West Grand Beach, Qingshui River, Qumar River, Wudaoliang, Xiushui River and Beilu River districts along the railway. The most damaged sections were located in the first six districts. Depending on the local environmental conditions and the construction materials appropriate and available, 91 sites employed various mechanical engineering measures, with a total length of 84 km, to control sand damage along the railway and to prevent further problems. The Railway crosses a large number of permafrost areas (affecting roughly 550 km of the line), also the environment is sensitive to damage at altitudes over 4500 m above sea-level. At present, there are two differing opinions about the effect of sand cover on ground

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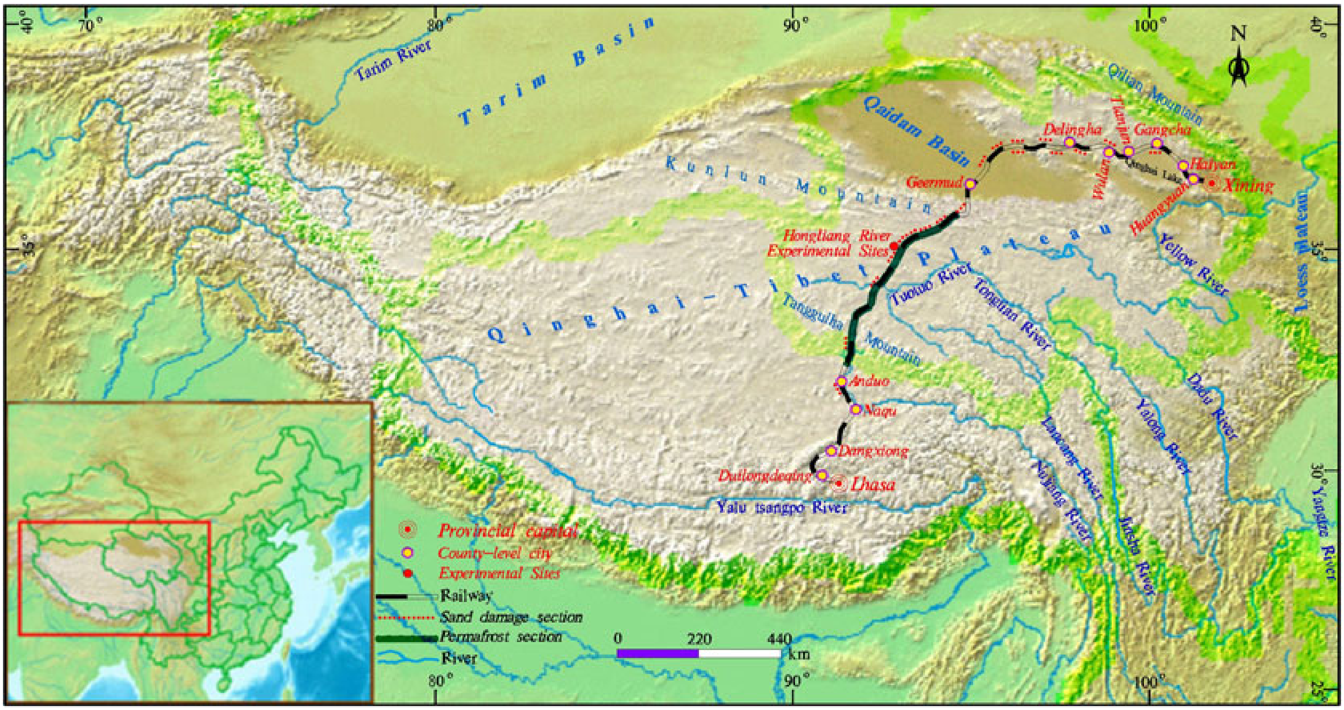

Figure 1. Schematic map of the Qinghai-Tibet Railway. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

temperature. One holds that the ground temperature under blown sand accumulation areas will be higher than that of an area without sand cover, which will then promote permafrost degradation (Huang *et al*., 1993; Qiu, 1982; Yang *et al*., 2004). The other opinion is that the effect of increased sand cover on ground temperature would depend on site specific factors. Although, the ground temperature under thick sand cover will be higher than that in the area with thinner sand, which will then promote permafrost degradation. Conversely, the temperature under thin sand cover should be lower, which will then prevent the permafrost from degradation (Lv *et al*., 2008; Wang and Xie, 1998; Wang *et al*., 2002). A number of studies on this issue have presented contradictory results. Therefore, we examine this topic in this paper in order to provide a clear understanding of the issue.

EXPERIMENTAL SITES AND THEIR DESIGN

The experimental sites are located along the western part of the Qinghai-Tibet Railway and on the northern side of the Hongliang River Bridge near milestone K1103+600, at latitude 35° 03’13"N, longitude 93° 01’07"E and an elevation of 4658 m. The sites lie at a distance of 50–150 m from the railway. They are located at the centre of the Qinghai-Tibet Plateau, which is characterised by permafrost and flat landforms; there is scarce vegetation cover and strong blown-sand activity in this region. All measures of mechanical sand control used are conventional ones such as sand blocking, sand fixation, sand transport and sand diversion (Di and Zhang, 1998). High-vertical sand-blocking fences which are vertically reinforced with cement columns are the main sand-blocking fences used with different ventilation coefficients, and nylon net fences having various porosities as outer sand-blocking measures. Meanwhile, semi-buried checkerboard sand-barriers, which consist of a rocky checkerboard and a nylon net checkerboard served as the sand-fixing

Figure 2. Sand-blocking fences. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Figure 3. Rocky checkerboard sand barrier. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

measures inside fences (Figures 2 and 3). At present, these comprise the main measures adopted for large-scale mechanical engineering activities along the Qinghai-Tibet Railway (Niu *et al*., 2009). In comparison, some sand transport and sand-diversion measures such as a wind guide on the leeward and the use of shallow grooves and 'feather' rows are seldom used because of their disadvantages. The ground temperature under a sand-blocking fences accumulating thick sandy sediments, the checkerboard sand barrier with thin sandy sediments and the natural surface without sandy sediments was examined in this study.

