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Discrete element modeling of subgrade frost heave in high-speed railway

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Abstract. Discrete element (DE) model which considered the interaction between fine particles and coarse particles was established in order to analyze railway subgrade frost heave in cold regions. The relationship between frost heave amount and the depth of railway subgrade and the proportion of frost heave amount of each layer in the total were explored in this paper. The influence of fine particle expansion rate, soil density, soil porosity and slab track load on the subgrade frost heave was studied. Results show that the subgrade frost heave amount grows along with the increase of the depth. Subsequently, the frost heave reaches the stability stage and the amount remains essentially unchanged. 65% of the total frost heave amount is produced within the surface layer of subgrade bed, 0.6 m in depth. The bottom layer of subgrade bed accounts for 33% with 2% of the soil below the bottom layer. As the main influencing factor of the railway subgrade, the fine particle expansion ratio has a significant influence on the subgrade frost heave, the amount of which increases approximately linearly with the fine particle expansion ratio. The influence of soil density and soil porosity on the subgrade frost heave is similar, the trend of which increases first and then decreases. The gravity effect of the slab track structure, whose load is an influencing factor to subgrade frost heave, can inhibit the development of the subgrade frost heave. The results are of reference value to survey, design, construct and maintain railway, providing the reliable materials for the establishment of the designing specification of railway in cold regions.

Key words. Subgrade frost heave, Fine particle expansion ratio, Soil density, Soil porosity, Slab track, Numerical simulation.

1. Introduction

With the development of high-speed railway industry, deformation of railway subgrade caused by frost heave happens frequently in the seasonally frozen regions in China. Up to 2017, the total mileage of the China's high-speed railway exceeded 22,000 km. At the same time, China is a country with large amounts of frozen soil

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and seasonally frozen regions accounting for about 53.5% [1-2]. Subgrade frost heave results in track irregularity and affects the safety and stationarity of the train directly [3]. In order to master the operation status of the railway subgrade and guarantee route security in cold regions, the subgrade frost heave and the influencing factors are studied in this paper.

In recent years, extensive research has been conducted on the subgrade frost heave through laboratory experiments and in-situ monitoring. Bronfenbrener L and Fowler A C et al., established the secondary frost heave model and analyzed the mechanism of subgrade frost heave[4-5]; T Jk et al., studied the chemical factors needed in the process of soil frost heave[6]; Akagawa S et al., proposed that frost heave mainly occurred in the surface layer of subgrade bed[7]; Ulitsky V M, Sheng Daichao and Liu D R et al., investigated the subgrade frost heave features through field measurement and numerical simulation, and proposed corresponding measures to prevent frost heave in addition [8-10]; Konrad J M and Jean Cote et al., proposed anti-freezing expansion method of subgrade using experiments [11-13]; Zhao Guotang proposed frost heave management standard and determination methods of high-speed railway through testing the route from Harbin to Dalian [14]; RR Gilpin established a model that predicted heave rates to prevent frost heave[15]; Ryu et al., proposed a new standard freezing and thawing testing apparatus to evaluate frost heave for soils[16]; Du Xiaoyan et al., studied frost heave mechanism and classification of subgrade filling through monitoring [17]. In summary, although the scholars have done a lot of research on subgrade frost heave, the relationship between the frost heave amount and the depth, as well as the influencing factors is still lack of study.

This paper analyzes the relationship between the subgrade frost heave and the depth, the proportion of each layer accounting for the total and the main influencing factors in DE software PFC. The results can provide important technology support to the construction, the operation and the maintenance of high-speed railway in cold regions.

2. Structure of railway subgrade and frost heave model

2.1. Railway subgrade structure

The railway subgrade is the structure that withstand the action of track and train dynamic, which is the basis of the track and the important structure that guarantees the running of trains. The railway subgrade is a multi-layer structure system, which is divided into the surface layer, the bottom layer and the soil below the bottom layer. The surface of railway subgrade has a width of 13.4 m.

The structure of high-speed railway subgrade is shown in Figure 1.

Due to the multi-layer structure of railway subgrade, the subgrade packing of each layer is different. According to the High-speed Railway Design Specification (TB10621-2014): packing of group A should be selected for the surface layer of subgrade bed; packing of group A and B should be selected for the bottom layer of subgrade bed; packing of group A, B and C are preferably selected for the soil below the bottom layer. Packing of group A, B and C are called high quality packing, good

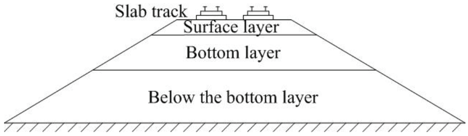

Fig. 1. Railway subgrade structure

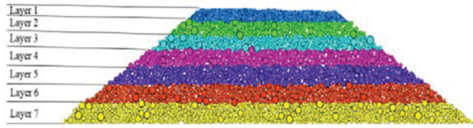

Fig. 2. DE model of railway subgrade

packing and available packing, respectively.

