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GEODESY AND GEODYNAMICS 2016, VOL 7 NO 2, 143–147

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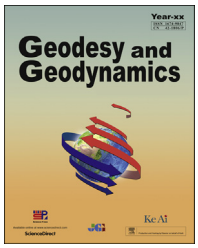

Analysis of railway subgrade frost heave deformation based on GPS

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ARTICLE INFO

Article history:
Received 16 January 2016
Accepted 15 February 2016
Available online 20 April 2016

Keywords:
GPS
Railway subgrade
Frost heave
Permafrost
Deformation monitoring

ABSTRACT

In order to analyze the connection between the railway subgrade frost heave deformation and temperature variation, five GPS stations' data were used to monitor the deformation on a certain section of railway subgrade in northeast China. GAMIT software is used to process the data, providing daily solution, daytime solution and nighttime solution. Vertical trends of these five stations were analyzed to investigate frost heave effect on railway subgrade deformation. The results show that the temperature difference between daytime and night induces stations, significant vertical displacement, and the temperature difference between seasons causes settlement of station which appears linear trend.

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How to cite this article: Ma F, et al., Analysis of railway subgrade frost heave deformation based on GPS, Geodesy and Geodynamics (2016), 7, 143–147, http://dx.doi.org/10.1016/j.geog.2016.04.001.

1. Introduction

With the development of high-speed railway industry, deformation of railway subgrade caused by frost heaving happens frequently in the high-latitude area in China. The major cause for the railway subgrade frost heave deformation is the freeze-thaw action of the permafrost. Due to the influence of the climate and the geographical condition in the northeast China region, the permafrost along the railway is the biggest obstacle to the normal operation of high-speed railway [1–3]. Using GPS technology to monitor the sedimentation of railway subgrade and to realize continuous observation of the real time data can obtain a global understanding of the changes of railway subgrade at different stages, in order to better master the operation status of the railway subgrade and guarantee route security [4–6]. Therefore, using GPS technology to get the deformation information of railway subgrade in the permafrost area is significant.

Zhang et al. [7] establishes a multi-antenna system with one GPS receiver, realizing the long-distance auto-

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Peer review under responsibility of Institute of Seismology, China Earthquake Administration.

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http://dx.doi.org/10.1016/j.geog.2016.04.001
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monitoring of the sedimentation of railway subgrade frost heaving. In this paper, Kalman filtering is also used to achieve the positioning accuracy of 2 mm–3 mm, proving that GPS technology is capable of monitoring railway subgrade. Xi et al. [8] develops a monitoring platform to detect the deformation of the short baseline in the Plough system, concluding that calculation of the deformation based on 4-h observation best reflects the actual deformation of the monitoring point, which can satisfy the need for highly precise monitoring of different engineering works and geological disaster. So, in this paper, 12-h observation can ensure the accuracy. Hu et al. [9] adopts GPS positioning technique to detect the landslide mass in the permafrost area and analyzes the features of landslide mass at different places. Yang et al. [10] develops an intelligent monitoring system, which can realize long-term monitoring of the strain permafrost status along with temperature changes. The paper also analyzes the changes of permafrost subgrade due to the factors of temperature and depth. Different GPS stations' foundation bed have different temperatures and geological conditions, so GPS stations in this paper are in the same depth to ensure the more conditions for consistency. Ma et al. [11] makes an analysis of the railway subgrade in permafrost region of Qinghai–Tibet railway, discovering that all the subgrade deformation mainly takes the form of sedimentation, and the amount of deformation is closely related to the changes of its underlying geothermal field. The paper explains the relation between the temperature and subgrade deformation in detail. In permafrost region, there is a sizable order of railway subgrade frost heave deformation, which deserves sufficient attention in engineering practice. Especially in the Qinghai–Tibet Plateau and northeast China, there are some monitoring systems, which can succeed monitor the deformation. However, the research about frost heave deformation hasn't involved the deformation changes of a day. The paper establishes a data collection platform to monitor the railway subgrade frost heave deformation in Heilongjiang Province based on GPS and exploits high-precision GPS positioning monitoring software to do data processing. The paper also analyzes the connection between the monitoring effect of GPS system and temperature variation in northeast China region.