In our experimental sites, there are three ground temperature holes (lined with pipes) installed each of: an established sand-blocking fences, a checkerboard sand barrier and a natural surface (Figure 4). Each ground temperature hole was covered after installation with 120, 8 and 0 cm-thickness of sand or other local sediment, respectively. The holes are 0·12 m wide and 20 m deep; the distance between each hole is within the range of 50–100 m. The soil texture of each hole was found to be similar with slight variation in soil water content and soil density (Figure 5, Table I). Thirty temperature sensors are installed in each pipe/hole with an interval of 0·5 m in the upper 10 m, 1 m at the depth of 10 to 20 m and 0·1 m in the topmost 1·0 m (Figure 6). To allow recovery of the natural thermo-regime of sites, the observations started 60 days after the holes were completed.

MATERIALS AND METHODS

The temperature sensors used were made by the State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences. They have a sensitivity of 0·01°C and an observational range of −40°C to 60°C. To prevent water seepage, the probes were fixed into 32 mm closed aluminum/plastic shrouds, which were inserted vertically into the holes/pipes. The circular space between the shroud and the hole was then backfilled with dry, fine sand. Observational data were collected automatically using CR3000® (Campbell Scientific, Inc., Logan, UT, USA).

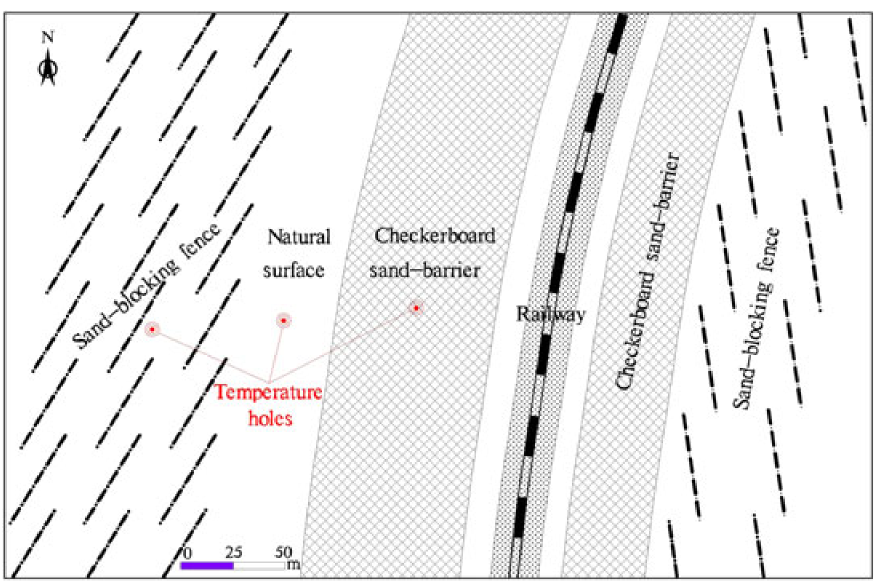

Figure 4. Relationships between temperature holes and measures for blown sand control in the Hongliang River district section of the Qinghai-Tibet Railway. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

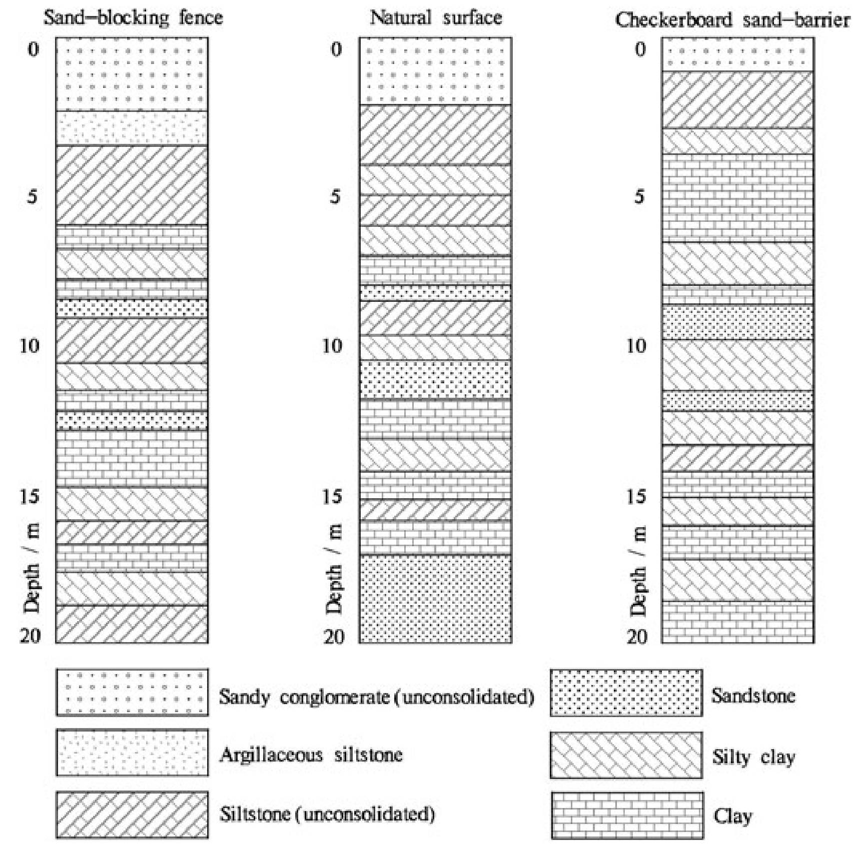

Figure 5. Soil texture of ground temperature holes in the Hongliang River district.

