A Study of Subgrade Frost Heave and Frost Penetration Depth Computation: the Case of Provincial Highway 102 in Jilin Province of China

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***Abstract* — This paper explores the: i) mechanism and influence factors of subgrade freezing damage in seasonal frozen ground areas, ii) using on-site observations, iii) analysis of concrete pavement freezing damage and iv) conducts a series of laboratory experiments. Jilin Province in the northeast of China is taken as an example, where the central areas are prone to frost heaving problems, and its effect is related to the dry unit weight (DUW) of soil. When the DUW is around 18KN/m³, the effect reaches its maximum. The high-fill embankment has the highest compressive stress towards subgrade which will inhibit the relief of the frost-heave effect. The frost depth is expressed by congelation index and accumulated temperature value, and an empirical formula is formed to measure the frost penetration depth value of given areas.**

Keywords - seasonal frozen ground; subgrade; frost-heave effect; frost penetration depth

I. INTRODUCTION

In the north of China, subgrade frost-heave is one of the most common problems that will cause highway subgrade failure. Therefore, it is important to explore the hidden reasons for this frost-heave phenomenon and understand the mechanical physical properties of the frosting process, integrating the theory with practice, and find out precaution and solutions[1].

Based on the properties of highway subgrade in seasonal frozen ground area in the north of China, this essay will focus on the case of Provincial Highway 102 in Jilin Province of China. Following the field trip and observation, a series of general physical and mechanical properties experiments on the soil were performed. A long-term tracking, observation and investigation on the subgrade situation were done to find out the frost-heave rules of highway subgrades in seasonal frozen ground area. On this basis, the subgrade defects would be discussed. The influence of the loads, natural environment, etc. towards subgrade's intensity and stability would all be taken into consideration. The results will be instructive significant to the subgrade highway design in seasonal frozen ground area. According to the <Standard of Climatic Zoning for Highway> of People's Republic of China(PRC) [2], the study belongs to Ⅱ Zone of the 1st level, which means the moisture seasonal frost zone in the middle east area.

II. FROST-HEAVE ANALYSIS OF CONCRETE CEMENT HIGHWAY SUBGRADE

A. Frost-Heave Causes

It was proved that the frost-heave rate increases along with the moisture content rate, being inversely proportional to its compaction degree, and the effect could be restrained by external loads [3]. And it is well known that the transportation of moisture in the soil will lead to an icy layer, which is the reason for the subgrade frost-heave phenomenon. This moisture begins to move when the temperature is between 0～-5°Cisotherms, and the water turns into ice around 0℃ isotherm where frost-heave occurs. During the soil freezing process, the external moisture will serve as a supplier and the water will move to a spot, turning into ice whose volume is 1.09 times bigger than the previous form. Sometimes the frost-heave rate η is around 10% to 20%, and it is called segregation heave. The reason for the soil frost-heave is that the external moving water turns into ice-polymer. The major composition of the soil frost-heave is the segregation heave capacity in saturated soil from open system. And the moisture transportation depends on the suction force including pore force, capillary force and crystallization force, especially the capillary action.

B. Main impact factors

1) Granulometric composition of soil

The soil granularity has a significant influence on frost-heave effect. The size of a soil particle reflects its surface field strength which has a direct impact on the moisture transfer ability, leading to the changes of frost-heave deformation result [4].

The study seasonal frozen ground area in this essay is in the middle area of Jilin Province, the northeastern part of China. The subgrade soil composition mostly is different kinds of silty clay, 3%～30% of clay particle and 30%～40% of silt particle. The soil composition in the eastern mountainous area is 3%～30% of clay particle and less than 30%～40% of silt particle. While the west area is mainly sand, silty sand, silty soil and the clay particle is less than 3% [5]. So the study area is the representative area which is prone to the frost-heave according to its particle size and content of the soil.

2) Soil body density

According to the indoor frost-heave experiment result (Table I), the average moisture content rate of the soil is 21.2%. Based on the steady moisture content rate, the relationship between dry weight and related frost-heave coefficient (fig.1).

