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Real-time Monitoring for Freezing and Thawing Process of Subgrade in Seasonal Frozen Regions

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Abstract

This research shows that there is a cosine changing of the distribution of the temperature field on an annual cycle, and a temperature changing lag exists for the different depth of subgrade. Based on the law of frozen depth of subgrade, the frozen procedures can be divided into four stages. Based on the observation data, the cathode surface temperature is positively correlated with both the frost heave quantity and the frozen depth. In addition, to reduce the observation cost and the measure difficulty, the frost heave quantity can be obtained through the observation of the frozen depth.

Keywords*: Seasonal frozen area; Frozen depth; Roadbed temperature field; Frost heave; Distribution law*

1. Introduction

In China, the seasonal frozen soil area is 513.7×104km^2, about 53.5 percent of the land area [1]. Among them, the deep seasonal frozen (frozen depth>1m) accounts for one-third of the national land area [2]. With the rapid development of China's economic construction, the development pace in seasonal frozen region will also increase, whether it is the construction industry or the transportation industry will face unprecedented challenges. In seasonal frozen soil area, roadbed water during the spring thaw, freeze in the fall. With the temperature decreasing, the pore-space water gradually phase into the pore ice, resulting in increased volume and uneven frost heave. As temperature rising, the pore ice gradually phase into the pore-space water which can't be timely dissipated. Subgrade soil will be softened, resulting in mud pumping phenomenon in the vehicle reciprocating loads. Eventually, the subgrade will lose the stability and the carrying capacity.

In northern China, frost subgrade has been plagued by the problem of road construction [3]. Currently, research on the temperature field of subgrade mostly concentrated in the permafrost regions [4-6], relatively few studies on the seasonal freezing regions [7-8]. Therefore, the research on the rules between heaving and thawing process of the subgrade in seasonal frozen regions is necessary.
[1]

2. Climatic Conditions

The test area is located in Harbin, Heilongjiang Province, which belongs to the typical continental monsoon climate. The area with an average annual temperature of 4.71℃, extreme maximum temperature of 31.4℃, extreme minimum temperature of -32.7℃; the annual average rainfall of 493mm, the average annual sunshine of 2726 hours, early freeze period in late October, thawing time for the mid-year in April, snowfall of up to six

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mouths. The area mostly blow with the southwest wind in spring, wind speed of 3-6m/s, the maximum wind speed of 30m/s. Winter for northwest wind, wind speed of 2-3m/s[9].

3. Structural Model Test Road

The observations in the model begin from October 2013. The study is based on the data from October 2013 to May 2014 to make the following analysis, including the changes between the frozen depth and frost heave displacement. It selects the observation section in deep frozen area. Structural model test rig is 5.5 meters long, 2.4 meters wide. The pavement structure is composed of a double bituminous surface layers and a semi-rigid base: 17mm fine dense graded asphalt concrete (AC-13) plus the medium-grained asphalt concrete (AC-20) and 40mm stable macadam including lime and fly ash. This kind of structure is the typical asphalt surface in the northeast. The model filler is the low liquid limit clay mixed with 6% lime, the foundation stratum is the silt soil with high groundwater contour.

The monitoring system is mainly for frost heave, freezing depth, different formation temperature as well as other aspects related to meteorology. The temperature detection system is established in order to observe the atmospheric temperature effects on the model temperature field. The temperature sensors are embedded in the subgrade at different locations and depths, which laying depth from the road down 0.57m, 0.80m, 1.2m, 1.6m, 1.8m, 2.2m, 3.2m. Ground temperature (0cm) is the average daily temperature values. The measurement accuracy of the temperature sensor is 0.1℃. The deformation monitoring system to monitor the overall deformation in subgrade and layered deformation, the former is used in geometric leveling, the latter by laying heave gauges at different depths of frost heaving stratification monitored. The heave gauge process is 60mm, the precision is 0.01mm. There are three heave gauges buried at each depth from the ground 0.6m, 1.0m, 1.5m. The monitoring instrument layout is shown in Figure 1.

