Research on Characteristics of freezing and thawing process controlled by Foundation temperature field

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Abstract: This research introduces the soil buildings’ foundation of geological structure in Liaodong Peninsula and the building foundation type. It 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 foundation. Based on the law of frozen depth of foundation, 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.

1. Introduction

Liaodong Peninsula is the main distribution area of coastal soft soil in northeast China[1]. The soft soil are mainly distributed in urban areas or old border region. The region’s building foundation is more soft soil. With the using time passing, the building foundations appear the following three kinds of common problems: the first is the strength and stability problems. When the foundation of the shear strength is not enough to support the weight of the upper structure and the external load, the foundation can produce local or overall shear failure. The second is compressed and uneven settlement problem. When the foundation is outside the dead weight of the upper structure and loads, it produces the excessive settlement and uneven settlement deformation which affects the normal use of structure. Especially when settlement at structure can allow the uneven settlement, the structure may crack damage. The third is when the foundation seepage quantity exceeds permissible value, and water loss will lead to the accident happens.

The characteristic of the masonry buildings is the poor integrity and low tensile shear strength, which is easy to produce cracks. The buildings’ integrity, durability and shock resistance are reduced with a long cycle using. Soft soil foundation with the temperature change of frozen heaving and the temperature has great influence to the stability of the foundation[3]. Therefore, it’s important to carry out some researches which include the mechanism of frozen heaving and reasonable protection of the old buildings’ durability.

2. Climatic and geological conditions of observation points in the experimental area

2.1 Geological conditions

The soft soil layer in Liaodong Peninsula is fluvial fancies sedimentation. According to the different lithology, it can be divided into four different main formations down from the surface: artificial filling
soil, brown-yellow powder clay layer, gray cohesive soil, yellow powder clay and silty sand layer. Among them, the brown yellow powder clay layer is the main bearing layer which belongs to the natural shallow foundation in Liaodong Peninsula. The thickness of strata gradually increases from west to east, from 1~2m to 4~5m. The composition of gray cohesive soil is relatively complex, and the layers rule is the cohesive soil alternate with the silty sand layer. The yellow clay and silty sand layer is the available bearing layer of pile foundation[4].

The gray cohesive soil is gradually thickened from east to west, the east is commonly 3~5m, and the west is generally 13~15m. From each of the soil layer is the silty clay, silt, silty sand, silt and silt soil. According to the different combinations with the buried depth, sequence and thickness, it makes up the different types of foundation soil. It can be summarized into three basic types, such as: general cohesive soil, silt soil, saturated sandy soil foundation. The reflection and adaptability from the different types of building foundations is quite different.

2.2 Climatic conditions
Liaodong Peninsula is located in the northeastern Bohai Bay, which belongs to half warm temperate zone monsoon climate. The area with an average annual temperature of 9.3℃, extreme maximum temperature of 33℃, extreme minimum temperature of -22℃; the annual average rainfall of 720mm, the average annual sunshine of 2588.7 hours, early freeze period in early November, thawing time for the mid-year in March, snowfall of up to five mouths. The area mostly blow with the southwest wind in spring, wind speed of 5-9m/s, the maximum wind speed of 40m/s. Winter for northwest wind, wind speed of 3-6m/s[9].

3. Monitoring system
The observations in the model begin from October 2014. The study is based on the data from October 2014 to May 2015 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. The foundation soil is divided into three layers: the first layer is muddy clay powder, yellowish gray, no bedding, thickness of 0.2-0.7m, the bottom elevation of 1.2-1.3m; the second layer is silty clay, yellowish gray, no bedding, thickness of 2.6-2.8m, the bottom elevation of 1.3-1.5m; the third layer is gray, plastic flow state, high compressibility.

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 foundation at different locations and depths, which laying depth from the road down 0.6m, 1.0m, 1.6m, 2.2m, 2.8m, 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 foundation 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 0.5m, 1.0m, 1.5m. The monitor system layout is shown in figure 1.
4. The analysis of observation result

4.1 The transformation law of foundation temperature field

Fig. 2 illustrates the variation of the temperature of different model levels with time during a wintering period from October 2014 to May 2015.