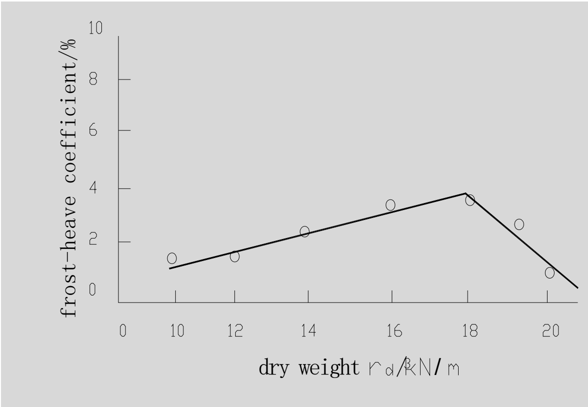

Figure 1. The relationship curve between dry specific weight and its frost-heave coefficient

When the dye specific weight Rd compactness of soil body reaches a certain threshold value, the soil porosity will achieve its minimum value which is also the best condition for particle agglomeration. Then the frost-heave intensity reaches its maximum. If it exceeds the threshold value, the frost-heave begins to decrease. The threshold value of Rd is proximately 18kN/m^3.

3) Moisture content of soil

One of the basic causes of the subgrade frost-heave problem is the moisture in the soil. Though the original moisture content rate in the open system is low, the external water would consciously move to the freezing frontal surface as a supplier. Then the frost-heave force is reinforced and the actual effect could be more than10 times bigger than the no water supplement situation [6-7], which could lead to great harm to the road.

A long-term observation experiment was conducted on some roads within the study area to analysis the relationship between moisture content rate and the frost-heave. The Table I shows the indoor frost-heave experiment result of silty clay from the soil sample of the study area (cement concrete highway subgrade sample from Highway 102 along Siping city). From the linear statistical analysis of the experimental data, a linear relation expression “$\eta=a\omega-b$” is formed and the modified regression equitation of η，ω is described as below:

$$\eta=0.389\omega-6.211 \quad (1)$$

and n=15（sample size） r=0.711（correlation coefficient).

TABLE I. THE INDOOR FROST-HEAVE EXPERIMENT RESULT OF SILTY CLAY

Sample No.	Natural moisture content rate ω/%	Frost-heave rate η/%
01	20.38	-0.695
02	21.55	4.210
03	18.35	1.320
04	22.09	2.089
05	18.02	0.176
06	30.01	5.220
07	24.03	4.110
08	24.37	4.020
10	17.95	0.790
11	23.36	0.670
12	17.88	-0.020
13	20.14	0.940
14	18.33	1.320
15	22.56	0.760

Through the correlation coefficient value is not good enough to demonstrate a strong correlation between them, it still proves that the frost-heave rate and the moisture content rate have a positive correlation. However, the regression analysis also shows that the

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relationship between$\eta$and (ω- ω_p[1]) is nonlinear structure.

The groundwater is the main source for the soil moisture content. Both the soil condition and the groundwater embedded depth have an inverse relationship with the frost-heave property of the soil. The influence depth of groundwater level is determined by rising height of capillary water from capillary action layer which is above the groundwater level. When the distance to the frozen frontal surface is higher than the capillary height, the groundwater will not affect the subgrade frost-heave any more.

4） The load

It is well known that the external loads could have an inhibitory effect on the frost-heave phenomenon of the soil body [8-9]. With the increase of the external pressure, the contact stress among particles will be enhanced then the freezing point of the soil will decrease. This would affect the liquid-solid transition of the water in the soil. Seen from the subgrade cross section, there is a big difference between the high-fill embankment subgrade and the excavated deep cutting subgrade: the first one is that the water movement of soil foundation from embankment has a much worse transfer condition than the cutting one. Therefore, the embankment has a smaller frost-heave capability. The second one is that the high-fill embankment has a much stronger compressive stress because of the thickened cushion than the cutting one, therefore the increased inhibitory effect will also reduce the frost-heave capability. This point of view could be demonstrated by the relationship curve between subgrade cross section forms and self-weight stress with the frost-heave capability from Changchun exit segment of Changchun-Dapu highway（fig. 2）.

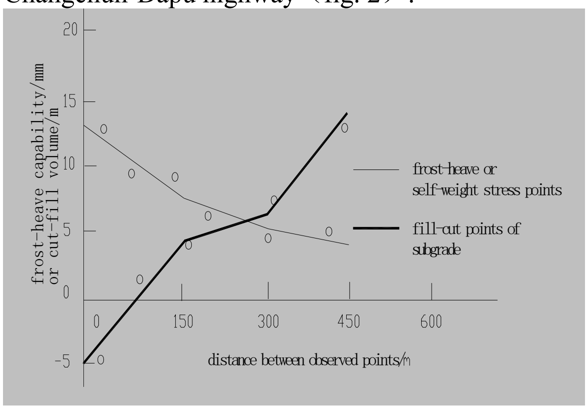

Figure 2. The relationship curve between subgrade cross section forms and self-weight stress with the frost-heave capability