OBSERVATIONAL RESULTS

Analysis was made on the difference between the permafrost thermo-regime covered with various thicknesses of sandy sediments and the natural surface from June 2010 to September 2010, which is considered a thawing season. Three indices were then compared.

Average Temperature

Figure 7 shows that the ground temperature of the permafrost with a negative gradient in the Hongliang River section decreased gradually along with an increase in depth.

The ground temperature within 20m depth from the surface with a sand sediment thickness of 120cm under the sand-blocking fences was lower than that of the natural surface. The average temperature decrease was 0·55°C, 0·67°C, 0·54°C and 0·39°C in June 2010, July 2010, August 2010 and September 2010, respectively. The maximum temperature decrease occurred near the ground surface, and the values were 3·72°C, 4·85°C, 3·16°C and 1·88°C, respectively, for the same months. The decrease in ground temperature became less pronounced once the accumulated surface sediment exceeded 4.0m in thickness.

Compared with the natural surface, the ground temperature at the permafrost table beneath a checkerboard sand-barrier (with 8-cm-thick accumulation of sandy sediments) decreased at 1·10°C, 1·41°C, 1·46°C and 1·12°C, respectively, during the same observation months. However, the decrease near the surface and below 8m was not distinct. The average decrease at 20m was 0·17°C, 0·24°C, 0·22°C and 0·19°C, respectively, during the same observation months.

In the active layer with a depth of 0 to 2·0m and in permafrost deeper than 5·5m, the temperature decrease caused by sand-blocking fences with thick sandy sediments was much higher than that of the checkerboard sand-barrier with thin sandy sediments, the difference of temperature decrease in other layers was not distinct. The average temperature decrease of sand-blocking fences with thick sandy sediments was higher than that the checkerboard sand-barriers that accumulated thin sandy sediments (being 0·38°C, 0·43°C, 0·32°C and 0·20°C within 20m of the surface-measured in the months of June 2010 to September 2010, respectively).

Thawing Depth

The observational data shown in Figure 8 show that from June 2010 to September 2010, the thawing depths beneath natural surfaces (i.e. without any sand control measures) were 2·0, 2·5, 3·0 and 0·3m, respectively; those beneath the

Table I. Soil water content and density of ground temperature holes below the sand layer in the Hongliang River district

	Under 120cm sandy sediment coverage		Without drifting sand cover		Under 8cm sandy sediment coverage	
Depth/m	Water content/%	Density/gcm^{-3}	Water content/%	Density/gcm^{-3}	Water content/%	Density/gcm^{-3}
0	7·56	1·70	7·77	1·79	11·10	1·83
0·5	5·20	1·64	5·96	1·59	9·97	1·75
1	3·22	1·49	5·83	1·28	11·07	1·25
1·5	4·57	1·22	5·85	1·33	13·97	1·39
2	4·21	1·78	6·47	1·58	14·82	1·56
2·5	6·06	2·01	10·27	1·91	15·48	1·80
3	13·29	1·75	9·93	1·94	16·64	1·80
3·5	13·43	1·83	14·39	1·90	15·20	1·50
4	18·17	1·52	17·71	1·39	17·58	1·72
4·5	16·52	1·57	15·31	1·55	15·75	1·62
5	17·00	1·51	15·58	1·46	16·73	1·28
5·5	15·34	1·47	14·65	1·77	16·77	1·55
6	15·16	1·61	14·87	1·77	15·03	1·56
6·5	15·51	1·20	14·90	1·60	13·49	1·43
7	15·38	1·21	14·79	1·38	13·97	1·65
7·5	13·65	1·42	12·97	1·54	14·68	1·73
8	12·60	1·52	12·08	1·38	14·63	1·59
8·5	13·92	1·72	12·41	2·07	12·92	1·58
9	12·27	2·05	13·43	1·65	11·54	2·01
9·5	13·51	1·66	13·54	1·86	13·96	1·99
10	13·57	1·90	12·57	1·93	12·92	2·04
11	12·59	1·69	13·83	1·72	11·72	1·81
12	14·24	1·80	13·62	1·95	12·14	2·02
13	17·81	1·99	17·68	1·69	16·78	1·65
14	15·36	1·77	14·91	1·64	14·46	1·74
15	13·57	1·64	11·65	2·00	12·13	2·17
16	14·61	1·57	14·17	1·70	13·52	1·90
17	14·99	1·47	13·97	1·70	15·67	2·04
18	14·18	1·52	14·64	1·72	13·13	2·06
19	14·79	1·87	14·15	1·72	15·02	1·63
20	16·16	1·89	15·45	1·97	15·06	1·99

checkerboard sand-barriers with thin sandy sediments were 1·5, 2, 2·4 and 2·6m, respectively; and those at the sand-blocking fences with thick sandy sediments were 1·0, 1·9, 2·7 and 2·8m, respectively. Therefore, the thawing depth under the sand-blocking fences with thick sandy sediments decreased by 1·0, 0·4, 0·3 and 0·2m, respectively and that under the checkerboard sand-barriers with thin sandy sediments decreased by 0·5, 0·5, 0·6 and 0·4m, respectively, during the observational months.