![Fig. 2 variations of foundation temperature with time at each depth in winter](image)

From figure 2, it can be seen that the foundation freezing period in the experimental site is 74 days, which is from 26 December 2014 to 10 March 2015. The melting period is 40 days, from 16 March 2015 to 28 April 2015. During the whole freezing and thawing time, the ground temperature decrease 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 result of the average temperature changes at the test period, the lowest average temperature is -22.8°C at 2014 January 21,
and the highest one is 30.5°C at 2014 May 31. The descent rate of temperature is relatively fast from 8 November to 21 January, and the drop temperature is 26.9°C. January is the coldest mouth, and the average temperature is -16.33°C. Through the observation of the lowest temperature at the depth of 0.6m and 1.0m, the respective date are 19 February and 24 February, and the respective temperature are -2.9 and -1.3°C.

Fig.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 foundation 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 20.1°C at the depth of 0.6m, it changed to 11.3°C at 1.0m, at the depth of 1.60m, the ranged is 5.1°C, and at 3.2m, the range of temperature change is only 0.6°C. The temperature change on the temperature field of foundation decreases. The process of heat transfer is accompanied by energy attenuation.

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.

\[ y = ax^2 + bx + c \]  

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.

| Soil depth/m | Regression coefficients | Correlation coefficient | R² |
|--------------|-------------------------|-------------------------|----|
| 0.6          | a 5.394×10⁻⁴  | b 0.354 | c 5.612 | 0.883 |
| 1.0          | a -3.848×10⁻⁴ | b 0.322 | c 6.790 | 0.869 |
| 1.6          | a -3.97×10⁻³   | b 0.308 | c 7.947 | 0.876 |
| 2.2          | a -5.07×10⁻³   | b 0.293 | c 9.023 | 0.872 |
| 2.8          | a -1.97×10⁻³   | b 0.261 | c 9.643 | 0.898 |
| 3.2          | a -1.76×10⁻³   | b 0.227 | c 10.242| 0.908 |

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

Table 2 Parameter changes in freezing process

| Soil           | Depth from the pavement/m | Start and end time   | time/d | Temperature change width/°C | Decreased rate(°C/d) |
|----------------|---------------------------|----------------------|--------|----------------------------|----------------------|
| Muddy silty clay| 0.2-0.7m                  | 2014.12.25-2015.2.18 | 53     | 23.4                       | 0.4415               |
| Silty clay     | 0.7-3.4m                  | 2015.2.18-2015.3.10  | 21     | 1.3                        | 0.0619               |

Table 3 illustrates the process of foundation freezing, and it can be seen that the effect of atmospheric temperature field on upper foundation is obvious, and the freezing time is 28 days. At this moment, the temperature get through 0°C 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, the effect is weak. At this stage, quick freezing happen, ice embryos and buds are formed. Then the lower foundation begins to freeze, and the rate of temperature fall of upper foundation is 0.4415 °C/d, and it differs a lot with that of lower foundation. 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 foundation during this period, the frozen cover keeps going down. The moisture content of foundation 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 0.0619 °C/d and it lasts 21 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

| Soil           | Depth from the pavement | Start and end time   | time | Temperature change width | Decreased rate |
|----------------|-------------------------|----------------------|------|--------------------------|----------------|
| Muddy silty clay| 0.2-0.7m                | 2015.3.3-2015.4.28   | 55   | 14.3                     | 0.26           |
| Silty clay     | 0.7-3.4m                | 2015.3.24-2015.4.28  | 34   | 3.9                      | 0.1147         |

Table 3 illustrates the melting process of foundation. Through this table, it can be seen that the upper foundation begin to melt at 3 March, and it lasts 55 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 foundation. During the melting, the temperature gradient of the foundation 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 foundation is shorter than the upper foundation, 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. It is illustrated that
melting time 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 problems usually occur under the action of foundation vehicle dynamic load, such as foundation frost boiling.