2. Data collection and data processing

2.1. *Data collection platform*

In order to carry out data quality and accuracy assessment of the railway subgrade deformation in high-latitude area in China, this study established five GPS stations on one section of the high-speed train railway in Heilongjiang Province. The five GPS stations formed a deformation monitoring net with the spacing distance ranging from 4.448 m to 237.404 m (The distribution of the stations is shown in Fig. 1). All five stations adopted TRIMBLE NETR9 receiver and CHOKE RING antenna (TRM59900.00). The antenna was fixed on the forced centering foundation bed, which is installed on a horizontal observation pillar. The data were collected from January 1st, 2015 to April 1st, 2015 (111 days in total) with 24-h uninterrupted observation and 15 s sampling interval.

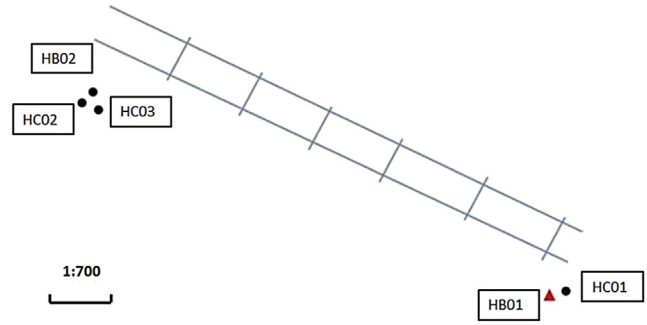

Fig. 1 – Experimental tracking stations.

2.2. *Data processing*

Based on the short baseline of deformation monitoring and the need for high accuracy, this paper refines GPS baseline solution model and unites the eight International GNSS Service (IGS) stations to do unified calculation by GAMIT software. The main models and the strategies of baseline processing are shown in Table 1.

Ambiguity resolution is a key issue in the high-precision GNSS deformation monitoring. In this software, ambiguity resolution followed a sequential strategy:

a) An independent set of double-difference phase biases are selected according to the baseline length.
b) For each baseline, the satellite with the most observations is selected as reference satellite and forms the DD ambiguities.
c) Form and solve the normal equation to obtain the float solution.
d) All the float ambiguities are sorted by the probability of being fixed to integers and those ambiguities with highest probability are firstly fixed to integers.

Table 1 – Strategies of baselines processing.

Item	Models & constraints
Observation session	24 h
Elevation angle cut-off	15°
Ephemeris	Broadcast ephemeris
Observations	Original L1 carrier phase observations are utilized to estimate all parameters L2 observations are only used for detecting cycle slips
Ionospheric delay correction	Double-difference (DD) model
Tropospheric delay correction	Saastamoinen model and the piecewise linear method is adopted to estimate the residual of troposphere delay effect
Solid Earth tides & ocean tide	IERS2010
Parameter estimation	Network-solution
Integer ambiguity estimation	Decision function + Bootstrap

e) Fix all the fixed ambiguities in d) and update the normal equation, repeat c)–e) until no more ambiguities could be fixed any more.

A searching criterion based on minimizing the estimated weighted sum of residuals squared ("chi squared") is employed for searching the remaining float ambiguities.

3. Analysis of the results

The research purpose of this study is to observe the deformation condition of the stations, i.e. the relative running tendency, instead of focusing on the absolute coordinate of the stations. Therefore, the initial coordinate does not affect the accuracy of this study. Considering the influence of the temperature difference of day and night, there are three output time frame solutions: day solution (00:00 – 24:00), daytime solution (6:00 – 18:00), and nighttime solution (18:00 to the next 6:00). The three time series subtracted mean value and obtained residual series on east (E), north (N), and up (U) coordinates respectively, among which the movement conditions of the stations in direction U is the strongest. Due to space limitations, the present paper only focuses on the movement in the vertical direction, analyzing the influence of temperature difference between day and night and among the seasons on railway subgrade frost heave deformation.