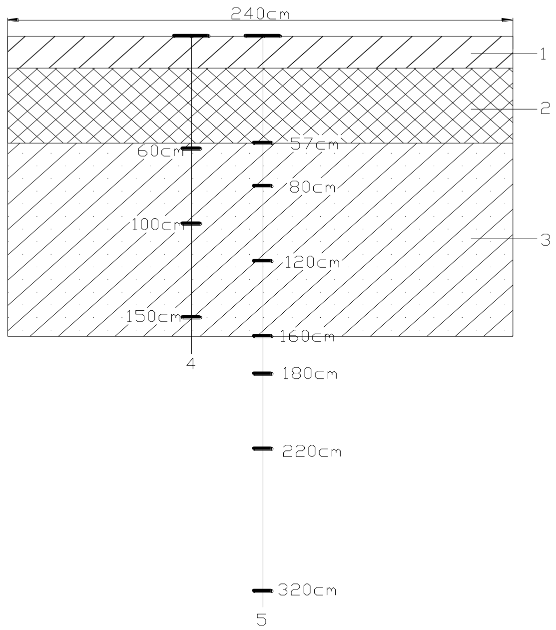


Figure 1. Sensors' Location in Subgrade Section

1-fine dense graded asphalt concrete (AC-13) plus the medium-grained asphalt concrete (AC-20); 2- stable macadam include lime and fly ash; 3- low liquid limit clay mixed with 6% lime; 4-heave gauge; 5- temperature sensor

4. The Analysis of Observation Result

4.1 The Transformation Law of Subgrade Temperature Field

Figure 2 illustrates the variation of the temperature of different model levels with time during a wintering period from October 2013 to May 2014.

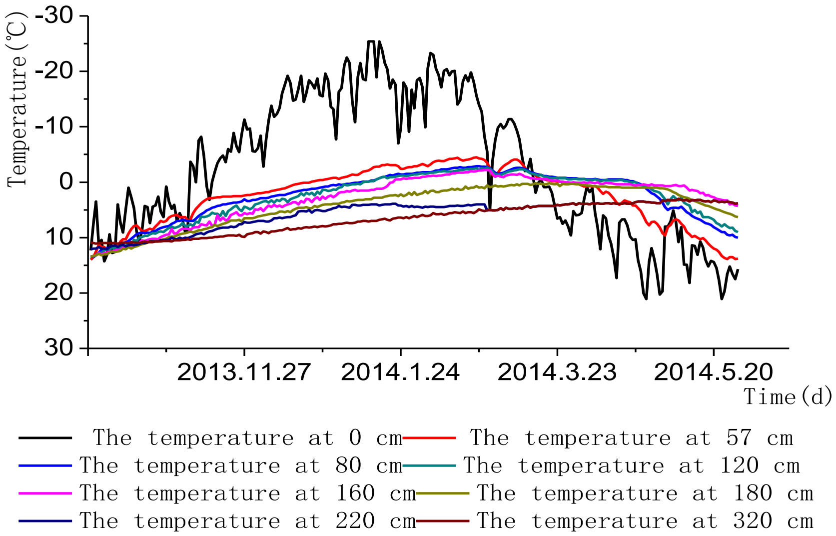


Figure 2. Variations of Subgrade Temperature with Time at each Depth in Winter

From Figure 2, it can be seen that the subgrade freezing period in the experimental site is 75 days, which is from 22 December 2013 to 7 March 2014. The melting period is 38 days, from 26 March 2014 to 3 May 2014. During the whole freezing and thawing period, the ground temperature decreased before increase, and it is shown as a cosine variation. However, there is a significant difference about the temperature extreme value and phase position at different depth [9]. Through the observation of the average temperature changes at the test period, the lowest average temperature is -25.4℃ at 12 January 2014, and the highest one is 29℃ at 31 May 2014. The descent rate of temperature is relatively fast from 15 November to 16 January, and the drop temperature is 25.3℃. January is the coldest mouth, and the average temperature is -17.52℃. Through the observation of the lowest temperature at the depth of 0.57m and 0.80m , the respective date are 20 February and 25 February, and the respective temperature are -2.9 and -2.6℃.