2.2. DE model of railway subgrade

DE method is mainly used to simulate the ballasted bed in the field of railway. Nevertheless, the simulation is more difficult due to that particles of railway subgrade are more and smaller than ballasted bed. Moreover, the railway subgrade frost heave is the difference value between frost heave pre and post in the cross section of subgrade. In order to save computation time and improve computational efficiency, the subgrade frost heave is simulated by PFC2D in this paper.

By setting different depths, the frost heave amount is obtained in the DE model. It is apparent that the frost heave of surface layer is the largest and gradually weakens along the depth. In order to find out the relationship between the frost heave and the depth, stratified frost heave of subgrade was developed.

The DE model of railway subgrade is shown in Figure 2 and microscopic model of subgrade is shown in Figure 3.

(a) Sufficient fine particles (b) Proper fine particles

Fig. 3. Microscopic model of subgrade

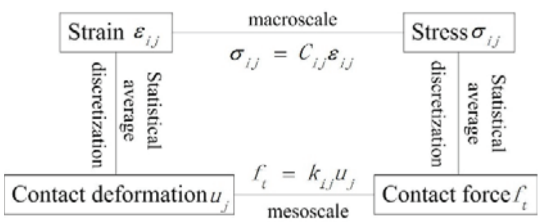

Fig. 4. The relationship of macroscopic and microscopic parameters

The subgrade frost heave is often caused by volume expansion of some fine soil particles under low temperature. In DE software PFC, the phenomenon is simulated by letting the fine particles expand. It can be seen from Figure 3(a) that the skeleton gap is filled with excessive fine particles content and the skeleton is uplifted when the frost occurs. On the macroscopically, the frost heave occurs. The fine particles content in Figure 3(b) just reaches saturation state and macroscopically frost heave doesn't happen.

2.3. Key parameters and values

There is a cohesive force among the subgrade particles, granular materials, which has a certain tensile and shear strength. The bond among the particles will be destroyed when the maximum stress exceeds the corresponding bond strength no matter which direction. This paper adopts parallel bond model to simulate the contact relation. In order to obtain the relationship between the macroscopic and microscopic parameters of the subgrade. Calibration experiments must be carried out.

In Figure 4, C_{ij} and K_{ij} are calibration coefficients. Through plane strain numerical tests and refer to existing studies [17], the mutual relationship was built and the microscopic parameters of the particles were determined. After the calibration experiment, the relationship between macroscopic and microscopic parameters of the particles are:

$$\varphi = \varphi(E_n, k_n/k_s, f), \tag{1}$$

$$c = c(E_n, k_n/k_s, f), \tag{2}$$

$$E_n = k_n/2t, \tag{3}$$

where φ is the internal friction angle; c is cohesion force; E_n is the contact deformation modulus among particles; and t is the thickness of the granular disk. In general, the defaults value is 1; k_n and k_s are respectively the particle normal and shear stiffness; and f is the friction coefficient of particles. The macroscopic and microscopic parameters of the subgrade structure are shown in Table 1 and Table 2, respectively.

Table 1. Macroscopic parameters of subgrade structure

Material type	Depth/m	Density/(kg.m^3)	Elasticity modulus/MPa
Surface layer	0.6	2200	180
Bottom layer	1.9	2000	110
Soil below bottom layer	2.5	1900	50

Table 2. Microscopic parameters of subgrade structure

Parameters	Normal and shear stiffness/(N/m)	Friction coefficient
Values	2×10^6	0.31

There exist rail, slab track and other structures in the upper part of railway subgrade. According to the standard for subgrade design in the China High-speed Railway Design Specification (TB10621-2014), 60 kg/m standard rail should be used, whose gauge is 1.435m. The thickness of slab track, CA mortar and concrete base should be 0.20 m, 0.05 m and 0.30 m, respectively. The external load can't be applied directly on the subgrade in DE software PFC, so the 0.002 m contacted balls are generated on the surface of the subgrade by clump command to apply the uniform load with a stress of 60.3 kPa.