C. *The frost-heave distribution pattern*

In the seasonal frozen ground area, knowing the basic rules of frost-heave distribution along the frost penetration depth is important for the precautionary action [10-11] and for the determination of gravel filling depth as well as width. It has been proved by the experiments that the distribution patterns of the frost-heave along the frost penetration depth is closely related to soil properties and groundwater level. According to the observation data on the Siping 102 cement concrete highway subgrade in the year of 2004-2005, the distribution patterns could be concluded in the following ways:

1) When the high frost-heave layer at the 30%-50% upper part of the frost line

From the observation data of No. 16 point on the south side of the Wujin Village toll station along the Highway 102，the groundwater embedded depth level here is around 3.5m, which is more like a closed system, and the moisture content rate in the lime-ash soil of the structural layer beneath the roadbed is 26%. The moisture content rate in the hill-skill stone cushion layer is less than 6% and the frost-heave distribution pattern is shown in fig.3. The main frost-heave body occupies 45% of the upper part, and the clay stratum under the cushion layer has relatively smaller frost-heave.

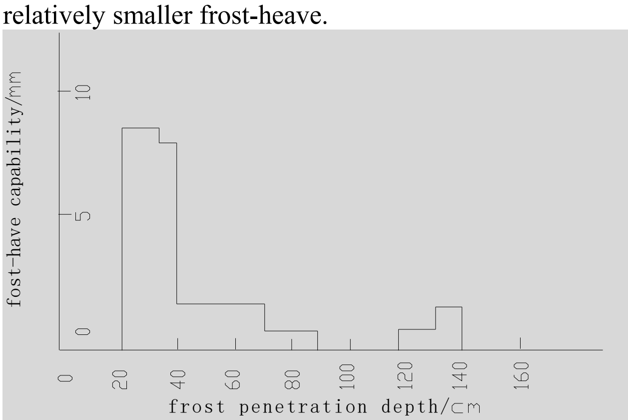

Figure 3. The distribution pattern of frost-heave in soil.

2) When the high frost-heave layer at the 50% lower part of the frost line

According to the observation data of No.11 point at the Siping south exit along highway 102, the groundwater shallow depth level is 1.7m, the moisture content rate of clay stratum under the cushion layer is 28%, much higher than the plastic limits of moisture content rate. It has a relatively large amount of frost-heave, and the main frost-heave body occupies 30% of the lower part. The distribution pattern could be seen from the fig.4.

[1] $\omega_{p:}$ soil's plastic limit value

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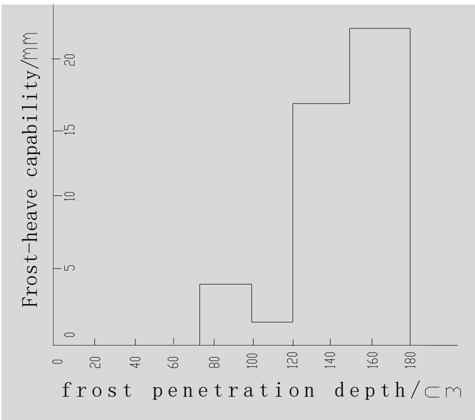

Figure 4. The distribution pattern of frost-heave in soil

The above illustrations of the frost-heave distribution pattern along the frost penetration depth show two typical types of distribution features. It proves the soil properties and groundwater level could determine the difficulty level of the water movement in the soil, which also determines the moisture content rate in soil as well as the frost-heave capability. What's more, it actuarially shows the frost-heave distribution pattern along the frost penetration depth is not a singleton pattern.

III CALCULATING METHOD

The frost-heave capability is closely related to its frost penetration depth. The frost penetration depth value is very crucial for anti-frost design depth of the roads, construction process and the choice of construction methods. As for the temperature difference, the different places in Jilin Province have different frost penetration depths [12]. According to the characteristics of the seasonal frozen ground and the influential factors of the frost penetration depth, this essay will put forward several methods to calculate the frost penetration depth.

A. The Air freezing index Ωd and negative temperature value Ωm

The related statistics from the local Meteorological Bureau was combined with the collected data of the frost penetration depth from the observations points to form an empirical formula that will describe the relationship between the frost penetration depth and freezing index as well as the accumulated value of negative temperature, through which the frost penetration depth will be calculated [13].

Air freezing index Ω_d: The product of the daily mean temperature that below 0ºC and the number of days that below 0ºC.

Accumulated value of negative temperatureΩ_m ： The sum of the monthly mean temperature that below 0ºC （usually four months all together: start from the Nov. of the current year to the Feb. of the next year）.