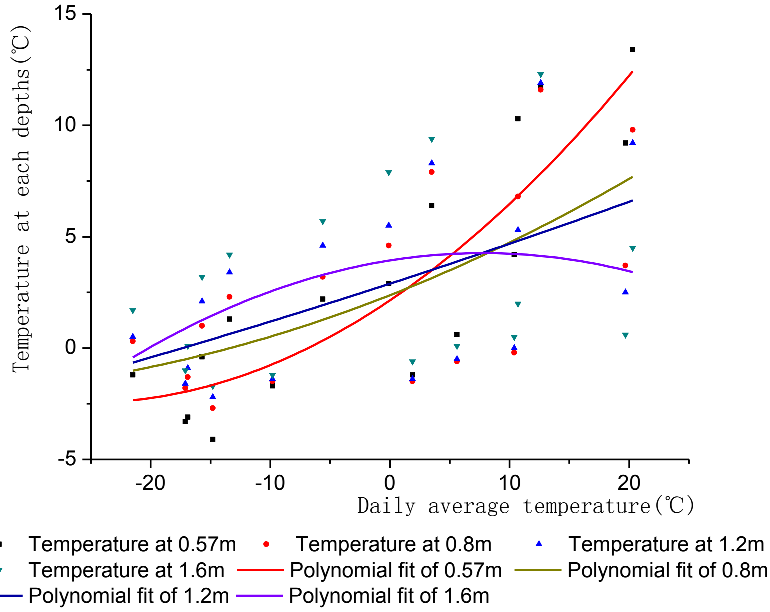


Figure 3. Relationships between each Depth Temperature and Daily Average Temperature

Through Figure 3, it can be seen that the variation tendency are basically same between the temperature field of roadbed at different depth and the change of daily average temperature. In addition, with the increase of depth, the range of temperature decreased. To be specific, the range of temperature change is 18.9℃ at the depth of 0.57m, it changed to 13.5℃ at 0.80m, at the depth of 1.60m, the ranged is 6.9℃, and at 3.2m, the range of temperature change is only 1.3℃. The effect of atmosphere temperature change on the temperature field of roadbed decreases. The process of heat transfer is accompanied by energy attenuation. Therefore, when analyzing the influence of temperature change on the design of highway, the roadbed depth should be regarded as non-steady temperature field.

By establishing the quadratic polynomial regression equation 1, the relationship between the daily average temperature (x) and roadbed depth (y) can be obtained, and in this formula, a, b and c are regression coefficients.

$$y = ax^2 + bx + c \tag{1}$$

In Table.1, it can be seen that with the increase of depth, the correlation between the two factors are weakened, and relative to atmosphere temperature change, there is a certain hysteresis effect of ground temperature change.

Table 1. Correlations Analysis of Binomial Regression Coefficient

Soil depth/m	Regression coefficients			Correlation coefficient
	a	*b*	*c*	R^2
0.57	0.003	0.358	2.911	0.830
0.8	0.001	0.201	3.262	0.595
1.2	-0.003	0.165	3.787	0.510
1.6	-0.008	0.083	4.583	0.320

Based on the statistical data of Figure 2, the transformation law of each temperature parameter at the process of roadbed freezing and melting can be summarized by Table 2 and 3.

Table 2. Parameter Changes in Feezing Process

Location		Depth from the pavement/m	Start and end time	time/d	Temperature change width/℃	Decreased rate/(℃/d)
Upper roadbed (0-0.3m)		0.57-0.87m	2013.12.20-2014.1.19	31	12.8	0.3879
Lower roadbed	Upper part (0.3-0.6m)	0.87-1.17m	2014.1.20-2014.2.3	14	9	0.6429
	Lower part (0.6-0.8m)	1.17-1.37m	2014.2.3-2014.2.28	24	5.8	0.2417
Subgrade (0.8-1.2m)		1.37-1.77m	2014.3.1-2014.3.12	11	2.5	0.2273
Subgrade (1.2-1.6m)		1.77-2.17m	2014.3.13-2014.4.3	21	1.1	0.0524

Table 2 illustrates the process of roadbed freezing, and it can be seen that the effect of atmospheric temperature field on upper subgrade is obvious, and the freezing time is 31 days. At this moment, the temperature get through 0 ℃ steadily, the depth of frost penetration develops downwards. The moisture content at frozen crust can receive a small amount of supplies with the moving down of frozen cover. As the moisture mainly consists of capillary water and film water, so the effect is weak. At this stage, quick freezing happens, ice embryos and buds are formed. Then the lower subgrade begins to freeze, and the rate of temperature fall of upper subgrade is 0.6429℃/d, and it differs a lot with that of lower subgrade. When the freeze develops to late January, the atmosphere temperature decreases to a minimum, and there is a significant phenomenon of moisture migration at lower subgrade during this period, the frozen cover keeps going down. The moisture content of subgrade soil increases at this thickness range. At the depth of 1.37m, where close to the maximum frozen depth, the rate of temperature fall is only 0.2273℃/d and it lasts 32 days. At this thickness range, the moisture content increases with the increase of depth, and it confirmed that moisture keeps going upward with the effect of temperature gradient. The phenomenon of water gathering will happen when there are enough water at the end of the freeze [10].