The initial temperature is set to 0°C accounting for that the initial freezing temperature of subgrade soil is usually lower than 0°C. The atmospheric temperature changes have the greatest influence on the surface of the subgrade. Under the effect of temperature gradient load, the temperature gradually descends from the subgrade surface. Considering the influence of subgrade temperature gradient [18], the fine particles expansion ratio is reduced from top to bottom in the simulation, as is shown in Figure 5.

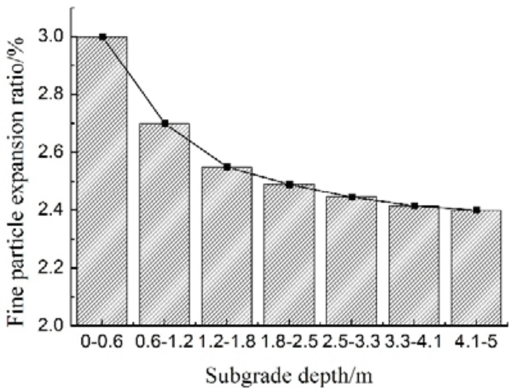

Fig. 5. Fine particles expansion ratio with depth

3. Analysis of frost heave of subgrade multi-layer structure

After carrying out stratified frost heave, the vertical displacements of subgrade are obtained by selecting multiple groups of particles at different depths as the measuring circle. The vertical displacements are the corresponding frost heave amount in the soil layer. In order to analyze the relationship between the frost heave amount and the depth, the relationship curve is plotted, as is shown in Figure 6 and Figure 7.

From Figure 6, it is clearly seen that the frost heave amount grows rapidly along with the depth at the different rate of growth. When the subgrade frost depth reaches 2.5 m, the curve becomes slower with the maximum amount of 22.534 mm. As is shown in Figure 7, the frost heave amount gradually decreases along with the different frost heave layers. When the layer depth reaches more than 2.5 m, the frost heave amount is tending to 0. In order to prevent subgrade frost heave, the proportion of each layer in the total is studied, as is shown in Figure 8.

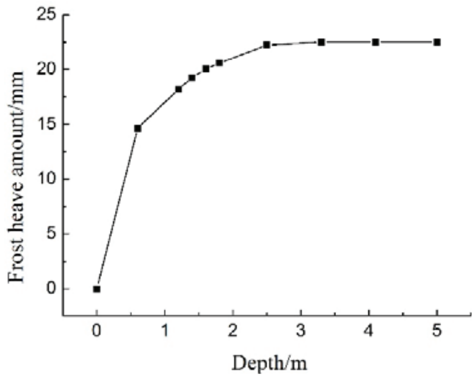

Fig. 6. Relationship curve between amount and depth

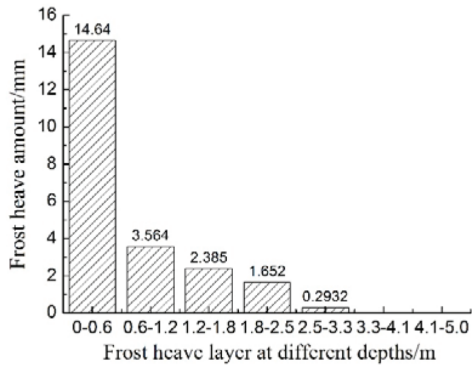

Fig. 7. The frost heave amount of layer at different depths

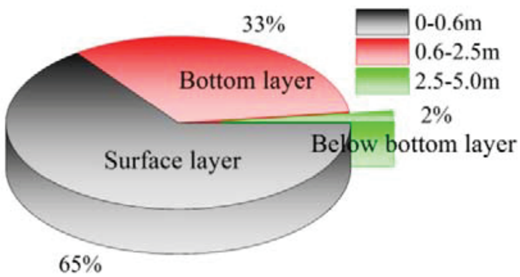

Fig. 8. The ratio of frost heave of each layer in the total frost heave

From Figure 8, it is noted that the frost heave of different structure layers is different obviously and composes the total subgrade frost heave amount. The frost heave amount of the subgrade bed surface layer is the main component of the total with proportion of 65%. Therefore, the surface layer of subgrade bed temperature is the lowest, and there is a certain temperature difference in the inner soil of the subgrade, which forms the phenomenon of transferring from high temperature to low temperature. Besides the in-situ frost heave, the moisture in the frost heave layer with a large depth of subgrade continuously migrates to the surface of the bed to form ice crystals, which leads to the largest amount of frost heave in the surface. The bottom layer of subgrade bed accounts for 33% of the total frost heave amount with the soil below the bottom layer accounting for 2%.