Apply the two-point method for the statistical computing and the results are shown in Table II.

TABLEII. THE STATISTICAL RESULTS OF FROST PENETRATION DEPTH, FREEZING INDEX AND ACCUMULATED VALUE OF NEGATIVE TEMPERATURE

ID	Frost penetration Depth h_0/cm	Freezing index Ω_d/℃d	Accumulated value of temperature Ω_m/℃m
05	176.5	901.4	30.7
06	165.2	907.2	31.2
07	156.4	895.7	31.2
08	170	1022.6	51.2
09	185.1	1229.6	56.7
10	148.2	886.5	30.9
11	162	886.5	30.9
12	174.1	886.5	30.9
13	209.8	2104.6	70.3
14	216.7	2163.7	70.3
15	198.5	1189.4	40.6
16	201.3	1198.7	39.5

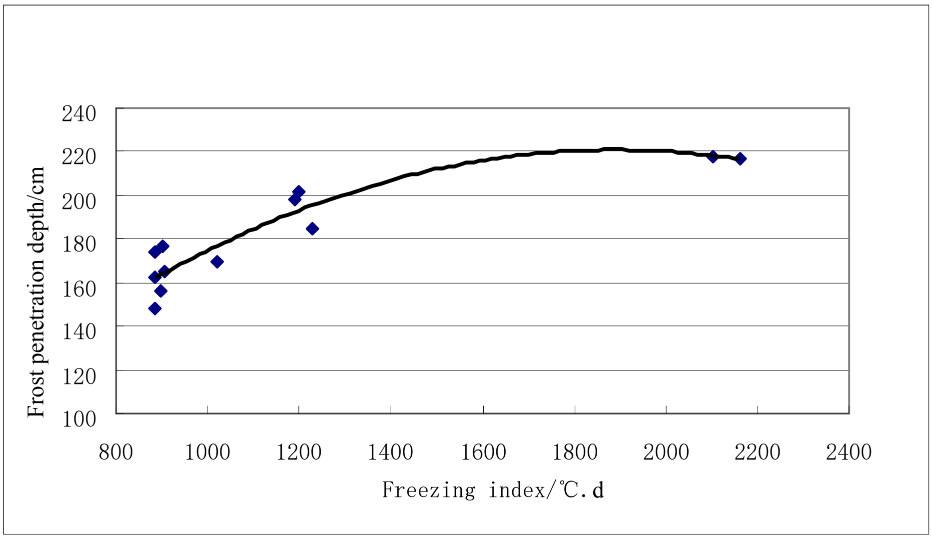

Fig 5 Diagram of frost penetration depth and freezing index

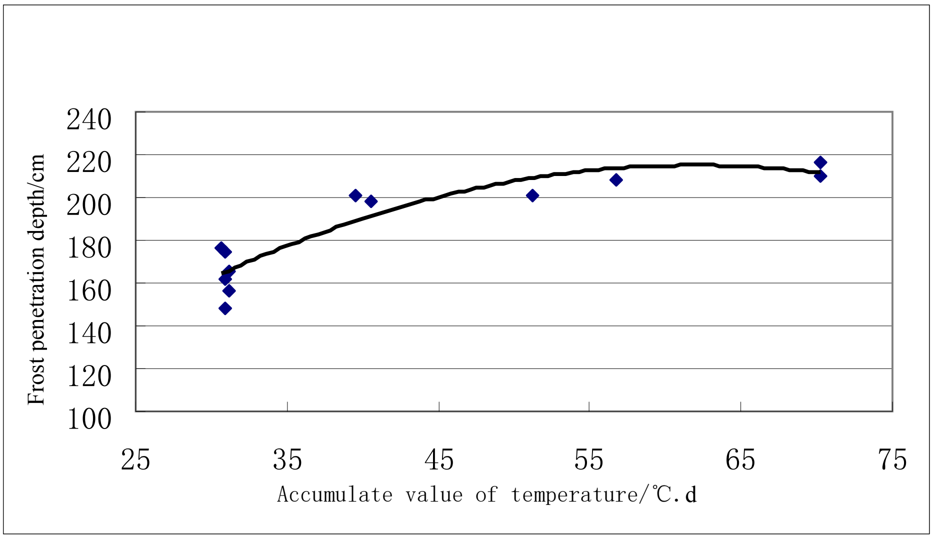

Fig 6 Diagram of frost penetration depth and accumulates value of temperature

According to the frost penetration depth value h_o, freezing IndexΩ_d and accumulated value of negative temperature Ω_m , a scatter plot was made (fig5 and 6), and a linear regression analysis was also performed to get an empirical regression formula:

$$h_0 = 0.036\Omega_d^{\ 2} + 135.48, \quad (2)$$

$n=12$, $R^2 = 0.843$;

$$h_0 = 15.27\left(\sqrt{\Omega_m} + 5.35\right), \quad (3)$$

$n=12$, $R^2 = 0.925$.