Table 3. Parameter Changes in Thawing Process

Location		Depth from the pavement/m	Start and end time	time/d	Temperature change width/℃	Increased rate/(℃/d)
Upper roadbed (0-0.3m)		0.57-0.87m	2013.3.24-2014.4.4	11	3.1	0.2818
Lower roadbed	Upper part (0.3-0.6m)	0.87-1.17m	2014.4.5-2014.4.23	18	4.7	0.2611
	Lower part (0.6-0.8m)	1.17-1.37m	2014.4.24-2014.5.5	11	3.7	0.3083
Subgrade (0.8-1.2m)		1.37-1.77m	2014.5.5-2014.4.17	18	0.9	0.02
Subgrade (1.2-1.6m)		1.77-2.17m	2014.4.16-2014.3.30	21	0.6	0.0286

Table 3 illustrates the melting process of roadbed. Through this table, it can be seen that the upper subgrade begin to melt at 26 March, and it lasts 9 days from top to bottom. Because of the high soil density and low ice content of this layer, so it is effected significantly by atmosphere temperature field, and melting time is shorter than that of lower subgrade. During the melting, the temperature gradient of the roadbed is smaller than that of freezing process, and it states that moisture migration driving force is mainly provided by gravity potential, and it has weaker relationship with temperature gradient. Therefore, it can be seen that the melting time of lower subgrade (0.6-0.8m) is shorter than the upper subgrade, at this thickness range, subgrade melting endothermic is provided by adjacent layers, heat transfer bilaterally to this layer, and temperature rate is significantly higher than the layer of 0.87-1.17m and 1.37-1.77m. It is illustrated that melting time at the depth of 1.17m is later than that of lower layers; the dry layers can be regarded as confining beds. Due to the upper water cannot infiltrate in time, the pore water pressure increases. Therefore, at the process of spring melting, some road problems usually occur under the action of subgrade vehicle dynamic load, such as road frost boiling.

4.2 The Relationship between the Depth of Freezing and Temperature

In order to conclude the relationship between the frozen depth (D_f) and temperature, it introduce the surface accumulation of negative temperature (ST_S) and daily average temperature (T_P) as the temperature variables. Through Figure 4, it can be seen that the frozen depth (D_f) is increasing with the increasing of the absolute value of the surface accumulation of negative temperature (ST_S) into the rapid growth phase. When 26 February 2014, the maximum frozen depth is 146.4cm, ST_S of -1527.9℃. At this stage, ST_S linearly correlated with D_f. Subsequently, due to the heat transfer is higher than the lower portion of the upper soil layer deep cold soil transfer, despite the ST_S is continued increasing, but the lower part of the roadbed has begun to melt, the frozen depth showed a decreasing trend. At end-March, the subgrade temperature is above 0℃, melting into the stable foundation stage. At early-May, the upper and lower melting layer overlapping, the melting process is over.

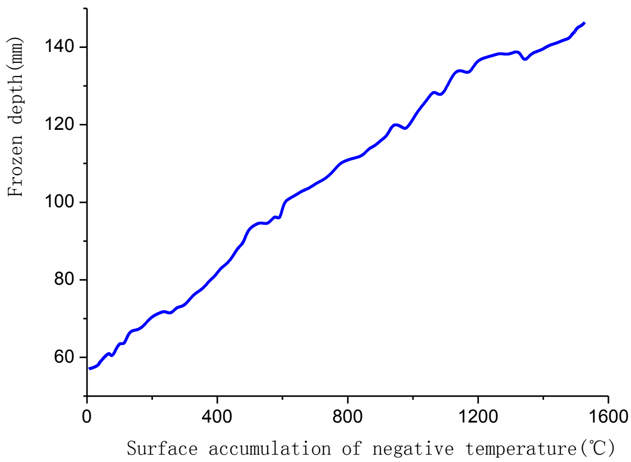


Figure 4. Relationship between the Frozen Depth and Surface Accumulation of Negative Temperature