There are two signals in deformation monitoring time series: trend term and periodic term. The following analysis focuses on deformation signals and the conditions of high-speed railway subgrade frost heave. The day, daytime, and night vertical residual series of the five stations are shown in Fig. 2. It can be seen that all the residual series fluctuate around zero and all the three solutions are consistent with each other. However, due to the influence of temperature difference between day and night and among the seasons, the time series of the three solutions are slightly different from each other. In general, all the five stations have non-ignorable movement trends on vertical direction, with a fluctuation range between −15 mm to 15 mm.

In order to make a comprehensive analysis of temperature influence on railway subgrade frost heave, this paper analyzes the meteorological data of the four months mentioned above, which is shown in Fig. 3. In this figure, the red line represents high temperature sequence, and the blue line represents low temperature sequence. There is a rising trend in temperature from DOY 001 to 112. During DOY 001 to 042, the lowest temperature reaches to 30 °C below zero. While

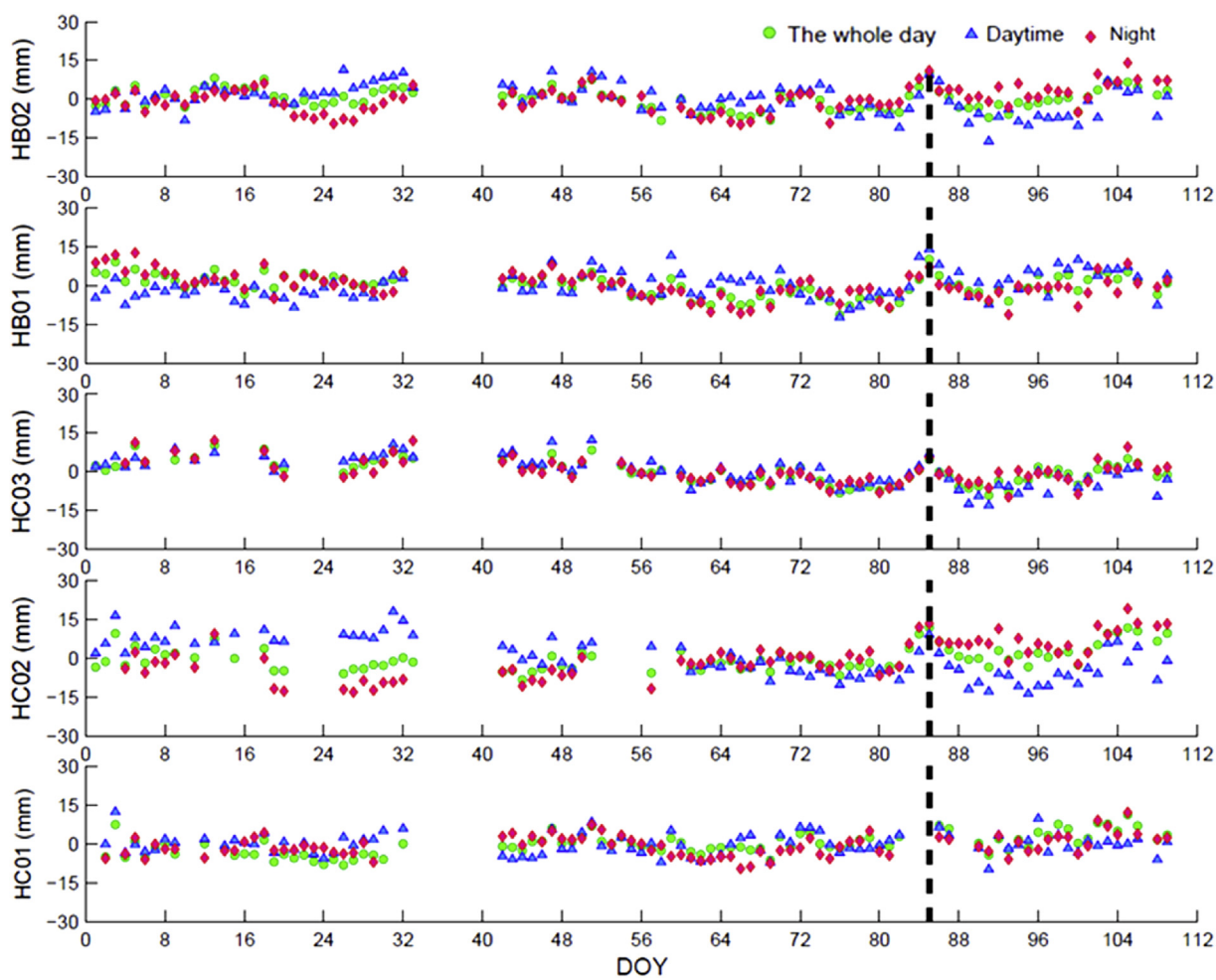

Fig. 2 – The vertical residual series of the whole day (0:00–24:00), daytime (8:00–20:00), and night (20:00-the next 8:00).

