Research on Frost Heave of High Speed Railway in Seasonal Frozen Region Based on Track Geometry Measurements

Xiang Wang¹*

¹ School of Traffic and Transportation, Beijing Jiaotong University, Beijing, 100044, China

*Corresponding author’s e-mail: 18120903@bjtu.edu.cn

Abstract. The frost heave and thawing settlement in the seasonal frozen areas can cause the track geometry change, even seriously affect the driving safety. Taking the HSR-A railway as the research object, this paper divides the change process of track surface during the period of frost heave and thawing settlement into four stages, and equates the four stages into a trapezoidal change process. Then the characteristics of these stages are summarized. Finally, based on the track geometry measurements (TGM), two different linear functions are used to represent the track surface changes before and after frost heave start respectively, and this essay proposes the start time estimations model(STEM) to estimate the start time of frost heave. STEM is applied to 10 typical frost heave positions in the HSR-A. The results show: the estimated effect is good.

1. Introduction

The frost heave problem of high-speed railway embankment in cold areas has greatly affected the safety of train running. In Northeast and Northwest China, there are many railways located in seasonal frozen areas and appearing frost heaves. In order to ensure the safety of travel, trains in seasonal frozen areas can only travel at a lower speed in winter. However, this measure not only affects transportation efficiency, but also still has certain risks. High-speed railways have extremely strict requirements for embankment deformation. Therefore, analysis of embankment frost heave in seasonal frozen areas has become an urgent task to be solved.

Azmatch¹ introduces the mechanism of embankment frost heave. It is believed that frost heave includes the original water in the soil and the water in the lower unfrozen soil transfer to the freezing front and the increase in soil volume caused by icing. It is generally believed that there are three factors affecting frost heave: moisture content, fine content, and temperature. Miao²,³ monitors the frost heave of the embankment during the operation of the Harbin-Dalian high-speed railway, and found that the frost heave of the cutting is more serious than that of the embankment, and the freezing depth at different mileages is different. Yan⁴ conducts multiple experiments to change the soil moisture content and salt content, and found that soils with different structures have different freezing temperatures. There are many studies on the prediction of frost heave at a single point on the railway subgrade. Based on the non-equal interval GM(1,1) optimized prediction model, Le⁵ uses support vector machine to correct the prediction residuals, establishes a combined prediction algorithm, and uses this algorithm to quantitatively predict the frost heave of railway subgrade.

At present, the researches on frost heave are basically carried out in a laboratory environment. A few on-site research only focuses on the frost heave of a single point in the embankment. As far as we know, there are no reports on the track irregularities caused by the embankment frost heave during operation. Based on this, this paper uses TGM to study the change characteristics of track surface caused by...
embankment frost heave in seasonal frozen areas, and proposes a method for estimating the start time of frost heave according to TGM.

2. Embankment frost heave characteristics

HSR-A is a high-speed railway located in Northeast China. Its geographic location is shown in Figure 1. The frost heave in embankment is analyzed by using TGM from October 2016 to June 2019 on the 436 km section in the HSR-A.

Figure 1. HSR-A geographic location

In the seasonal frozen areas, the key factor affecting railway operation is the track irregularity caused by the frost heave of the embankment. The track geometry parameter data obtained by TGM just reflects the track irregularity. Frost heave causes large changes of track surface, even exceed the limit, while it has no effect on other track geometric parameters (such as alignment, gauge). Therefore, this paper studies the changes circumstances of track surface during frost heave.

In Northeast China, frost heave generally begins in mid-to-late November, and begins thawing settlement in March of the following year. The change process of the track surface can be divided into four stages: small fluctuations, rapid development, stable development, and thawing settlement[6], as shown in Figure 2(a). The small fluctuation stage in the frost heave process is not obvious and will not affect the actual operation, so this process can be ignored. The change process is equivalent to a trapezoidal change process. as shown in Figure 2(b).

Figure 2. track surface change process and Trapezoid diagram

The part compares the maximum surface increase value (the difference between the track surface value in the stable development stage and the value before frost heave, MSIV) of the 10 typical frost heave positions in the HSR-A in three years, as shown in Figure 3. For this three years, the averages of MSIV are 3.2mm, 3.3mm, 3.1mm. The correlation coefficients between any two years are 0.95, 0.96, 0.92. It can be found that the annual MSIV is the same during frost heave in three years.
Frost heave is a one-way freezing process from the embankment top downwards, and thawing settlement is a two-way melting process from the top and bottom to the middle at the same time\cite{7}. Due to the two-way nature of thawing settlement, the time in the thaw settlement (thawing settlement time) is shorter than that in the rapid development stage (rapid development time). Figure 4 shows the comparison between the rapid development time and the thawing settlement time of 10 typical frost heave positions in the HSR-A. Obviously, the rapid development time is much longer than the thawing settlement time.

The comparison between the track surface value before frost heave begins and after thawing settlement finishes in the HSR-A in three years is shown in Figure 5. It can be seen that the track surface value before and after frost heave are highly consistent, and the track surface value in the seasonal frozen areas will return to the value before frost heave after thawing settlement.

3. The start time estimations model and Solution

For a position of frost heave, the MSIV every year is the same. As long as the railway staff know the time when the embankment begins frost heave, and then obtain the MSIV according to historical TGM, then they can take measures to carry out preventive repairs to the track. Therefore, this section proposes the start time estimations model(STEM) to estimate the start time of frost heave based on TGM.