Diurnal Variation of Ground Temperature

The data collected at a depth of 0·1m in July 2010 and August 2010 show that the minimum ground temperature occurred at 8:00am and the maximum at 18:00pm with an average daily range of 6·18°C and 5·78°C, respectively, under the natural surface. On-the-other-hand, the minimum and maximum ground temperature occurred at 12:00a.m. and 24:00p.m., respectively, with a corresponding average daily range of 1·71°C and 1·76°C, under the thin sandy sediment produced by checkerboard sand-barriers. The thicker the sandy sediment above the hole, the smaller the amplitude of the diurnal ground temperature variation, which can be described by a negative correlation. There was nearly no diurnal variation in ground temperature under the thick sandy sediment produced by the sand-blocking fences (Figure 9).

In general, the amplitude of diurnal ground temperature variation decreased with the depth from the surface. The maximum amplitude of diurnal ground temperature variation occurred at the natural site, followed by the site with thin sandy sediments produced by a checkerboard sand-barriers and finally, the site with thick sandy sediments produced by the sand-blocking fences. There was no obvious diurnal variation in ground temperature at the site with thick sandy sediments beneath the surface produced by the sand-blocking fences (Figures 10, 11 and 12).

ANALYSES AND DISCUSSION

Based on the data collected by the Qinghai-Tibet Plateau Research Base, State Key Laboratory of Frozen Soil Engineering,

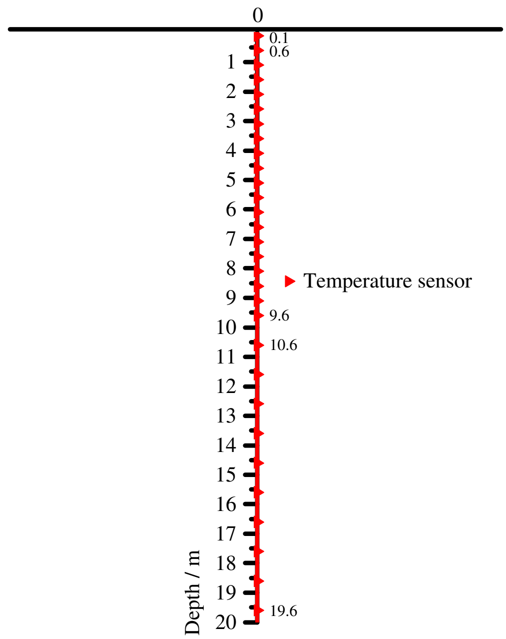

Figure 6. Position of temperature sensors. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, the mean annual ground temperature of the permafrost at the Hongliang River site (at a depth of 15 m) was less than −0·5°C, so the permafrost was relatively stable. Permafrost degradation occurred mainly in the thawing season, with the thawing processes occurring rapidly from early June to early September (Zhou *et al*., 2000), which is beneficial in the investigation of the permafrost thermal regime covered with different thicknesses of sandy sediments.

For the Qinghai-Tibet Railway sand prevention system, the main methods used were sand blocking and sand fixation. However, wind-blown sand disasters occur frequently, and so sand accumulates continuously because of sand blocking and sand fixation. This means that sand is always moving and accumulating gradually on areas within 100–200 m of the railway after the establishment of sand-blocking fences and checkerboard sand-barriers. The reflectivity of the sandy surface to solar radiation ranges from 0·25 to 0·4, whereas that of the ordinary, bare surface ranges from 0·1 to 0·25. The net surface radiation of the sandy surface is much less than that of the natural surface. As a result, a large amount of heat in the sandy sediment dissipates to the atmosphere by ground long-wave radiation and through massive changes in the earth-atmosphere system. The heat conducted by the sensible heat of the soil beneath the sandy sediment decreases, which makes the ground temperature below the sandy cover become lower than that of the natural surface. Meanwhile, the thawing depth decreases, and the freezing depth increases. These findings can be verified by the contrasting observation results of Yingqin Xie *et al*. on the ground surface heat balance in the two fields in the Qinghai-Tibet Plateau. The incoming heat in the sand-covered field was slightly lower than that in the original field. Soil heat exchange accounted for 2·7 per cent of the total outgoing heat in the sand-covered field and 5·6 per cent of that in the original field. Therefore, soil heat exchange is favourable to the increase in ground temperature during summer. In addition, the results on incoming heat and heat conduction to the earth in the sand-covered field were always lower than those in the original field. Therefore, the ground temperature in the sand-covered field was lower than that in the original field, and the maximum seasonal thawing depth decreases (Xie *et al*., 1995).