The frozen depth (D_f) and daily average temperature (T_P) relationship curve is shown in Figure 5. It can be seen that the upper subgrade (0.57m) starts to freeze when entering the initial freeze time, the temperature fluctuation from -3.5℃ to -6.5℃. The moisture migrates from unfrozen layer to frozen layer, where the frozen depth moves down to push the maximum until the late February. The daily average temperature and the frozen depth (D_f) of freezing over time experience gradual upgrade process, up to a maximum and then decrease [11]. The daily average temperature of cooling period is shorter than the heating period, about three-fifths of heating period. But the frozen depth process of change is opposite. The frozen depth develop to the maximum by 88s days, compared to the daily average temperature of cooling time lagging 26s days. When the daily average temperature reaches the lowest, the frozen depth only develop to a maximum of 71%; when the daily average temperature rise to 0℃, the soil in lower subgrade is only 10.6% melted.

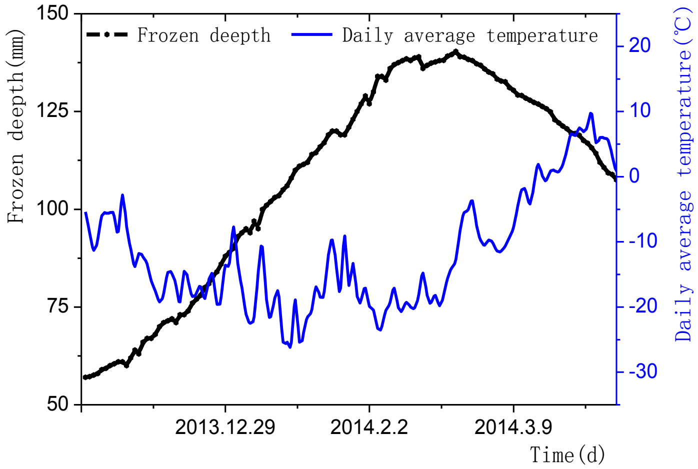
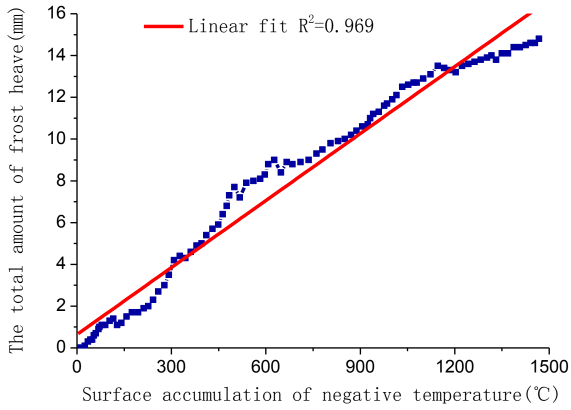


Figure 5. Variations of Frozen Depth and Daily Average Temperature with Time

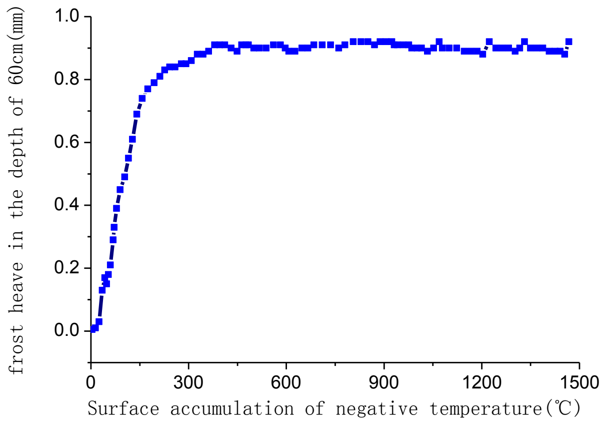
Therefore, it sums up the frozen depth changes with time in four stages. Phase one is rapid growth phase, the frozen depth goes down with time by using 88s days, the freezing rate is 16.6mm/d; phase two is steady phase, the frozen depth basically unchanged with time by using 16s days; phase three is unstable thawing phase, the frozen depth has moved upward trend with time by using 5s days, it's changed to a less extent; phase five is stable thawing phase, the frozen depth continued moves up with time by using 30s days.