It can be seen from the experimental results of Harbin to Dalian high-speed railway in reference [14], the frost heave amount becomes invariable when the depth reaches 2.7 m, with surface layer of subgrade bed accounting for 68% of the total. In the numerical simulation, when the subgrade frost depth reaches 2.5 m, the frost heave amount becomes invariable, with surface layer of subgrade bed accounting for 65%. The results of numerical simulation are in good agreement with the field tests, which is proved that the model is reliable for the analysis of subgrade frost heave.

4. The influencing factors analysis of subgrade frost heave

There are many complicated factors that influence subgrade frost heave, which relates to the local temperature and soil property. In general, the frost heave may happen until the three following cases are met: the freeze prone subgrade soil, high water content of the subgrade and low enough temperature of the cold season.

That soil is prone to freeze is the internal cause of frost heave, of which the significant factor is the temperature gradient. Therefore, this paper simulates frost heave of subgrade according to the influence of fine particle expansion ratio, soil density, soil porosity and external load of slab track.

4.1. The influence of the fine particle expansion ratio

The fine particle expansion ratio is different in each layer and the frost heave amount of the subgrade bed surface layer is the main component of the total. Thus, the section analyzes the changes of subgrade frost heave of surface layer with different fine particle expansion ratios, which relate to the temperature gradient and are the main influencing factor of subgrade frost heave. This section changes the fine particle expansion ratios to study the change values of the frost heave by setting temperature gradient. In the model, 7 cases of the fine particle expansion ratio from 1% to 4% were analyzed.

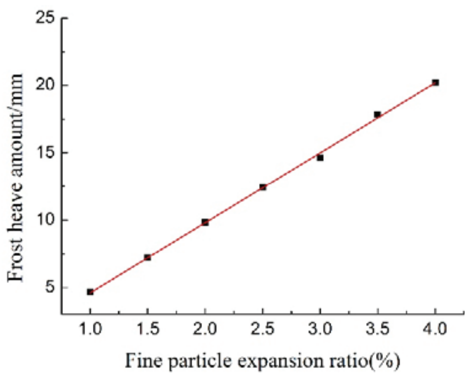

Fig. 9. Influence of fine particle expansion ratio on frost heave

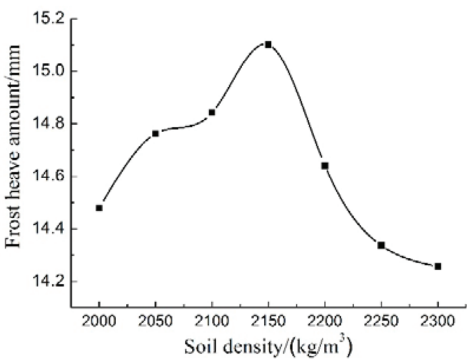

Fig. 10. Influence of soil density on frost heave

From Figure 9, it can be seen clearly that there is a linear relationship between frost heave and fine particle expansion ratio. As the fine particle expansion ratio increases, the frost heave amount increases. The subgrade frost heave numerical simulation is developed by setting different fine particle expansion ratios and the calculation results of DE model are fitted. The fitting curve is:

$$y = -0.571 + 518.789x, \tag{4}$$

where y is the frost heave amount of surface layer of subgrade bed, mm; and x is the fine particle expansion ratio.

4.2. The influence of the soil density

The section analyzes the influencing factor of soil density on the surface layer of subgrade bed frost heave. In the model, 7 cases of soil density from 2000 kg/m3 to 2300 kg/m3 were analyzed and the interval was 50 kg/m3. In general, as soil density increases, the pores of the soil reduce and the water content is constant while the soil is saturated. The relationship between soil saturation and density satisfies the following relation:

$$S_r = \frac{WG_s\rho_d}{G_s\rho_w - \rho_d}\,, \tag{5}$$

where S_r is the soil saturation (%); W is the water content (%); G_S is the particle proportion; ρ_d is the soil dry density (g/cm3); and ρ_w is the water density.

In the case that other factors are invariable, the soil particles have sufficient gap for free expansion when the soil density is small. As soil density increases, the saturation of soil increases. Meanwhile, the frost heave grows and reaches to the maximum at a certain density where the saturation and porosity of the soil is optimum to freeze. When the soil density exceeds this limit, the subgrade structure gravity will restrain frost heave.