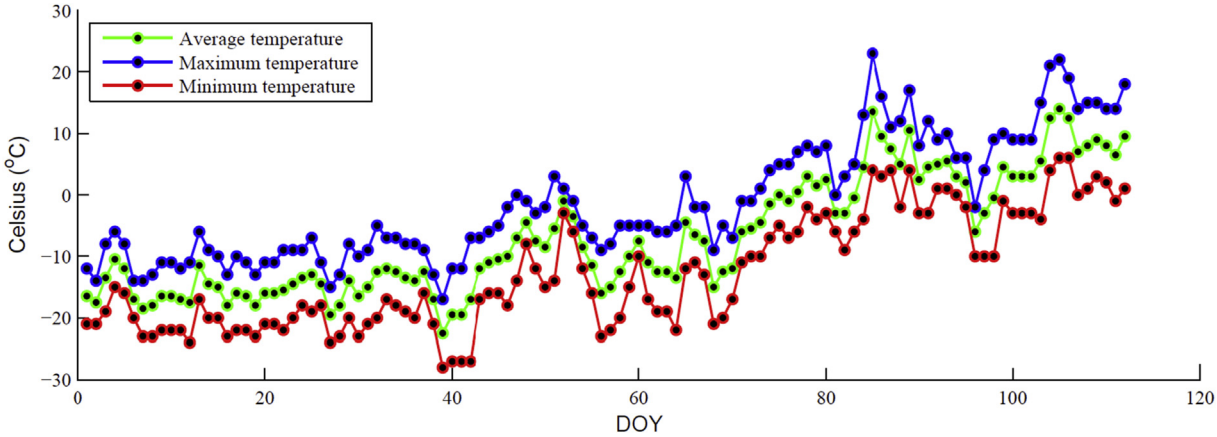

Fig. 3 – The local temperature time series from Jan/2015 to Apr/2015.

during DOY 085 to 104, the highest temperature reaches to 30 °C above zero. There is a drastic temperature change as well as a periodic temperature change every day.

There are many factors affecting railway subgrade sedimentation, including natural setting, the effect of the earth's surface heat expansion and cold contraction, and frost heave effect of permafrost. Based on relevant literature, the study concludes that there is a periodic change in the sedimentation of the stations due to the influence of temperature. When a whole day's temperature is below 0 °C, as the tundra deepens, the frost heave increases, but the range decreases. The earth's surface heat expansion and cold contraction usually happens during the daytime, especially in sunny days. When the temperature during the daytime is above 0 °C and the temperature during the nighttime is below 0 °C, the tundra no longer deepens, and the earth surface melts during the daytime and freezes during the nighttime. Thus, the effect of heat expansion and cold contraction is more obvious during the daytime. When the whole day's temperature is above 0 °C, the tundra continuously melts, and the frost heave effect falls.