The thermal conductivity and thermal diffusivity of dry sand are 0·1524 W/m°C and 0·0013 $cm^2 s^{-1}$, respectively, whereas those of natural soil are 0·188 W/m°C and 0·007 $cm^2 s^{-1}$, respectively. Therefore, the 1·2-m-thick sand sediment in the sand-blocking fences at the temperature measurement hole with little water content is identical to dry sand in terms of poor thermal conductivity and good ventilation (Oke, 1978), which prevent underground heat transmission strongly. This is the reason for the significantly lower ground temperature within the sand-blocking fences covered with thick sandy sediments compared with that of the natural surface. As a result, the thawing depth decreased from June to September, and the temperature decreased along with an increase in depth. These results were very similar to the observation results of Shaoling Wang *et al*. on the Qumar River, Qinghai-Tibet Plateau (Wang and Zhao, 1999). Compared with that of the thick sandy sediment held by the sand-blocking fences, the heat transmission from a nearby natural surface is easier (because the 0·08-m-thick sandy sediment and has lower thermal resistance at the temperature measurement hole within the checkerboard sand-barrier). Therefore, the difference between the ground temperature for a surface within the checkerboard sand-barriers and at the natural surface was not distinct. Except for the boundary layer, the permafrost table, which has less effect of heat transmission from both surface and underground, the temperature decrease was obvious at the thin sandy sediment within the checkerboard sand-barriers. In contrast, the temperature difference at the depth, above or below the permafrost table, was not obvious.

The diurnal variation in ground temperature depends mainly on solar radiation. During daytime, the ground surface temperature increases because of absorption of solar radiation energy and heat transmission from the surface to underground. During night-time, the surface ground temperature decreases because of radiation cooling, which is the opposite of the phenomenon that occurs

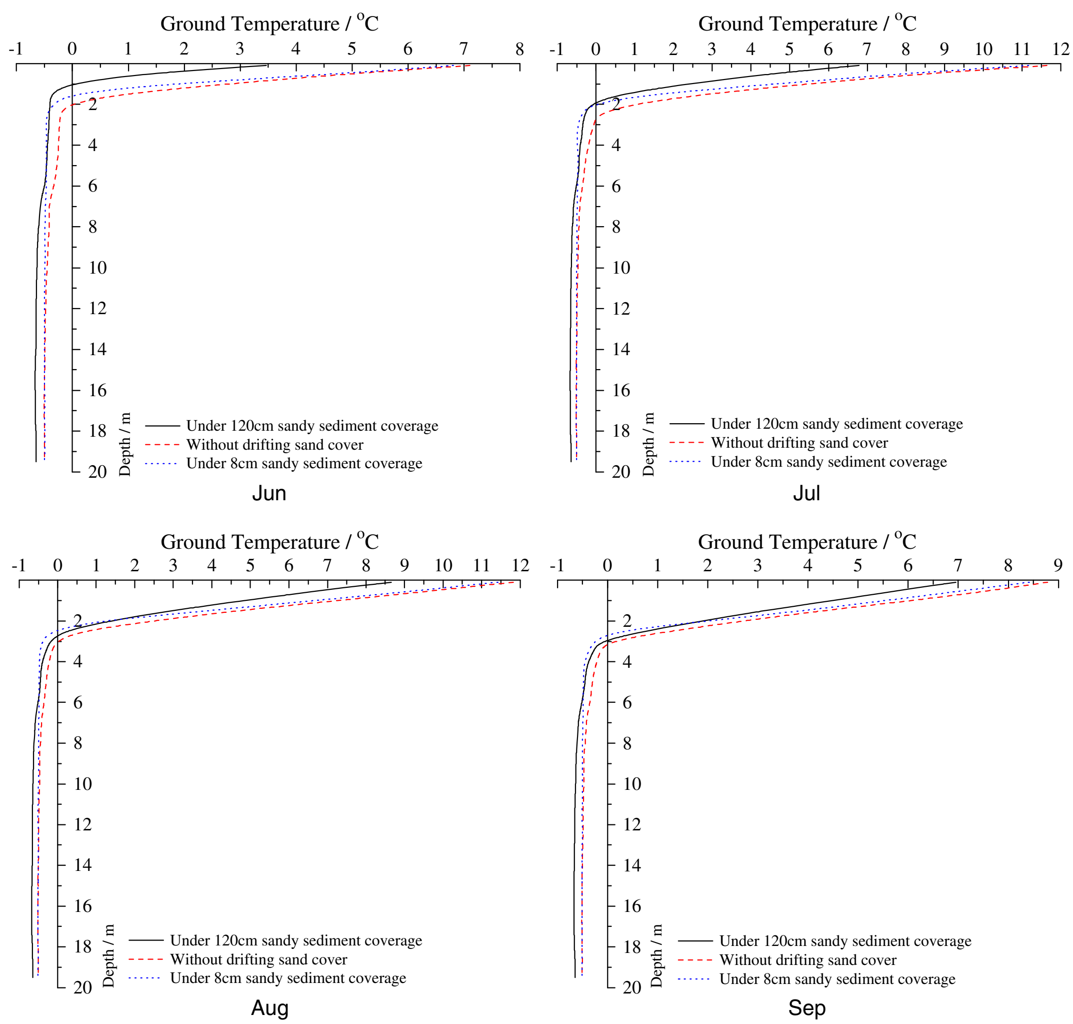

Figure 7. Average temperature curves of the permafrost in the Hongliang River district (June 2010–September 2010). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