4.3 The Relationship between the Frost Heave and Frozen Depth

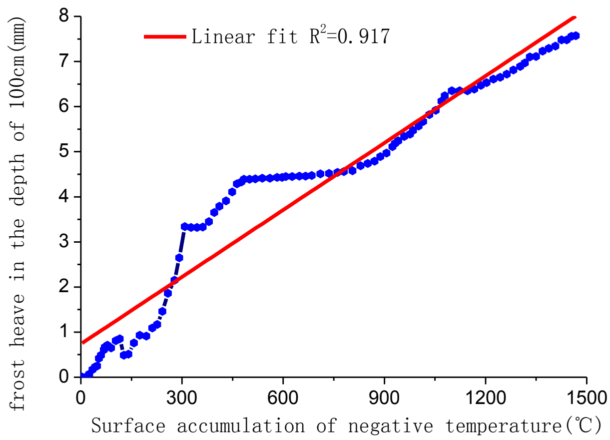
By monitoring the overall and layered deformation, it has received the statistical data as Figure 6. The frost heave in the depth of 60cm (D_{Z60}) occurs from Nov.26. When the surface accumulation of negative temperature (｜ST_S｜) of 361.3℃, the frost heave in the depth of 60cm increases to a maximum of 0.89mm lasted about 29s days. Subsequently, the frost heave remains level during the freezing. The frost heave in the depth of 100cm (D_{Z100}) appears a linear increasing trend when the value of ｜ST_S｜is between 0℃ and 607.5℃, the frost heave reaches to 4.46mm at this stage; then D_{Z100} maintain the level of state when the value of｜ST_S｜is between 607.5℃ and 976℃; finally, D_{Z100} appears a linear increasing trend again when the value of｜ST_S｜is between 976℃ and 1467.7℃, the frost heave in the depth of 100cm increases to a maximum of 7.57mm at March 12,2014. The frost heave in the depth of 150cm (D_{Z150}) is always 0mm lasted about 27s days when the value of｜ST_S｜is between 0℃ and 308.2℃; Finally, D_{Z100} appears a linear increasing trend to a maximum of 6.31mm.


Linear fit R^2=0.969
The total amount of frost heave(mm)
Surface accumulation of negative temperature(℃)
0
2
4
6
8
10
12
14
16
0
300
600
900
1200
1500

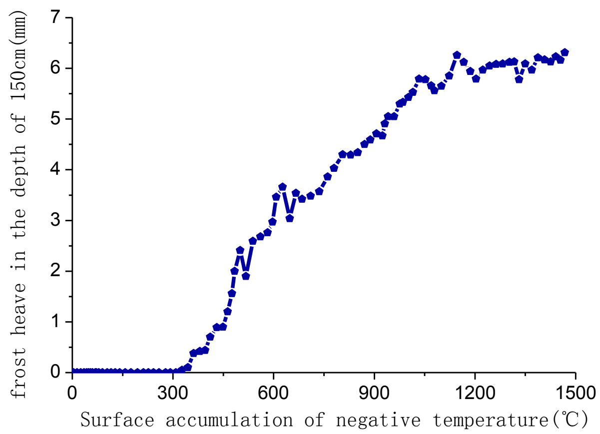
(a)


frost heave in the depth of 60cm(mm)
Surface accumulation of negative temperature(℃)
0.0
0.2
0.4
0.6
0.8
1.0
0
300
600
900
1200
1500

(b)


Linear fit R^2=0.917
frost heave in the depth of 100cm(mm)
Surface accumulation of negative temperature(℃)
0
1
2
3
4
5
6
7
8
0
300
600
900
1200
1500

(c)



(d)

Figure 6. Relationships between Frost Heave and Surface Accumulation of Negative Temperature

Among them, the frost heave of D_{Z100} reading 7.57mm which located in the upper part of lower subgrade is higher than other depths. The data illustrates this layer of soil forming the ice layer and appearing significant moisture migration. The frost heave of D_{Z150} reading 6.24mm which located in frost front prove that the frost front form the ice layer when the groundwater table is shallow and the water can be added timely. According to the variations between total amounts of frost heave (D_Z) and the frost heave of D_{Z100} with the value of ST_S can get linear regression equation 2 and 3.

$$D_z = 0.010ST_S + 0.646 \quad (2)$$

$$D_{Z100} = 0.004ST_S + 0.766 \quad (3)$$

Both Sig are less than 0.01, indicating the differences are significant and the results fit well. But the relationships between D_{Z60} and D_{Z150} with the value of ST_S can't get linear regression.