From Figure 10, it is noted that the relation between soil density and frost heave is an exponential curve. As the soil density increases, the fine particles of the unit volume in the skeleton increases when the density is small. Hence, the frost heave amount increases along with the soil density increases. Furthermore, the subgrade frost heave amount reaches its peak at a particular value (about 2150 kg/m3) and the maximum is 15.10 mm. When the density increases continuously, the frost heave amount decreases due to subgrade structure gravity.

4.3. The influence of soil porosity

The soil porosity is the main influencing factor of subgrade frost heave. The section analyzes the influencing factor of the soil porosity on the subgrade frost heave. In the model, the change quantity of the subgrade frostheave amount was analyzed in 8 cases of soil porosity from 4% to 18% with the interval of 2%.

The relationship between frost heave and soil porosity is shown in Figure 11. As soil porosity increases, the frost heave amount increases when the soil porosity is low. Then the amount of frost heave reaches to the maximum, 22.534 mm, till the porosity is about 12%. When the soil porosity continues to increase, the frost heave amount decreases. This is because water does not penetrate easily and the water content is relatively small when the soil porosity is small. As the soil porosity increases gradually, the water content becomes larger and the ice crystals are formed, which makes the frost heave amount increased. When an optimal porosity is reached, the ice crystals are at most and the frost heave reaches the maximum. As the soil porosity increases continuously, the difference values between volume expansion and gap volume reduce gradually and the frost heave amount decreases.

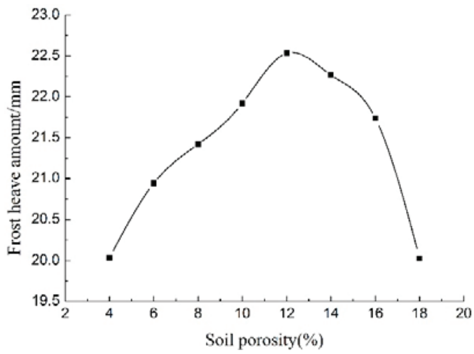

Fig. 11. Influence of soil porosity on frost heave

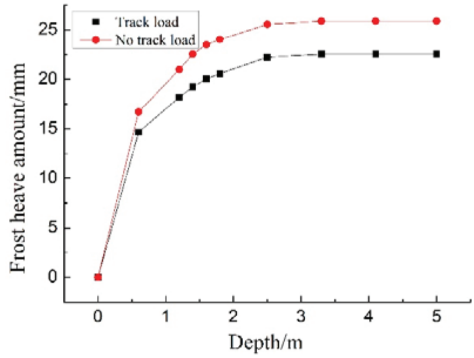

Fig. 12. Influence of track load on frost heave

4.4. The Influence of Slab Track Load

The upper part of the high-speed railway subgrade is the slab track, which consists of the rail, the fasteners and the slab track bed structure. The gravity load of rail and fasteners are small, while the slab track bed structure has a big weight with a thickness of 55 cm. In this paper, the influence of track load on frost heave of subgrade was studied, as is shown in Figure 12.

From Figure 12, it is clearly seen that the subgrade frost heave amount reaches 25.890 mm without the load and reaches 22.534 mm with the gravity load of slab track. In both cases, the trend of the subgrade frost heave is basically consistent. However, the gravity effect of the slab track structure can inhibit the development of the subgrade frost heave. In addition, the gravity load will increase the contact stress between the soil particles and reduce the freezing point of the water in the soil, which can inhibit water migration and affect the liquid and solid transformation of soil water. Therefore, it is necessary to consider the gravity load of slab track in the simulation analysis of the subgrade frost heave.

5. Conclusions

In this study, railway subgrade frost heave model was established in DE software PFC. Then the relationship between frost heave amount and the depth of railway subgrade was studied in this paper. In addition, the influences of fine particle expansion ratio, soil density, soil porosity and track load on subgrade frost heave were analyzed. Some conclusions are drawn:

(1) The subgrade frost heave amount grows along with the frost heave depth. When the depth reaches 2.5 m, the frost heave is essentially unchanged and the maximum is 22.534 mm.

(2) The relationship between the frost heave amount and depth is nonlinear. This is because the contribution of the frost heave in each layer of the total is different. The frost heave amount of the surface layer of subgrade bed is the main component

of the total with proportion of 65%.

(3) The frost heave amount increases approximately linearly with the fine particle expansion ratio. The influence of soil density and soil porosity on the subgrade frost heave is similar, whose trend increases first and then decreases. The gravity load of slab track has a certain inhibitory effect on the frost heave.

Acknowledgement

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