during daytime. Because of the diurnal variation in solar radiation, the air temperature also has a diurnal variation. At noon time, solar radiation is strongest, and the solar altitude angle is the largest. However, time is needed for absorbing and storing the solar radiation energy and then transmitting this energy toward the atmosphere and downward to soils and rocks. Therefore, the moment the extreme value of air and ground temperature appears lags behind the moment, the strongest solar radiation occurs. The atmospheric thermal diffusivity is near 0·161 $cm^2 s^{-1}$, which is much higher than that of natural soil (0·007 $cm^2 s^{-1}$) and sand (0·0013 $cm^2 s^{-1}$) (Zhou *et al*., 1997), so the speed of solar radiation energy transmission from the surface upward to the atmosphere is much faster than that from the surface downward in to the soil and rocks. As a result, there is a time lag of the maximum ground temperature at different depths behind the moment of maximum air temperature. The greater the thickness of the sand sediment on the surface, the greater is the resistance of heat transfer down to the soil, which leads to a decrease in the diurnal variation amplitude of ground temperature as the sand sediment thickens on the surface. Within a cycle of solar radiation, the diurnal variation in ground temperature appears mainly at depths from 0 to 0·5 m (Tang, 1989). The diurnal variation beneath 0·5 m was not obvious regardless of covering with sandy sediments on the surface. Therefore, there was almost no diurnal variation in ground temperature with the use of a sand-blocking fences with 1·2-m-thick sandy sediments.

The maintenance of permafrost stability is a major challenge in the safe operation of the Qinghai-Tibet Railway. The environmental effects of blown sand and the control measures for blown sand damage have become key problems in recent years. Our preliminary observational results for the warm season (from June 2010 to September 2010) show that the

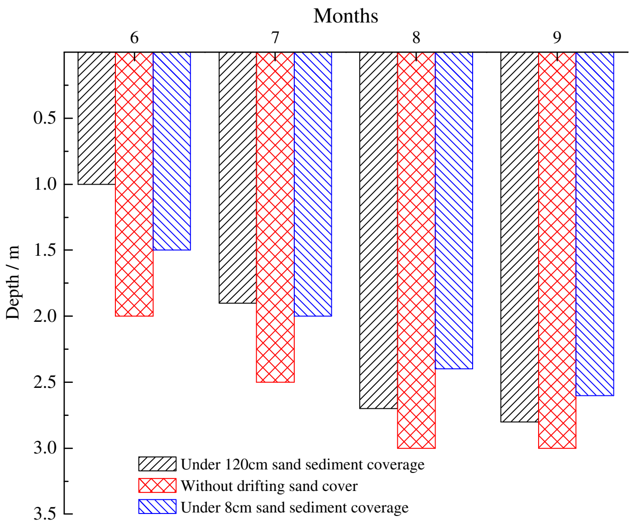

Figure 8. Thawing depth of the permafrost in the Hongliang River district (June 2010–September, 2010). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

measures adopted for controlling blown sand can control sand damage and ensure permafrost stability by preventing permafrost degradation.

CONCLUSIONS

Our preliminary results indicate that the ground temperature under both sand-blocking fences and checkerboard sand-barriers was lower than that of the natural surface, which resulted in the decrease in seasonal thawing depth, thickening of the freezing layer and protection of the permafrost instead of degradation.

The change in the thermal regime can be attributed mainly to differences in reflectivity, thermal conductivity and thermal diffusivity for various materials. Because of the high reflectivity and poor thermal conductivity of sandy sediments, and the thicker sand cover, less heat is transferred to the underground. Therefore, our preliminary conclusion is that sand cover on the ground surface protects the permafrost

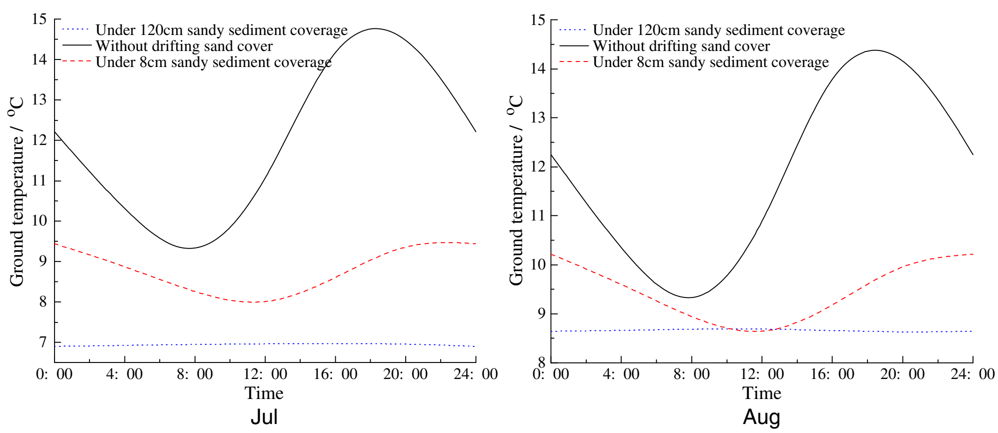

Figure 9. Average diurnal variation in ground temperature at the depth of 0·1 m in the Hongliang River district (July 2010 and August 2010). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