Both Figs. 2 and 3 show that due to the influence of temperature difference between day and night and among the seasons, the five stations show significant movement trends to induce enough deformation of railway subgrade. Station HC01 has a stable movement trend in general with relatively small fluctuation range. And temperature difference does not have a significant effect on the displacement of this station. Station HC02 has quite a fierce movement trend, strongly influenced by the temperature difference between day and night with the largest displacement distance up to 20 mm. Based on the local temperature time series, the strongest movement trend happens in the DOY 024 to 032 and DOY 090 to 102. During the DOY 024 to 032, the highest temperature is around −10 °C. The stations move upwards during the daytime and move downwards during the nighttime, meaning that the temperature during the daytime keeps rising. Compared to the fall of permafrost frost heave, the heat expansion and cold contraction of the observation pillar is much more obvious. During the DOY 090 to 102, the lowest temperature is around 0 °C. The stations move downwards during the daytime and move upwards during the nighttime, which shows that when the lowest temperature is above 0 °C, the tundra is beginning to melt. Compared to the heat expansion and cold contraction of the observation pillar, the fall of permafrost frost heave is more obvious. The temperature difference between day and night almost has no influence on Station HC03's motion state. This means that the geological conditions of Station HC03 are comparatively stable. In order to further analysis, the connection of the temperature and the deformation, this paper calculate the correlation between the temperature and three solutions, which are shown in Table 2.

According to the correlation law, when the absolute value of correlation coefficient is less than 0.4, the correlation is weak correlation. When the absolute value of correlation coefficient is greater than or equal to 0.4 and less than 0.7, the correlation is significant correlation. When the absolute value of correlation coefficient is greater than or equal to 0.7, the correlation is high correlation. It can be seen from Table 2 that HB02 and HB01 station's three correlations are less than 0.4, this is due to the fact that these stations are base stations with the deep foundation which can reach the bed rock. So,

Table 2 – The correlation between the three temperature and the corresponding three solutions.

Site	Correlation between average temperature and the whole solution	Correlation between maximum temperature and daytime solution	Correlation between minimum temperature and night solution
HC01	0.5352	0.1652	0.3321
HC02	0.681	−0.0477	0.6727
HC03	−0.1684	−0.324	−0.0488
HB01	−0.0966	0.365	−0.1788
HB02	0.0361	−0.2284	0.3982

the temperature has little influence on the base stations' deformation. The other stations are monitoring stations, which set up by the side of railway subgrade. Most of the monitoring stations' correlations are significant correlation, and they can reflect the deformation of railway subgrade frost heave of this section. However, due to the lack of data integrity for stations' three solutions, some of the correlations between the temperature and the corresponding solutions may have deviation. In further analysis, because of the indeterminacy of the last time of maximum and minimum temperature in a day, it's difficult to scientifically evaluate the maximum or minimum temperature has relation with deformations. But, the relation can be characterized by average temperature in theory. There is an obvious diurnal motion tendency in the vertical displacement sequence of the five stations, measuring from 5 mm to 10 mm. One of the factors can be attributed to the heat expansion and cold contraction of the observation pillar caused by temperature difference between day and night. The other factor is related to satellite diurnal motion tendency and multipath effect.

To make a general analysis of the day solution time series of the five stations among the seasons, all of which show a sedimentary tendency to different degrees. Station HC03 shows the most obvious sedimentation ranging from 5 mm to 10 mm. As the imaginary line shows in Fig. 2, on the 85th day, all the other four stations show obvious rising tendency on the vertical direction with the displacement around 10 mm except the missing data for Station HC01. Based on the temperature time series and local meteorological data, the 85th day has extremely high temperature, 10 °C higher than the normal temperature of the month. Thus, this paper argues that the major factor for the rising of the stations can be attributed to the heat effect of the observation pillar and the station basement caused by extremely high-temperature weather [12].

4. Conclusion

As a method of geodetic surveying, GPS technology has the advantages of high accuracy and high automaticity, which has been applied for monitoring the deformation of various works. Based on this technology, this study monitors the actual deformation status of the high-speed railway subgrade frost heave in the permafrost section. Through the analysis of the deformation status after data processing, this paper concludes that GPS technology is a good monitoring tool for the sedimentation of railway subgrade caused by the melting of the tundra, and the railway subgrade frost heave deformation is closely related to the change of temperature. Temperature difference between day and night can cause obvious movement to the observation stations, inducing relatively large deformation of the high-speed railway subgrade. Temperature difference among the seasons cause varying degrees of sedimentary tendency of the stations, with Station HC03 being the most evident case. There exists obvious diurnal motion tendency in the vertical displacement sequence of the five stations, measuring from 5 mm to 10 mm.

Acknowledgments

This research is supported by the National Natural Science Foundation of China (41374033).

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