Before and after frost heave begins, the change of track surface value can be divided into two parts. The track surface value develops stably before frost heave begins, and the track surface value develops rapidly after frost heave begins. The start time of frost heave can be regarded as a change point in the track surface value data. Before and after the change point, the track surface value data are fitted with different linear functions, as shown in equation (1) and equation (2).

\[ y'_i = a_i + b_i, i = 1, 2, \cdots, k \]  
\[ y'_i = a_i + b_i, i = k, k + 1, \cdots, n \]
Where \( i \) is the inspection order of TGM, \( y_i' \) is the fitted value of \( i^{th} \) inspection, \( n \) is total inspection number of TGM in the research period. \( k \) is the inspection order when frost heave begins \((2 \leq k \leq n-1)\) and \( a_1, a_2, b_1, b_2 \) are parameters, which can be estimated by the ordinary least squares or the maximum likelihood.

The objective function of STEM is the correlation coefficient between the actual value of track surface and the fitted value, as shown in equation (3).

\[
Z = \max \left\{ \frac{\text{Cov}(y, y')}{{\text{Var}(y)^{1/2}} \text{Var}(y')^{1/2}} \right\}
\]

Where \( y \) and \( y' \) are determined by equation (1) and equation (2).

STEM solution is to calculate the position of the change point according to the historical track surface data. The specific process is shown in Figure 6. Take the value of \( k \) from 2 to \( n-1 \), calculate the four parameters \( a_1, b_1, a_2, b_2 \) according to the value of \( k \) (estimated by the ordinary least squares method in this paper, as equation(4)), and obtain \( y' \) according to equation(1) and equation(2), and then calculate the correlation coefficient between \( y \) and \( y' \). Calculate the correlation coefficient corresponding to each \( k \), and the change point is \( k \) where the correlation coefficient reaches the maximum value.

\[
a_1 = \sum_{j=1}^{k} jy_j - \frac{1}{k} \sum_{j=1}^{k} j\sum_{j=1}^{k} y_j, \quad a_2 = \sum_{j=k+1}^{n} jy_j - \frac{1}{n-k+1} \sum_{j=k+1}^{n} j\sum_{j=k+1}^{n} y_j
\]
\[
b_1 = \sum_{j=1}^{k} y_j - a_1 \frac{1}{k} \sum_{j=1}^{k} j, \quad b_2 = \sum_{j=k+1}^{n} y_j - a_2 \frac{1}{n-k+1} \sum_{j=k+1}^{n} j
\]

**Algorithm 1: The solution method for STEM**

input: \( y, n \)
output: \( Z, k \)
1: for \( k=2:n-1 \)
2: Use equation (4) to get \( a_1, b_1, a_2, b_2 \)
3: for \( i=1:k \)
4: \( y'_i = a_1 i + b_1 \)
5: end
6: for \( i=k+1:n \)
7: \( y'_i = a_2 i + b_2 \)
8: end
9: Calculate \( Z_k \) based on \( y, y' \)
10: end
11: \( Z=\max(Z_k) \)
12: \( k=\arg\max(Z_k) \)

**Figure 6. STEM solution method flowchart**

According to the data from November 2018 to January 2019, STEM is applied to estimate the time to start frost heave in the HSR-A, and the results of HSR-A #1 frost heave position are shown in Figure 7(a). In this position, frost heave occurred at the 6th inspection, the corresponding date was December 17, and the correlation coefficient was 0.9875. The comparison between the actual value and the fitted
value is shown in Figure 7(b), STEM estimates the start time of frost heave appropriately.

The results of estimating the start time of 10 typical frost heave positions in the HSR-A are shown in Table 1. It can be seen that the correlation coefficients of each frost heave position are high, and STEM and solution is highly reasonable. At the same time, the start time of the embankment frost heave in different positions is not the same, and there is a big gap.

![Figure 7. STEM Result analysis](image)

Table 1. Estimated the start time of 10 frost heave positions

| Frost heave position number | start frost heave time | correlation coefficient |
|-----------------------------|------------------------|-------------------------|
| #1                          | December 17            | 0.9875                  |
| #2                          | December 5             | 0.9546                  |
| #3                          | December 5             | 0.8933                  |
| #4                          | December 11            | 0.9261                  |
| #5                          | November 30            | 0.9023                  |
| #6                          | December 25            | 0.9285                  |
| #7                          | December 31            | 0.9473                  |
| #8                          | December 11            | 0.9146                  |
| #9                          | November 30            | 0.9378                  |
| #10                         | January 4              | 0.9659                  |

4. Conclusion

The phenomenon of frost heave is widespread in the world, and the research on related aspects has great practical significance. This paper studies the change process of track surface during the freezing period in the HSR-A, establishes the trapezoidal change process, proposes STEM to estimate the start time of frost heave, and applies it to 10 frost heave positions in the HSR-A. As for the results, STEM has a good estimation effect. The method can provide suggestions for railway staff to prevent frost heave.

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Conflict of interest

The author is solely responsible for this paper and assumes responsibility for all issues that may arise from the paper. My tutor does not know about the writing and content of the paper.

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