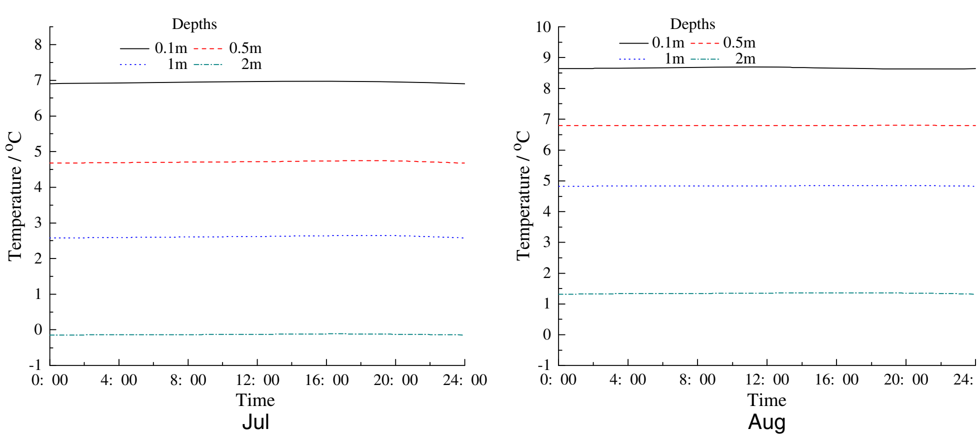

Figure 10. Average diurnal variation in temperature at different depths under the sand-blocking fences in the Hongliang River district (July 2010 and August 2010). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

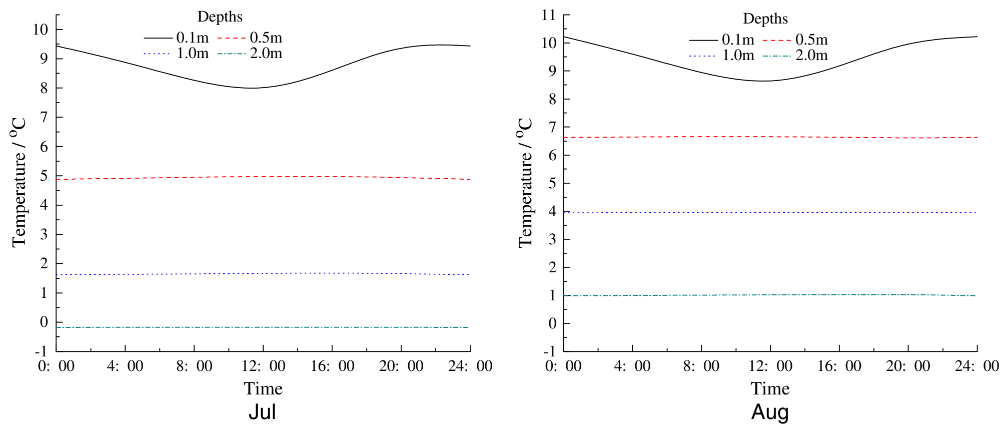

Figure 11. Average diurnal variation in temperature at different depths under the checkerboard sand barrier in the Hongliang River district (July 2010 and August 2010). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

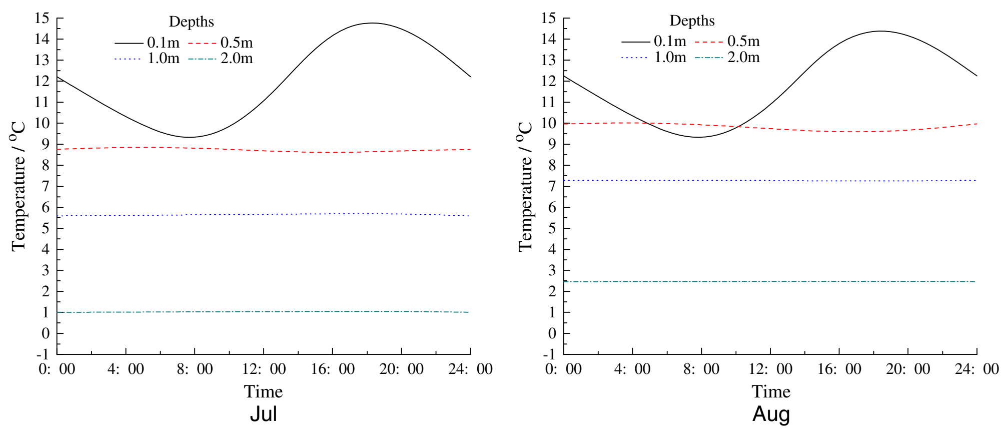

Figure 12. Average diurnal variation in temperature at different depths under the natural surface in the Hongliang River district (July 2010 and August 2010). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

environment in the Qinghai-Tibet Plateau, perhaps even if the global climate eventually becomes warmer in the future. Sand cover can be used for the protection of the permafrost environment and foundation stabilisation without major ill-effects like static surcharge or dynamic pressure.

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REFERENCES

Cheng GD, Sun ZZ, Niu FJ. 2008. Application of the roadbed cooling approach in Qinghai–Tibet Railway engineering. *Cold Regions Science and Technology* **53**: 241–258.

Cheng GD, Wu QB, Ma W. 2009. Innovative designs of permafrost roadbed for the Qinghai-Tibet Railway. *Science in China Series E: Technological Sciences* **52**: 530–538.

Cheng GD, Zhang JM, Sheng Y, Chen J. 2004. Principle of thermal insulation for permafrost protection. *Cold Regions Science and Technology* **40**: 71–79.

Di YQ, Zhang KZ. 1998. *Railway Sand Damage and Its Control in China*. China environment science press, Beijing, p. 148–153 (in Chinese).

Duan QL. 2001. The formation mechanism and treatment measure of the motive sand-flood of Cuona lake on Qingzang Railway. *Geotechnical Engineering Technique* **6**: 311–314 (in Chinese with English abstract).

Huang YZ, Guo DX, Zhao XF. 1993. The desertification in the permafrost region of Qinghai-Xizang Plateau and its influences on environment. *Journal of Glaciology and Geocryology* **15**: 52–57 (in Chinese with English abstract).