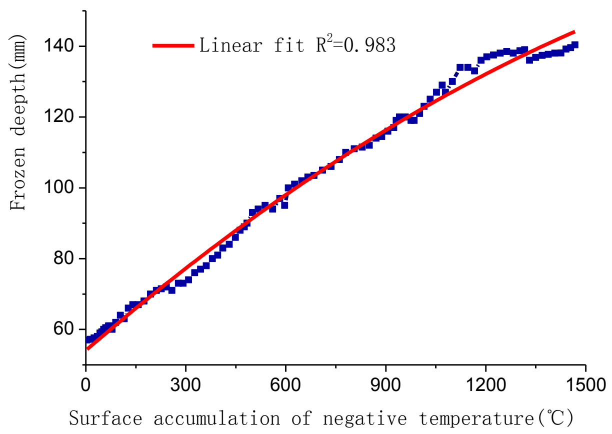


Figure 7. Relationships between Frozen Depth and Surface Accumulation of Negative Temperature

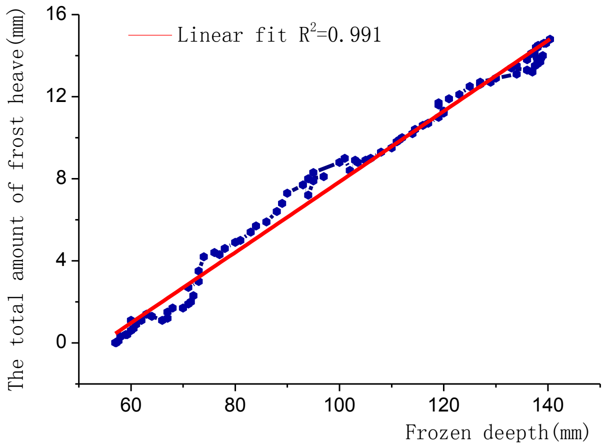


Figure 8. Relationships between Total Amount of Frost Heave and Frozen Depth

From Figure 6 and 7, it can be seen that the total amount of frost heave (D_Z) and the frozen depth (D_f) have strong correlations with the surface accumulation of negative temperature (ST_S). Figure 8 shows the variation curve between the total amount of frost heave (D_Z) and the frozen depth (D_f). According to the variations between (D_Z) and D_f can get linear regression equation 4.

$$D_z = 0.013D_f + 0.638 \quad (4)$$

The linear equation fitting result is better. The frost heave can be known by monitoring the frozen depth, which decreases the cost and difficulties.

4. Conclusion

Based on the test section of subgrade temperature and deformation observation data analysis during the winter from October 2013 to June 2014, this paper can draw the following conclusions:

The temperature field at different depths and the average daily temperature trends are basically same in test section. The correlation between the ground temperature and air temperature gradually weakened with increasing depth. With respect to changes in temperature, ground temperature changes exhibit hysteresis.

During the observation of the freezing process, ice layer appears at the upper part of under roadbed and the end of frozen depth, water aggregation phenomenon is obvious; during the observation of the thawing process, gravitational potential energy provides the main driving force of moisture migration, which affected by the temperature gradient is weak. According to the subgrade freezing depth changes, this paper divides freeze process into four main stages.

By observing the amount of frost heave in the test model, the study found that the most prominent position is the upper part of under roadbed (D_{Z100}), the second place is the end of frozen depth (D_{Z150}), the minimum place is at the subgrade of 60cm depth (D_{Z60}) .The data shows the location of the ice layer gathered in D_{Z100} and D_{Z150}. There are changes in the relationship between water migration and frost heave, also have a relationship with the soil.

The study has shown that the total amount of frost heave (D_Z) and the frozen depth (D_f) present a significant positive correlation with the surface accumulation of negative temperature (｜ST_S｜) . The fitting results show that both Sig<0.01, the difference is significant and the results fit better. At the same time, the study finds out a linear regression relationship between the total amount of frost heave (D_Z) and the frozen depth (D_f). The frost heave can be known by monitoring the frozen depth, which decreases the cost and difficulties.

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