4.2 The relationship between the depth of freezing and temperature
In order to conclude the relationship between the frozen depth (Df) and temperature, it introduce the surface accumulation of negative temperature (STS) and daily average temperature (TP) as the temperature variables. Through figure 4, it can be seen that the frozen depth (Df) is increasing with the increasing of the absolute value of the surface accumulation of negative temperature (STS) into the rapid growth phase. When 21 February 2015, the maximum frozen depth is 116.4cm, STS of -1029.8℃. At this stage, STS linearly correlated with Df. Subsequently, due to the heat transfer is higher than the lower portion of the upper soil layer deep cold soil transfer, despite the STS 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 foundation temperature is above 0℃, melting into the stable foundation stage. At early-May, the up melting layer overlapping, the melting process is over.

![Fig.4 relationship between the frozen depth and surface accumulation of negative temperature](image)

The frozen depth (Df) and daily average temperature (TP) relationship curve is shown in figure 5. It can be seen that the upper foundation (0.6m) 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 (Df) 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 90s days, compared to the daily average temperature of cooling time lagging 28s days. When the daily average temperature reaches the lowest, the frozen depth only develop to a maximum of 73%; when the daily average temperature rise to 0℃, the soil in lower subgrade is only 9.6% melted.
Fig. 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 90s days, the freezing rate is 15.6mm/d; phase two is steady phase, the frozen depth basically unchanged with time by using 14s 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 50cm (DZ50) occurs from Nov.26. When the surface accumulation of negative temperature (|STS|) of 159.7℃, the frost heave in the depth of 50cm increases to a maximum of 0.91mm lasted about 29s days. Subsequently, the frost heave remains level during the freezing. The frost heave in the depth of 100cm (DZ100) appears a linear increasing trend when the value of |STS| is between 0℃ and 444.1℃, the frost heave reaches to 4.46mm at this stage; then DZ100 maintain the level of state when the value of |STS| is between 441.1℃ and 630℃; finally, DZ100 appears a linear increasing trend again when the value of |STS| is between 630℃ and 1445.7℃, the frost heave in the depth of 100cm increases to a maximum of 7.57mm at March 12, 2015. The frost heave in the depth of 150cm (DZ150) is always 0mm lasted about 27s days when the value of |STS| is between 0℃ and 444.1℃; Finally, DZ100 appears a linear increasing trend to a maximum of 6.68mm.
Fig. 6 relationships between frost heave and surface accumulation of negative temperature

Among them, the frost heave of DZ100 reading 7.87mm which located in the upper part of lower foundation 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 DZ150 reading 6.31mm 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 (DZ) and the frost heave of DZ100 with the value of STS can get linear regression equation 2 and 3.

\[
D_z = 0.010ST_z + 0.646 
\]  
(2)

\[
D_{Z100} = 0.004ST_z + 0.766 \]  
(3)

Both Sig are less than 0.01, indicating the differences are significant and the results fit well. But the relationships between DZ50 and DZ150 with the value of STS can’t get linear regression.
Fig.7 relationships between frozen depth and surface accumulation of negative temperature

Fig.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 (DZ) and the frozen depth (Df) have strong correlations with the surface accumulation of negative temperature (STS). Figure 8 shows the variation curve between the total amount of frost heave (DZ) and the frozen depth (Df). According to the variations between (DZ) and Df can get linear regression equation 4.

\[ D_z = 0.013D_f + 0.638 \]  

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

5. Conclusion

Based on the test section of foundation temperature and deformation observation data analysis during the winter from October 2014 to June 2015, this paper can draw the following conclusions:

The temperature field at different depths and the average daily temperature trends are basically the 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 foundation 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. 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 foundation (DZ100), the second place is the end of frozen depth (DZ150), the minimum place is at the foundation of 60cm depth (DZ50). The data shows the location of the ice layer gathered in DZ100 and DZ150. The amount of frost heaving deformation is related to soil quality and moisture migration.

The study has shown that the total amount of frost heave (DZ) and the frozen depth (Df) present a significant positive correlation with the surface accumulation of negative temperature (|STS|). 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 (DZ) and the frozen depth (Df). The frost heave can be known by monitoring the frozen depth, which decreases the cost and difficulties.

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