Li GY, Mu YH, Zhang X. 2009. Thermal characteristics of the embankment with crushed rock side slope to mitigate thaw settlement hazards of the Qinghai-Tibet Railway. *Acta Geologica Sinica-English Edition* **83**: 1000–1007.

Liu L, Liu SH, Xu ZY. 2007. Efficiency of wind erosion control measures at the Dk1562 section of the Qinghai-Tibet Railway. *Principles and practices of desertification control* **1**: 223–229.

Liu SH, Feng LZ, Xu ZY. 2010. Study on effect of wind erosion controlling in the Geermu-Lhasa Section of the Qinghai-Tibet Railway. *Journal of the China Railway Society* **32**: 133–136 (in Chinese with English abstract).

Lv LZ, Jin HJ, Wang SL, Xue X, He RX, Yu SP. 2008. Dual influences of local environmental variables on ground temperatures on the interior-Eastern Qinghai-Tibet Plateau (II): Sand-layer and surface water bodies. *Journal of Glaciology and Geocryology* **30**: 546–554 (in Chinese with English abstract).

Niu FJ, Xu J, Lin ZJ, Wu QH, Cheng GD. 2008. Permafrost characteristics of the Qinghai-Tibet Plateau and methods of roadbed construction of railway. *Acta Geologica Sinica-English Edition* **82**: 949–958.

Niu QH, Qu JJ, Zhang KC, Han QJ, Ma R. 2009. Status of aeolian-sand disaster and estimation of mechanical sand-controlling benefit at typical sections of Qinghai-Tibet Railway. *Journal of Desert Research* **29**: 596–603 (in Chinese with English abstract).

Oke TR. 1978. *Boundary Layer Climates*. Wiley and Sons, New York, NY; 43–49.

Qiu GQ. 1982. *Distributive features and formation conditions of taliks and permafrost in the Tuotuohe River Basin on the Qinghai-Tibet Plateau*. Proceedings of the Chinese Conference on Glaciology and Geocryology (Geocryology Volume). Science Press, Beijing; 19–26 (in Chinese).

Sun BX, Xu XZ, Lai YM, Wang SJ, Zhang JZ. 2005. Mechanism of evolution on winter-time natural convection cooling effect of fractured-rock embankment in permafrost regions. *Chinese Science Bulletin* **50**: 2744–2754.

Tang MC. 1989. *Generality of Theory Climatology*. Meteorology Press, Beijing, p. 241–242 (in Chinese).

Wang SL, Xie YQ. 1998. Study on the ground temperature of sandy area in the Qinghai-Xizang Plateau. *Journal of Desert Research* **18**: 137–142 (in Chinese with English abstract).

Wang SL, Zhao L, Li SX. 2002. Interaction between permafrost and desertification on the Qinghai-Tibet Plateau. *Journal of Desert Research* **22**: 33–39 (in Chinese with English abstract).

Wang SL, Zhao XM. 1999. Analysis of the ground temperatures monitored in permafrost regions on the Tibetan Plateau. *Journal of Glaciology and Geocryology* **21**: 351–356.

Wu QB, Cheng HB, Jiang GL, Liu MW, Zhi Y. 2007. Cooling mechanism of embankment with block stone interlayer in Qinghai-Tibet Railway. *Science in China Series E: Technological Sciences* **50**: 319–328.

Xie YQ, Wang HM, Li G. 1995. *The interaction between desertification and permafrost in the Tibetan Plateau according to surface heat balance*. Annual Report of the Comprehensive Observatory and Research Station on the Qinghai-Tibet Plateau, Chinese Academy of Sciences, vol. 3. Lanzhou University Press, Lanzhou; 56–62 (in Chinese).

Yang MX, Wang SL, Yao TD, Guo XH, Lu AX, Guo XJ. 2004. Desertification and its relationship with permafrost degradation in Qinghai-Xizang(Tibet)Plateau. *Cold Regions Science and Technology* **39**: 47–53.

Yu YJ, Shi PJ, Lu CX. 2001. Research on characteristics of wind-sand fluid and sand disaster reduction at Kecheng(K454~458) section along Qing-Zang Railway. *Journal of Natural Disasters* **10**: 30–36 (in Chinese with English abstract).

Zhang KC, Niu QH, Qu JJ, Yao ZY, Han QJ. 2010a. Wind-blown Hazard and its Dynamic Environment in Tuotuohe Region along Qinghai-Tibet Railway. *Journal of Desert Research* **30**: 1006–1011 (in Chinese with English abstract).

Zhang KC, Qu JJ, Liao KT, Niu QH, Han QJ. 2010b. Damage by wind-blown sand and its control along Qinghai-Tibet Railway in China. *Aeolian Research* **1**: 143–146.

Zhang KC, Qu JJ, Niu QH, Zhang WM, Han QJ. 2010c. Simulative research on the mechanism of rocky checkerboard sand barriers along Qinghai-Tibet Railway in wind tunnel. *Advances in Earth Science* **25**: 284–289 (in Chinese with English abstract).

Zhou SZ, Zhang R.Y, Zhang C. 1997. *Meteorology and Climatology*. Higher Education Press, Beijing, p. 190–193 (in Chinese).

Zhou YW, Qiu GQ, Guo DX, Cheng G.D, Li SD. 2000. *Geocryology in China*. Science Press, Beijing; 65–73 (in Chinese).