It could be seen from the figures above that a strong relationship does exist among the three which will prove the effectiveness of the empirical formula, especially the (3) that has a higher correlation.

According to the meteorological data, the frost penetration depth could also be calculated by the formula below：

$$h_0 = C\sqrt{\Omega_d} \quad (4)$$

where： C is constant， is related to the sunshine condition of the roadbed, soil properties and drainage condition etc. Based on the realistic situation of study are, the appropriate value of C is 5. And the comparison could be made between the calculated value and actual value in Table III as below:

TABLE III. THE COMPARISON BETWEEN THE ACTUAL AND CALCULATED VALUE OF FROST PENETRATION DEPTH

ID	Actual value h_{01} /cm	Calculated value h_{02} /cm	Freezing index Ω_d/℃d
05	176.5	150.1	901.4
06	165.2	150.6	907.2
07	156.4	149.6	895.7
08	170.0	159.9	1022.6
09	185.1	207.9	1729.6
10	148.2	148.9	886.5
11	162.0	148.9	886.5
12	174.1	148.9	886.5
13	209.8	232.1	2154.6
14	216.7	232.6	2163.7
15	198.5	172.4	1189.4
16	201.3	173.1	1198.7

TABLE IV. THE RELATIONSHIP BETWEEN THE FREEZING INDEX AND THE CONSTANT C

Freezing index Ω_d/℃d	901.4	907.2	895.7	1022.6	1729.6	886.5	886.5	886.5	2154.6	2163.7	1189.4	1198.7
Constant C	5.88	5.48	5.22	5.32	4.45	4.98	5.44	5.85	4.52	4.64	5.76	5.81

It is obvious that the overall calculated values are lower than the actual values and that is because of the value of C. According to the rules, when C=5 the condition is prone to the frost-heave, when C=3 the condition is unlikely to have the frost-heave problem and when the condition is moderate the C=4. But in real situation, the value of C is dependent on a variety of reasons, such as the particle composition, the compactness, the moisture content rate, the groundwater level and the climate condition etc. In order to get the actual value of C, the freezing Index should be combined with the actual frost penetration depth value (Table IV).

The results of Table IV show that the values of C are basically around 4-6, and most of them are above 5. This results also prove that the study area is prone to the frost-heave problem. To ensure the frost penetration depth formula’s practicability and simplicity, use the mean value of C, which means the maximum 5.88 and minimum value 4.45 will be removed. And the mean value of C is 5.3. According to the formula (4) above:

$$h_0=5.3\sqrt{\Omega_d} \qquad (5)$$

Through the above analysis, it could be concluded that the mean value of frost penetration depth could not be used in the designing process, and the empirical formula for calculating the frost penetration depth should be able to reflect the actual situation as much as possible. Therefore, the formula (2), (3) and (5) meet the basic requirements, especially in the study area.

VI. CONCLUSION

This essay has done the research on the frost damage of the cement concrete highway subgrade in the seasonal frozen ground area. The conclusions are:

- There are two kinds of frost-heave: one is in-situ frost-heave, and the other is segregation frost-heave. In the open system, the segregation frost-heave capability in saturated soil is the major reason for the frost-heave problem. With regard to the particles, the finer particles, the higher moisture content rate and the severer the frost-heave problem is. The frost–heave capability is also related to dye weight of the soil and when the value is 18kN/m³ the frost-heave capability reaches its peak value.
- The frost-heave rate is directly proportional to the moisture content rate. The high-fill embankment has a cushion whose depth will have a compressive stress on the subgrade. This inhibitory action will reduce the amount of frost-heave effectively.
- The distribution pattern of frost-heave along the frost penetration depth is not just one mode. When the groundwater is buried deep, the frost-heave amount in the upper part is big. When the groundwater is buried shallow, the frost-heave amount in the lower part is big.
- The local frost penetration depth empirical formula depends on its air freezing Index and the accumulated value of negative temperature. When the air freezing index is settled, the higher the moisture content rate is, the stronger the frost-heave capability is while the frost penetration depth will be smaller. In the same way, if the moisture content rate is getting lower, the

frost-heave capability will get weaker, and the frost penetration depth will grow bigger.

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