Study on Frost Heaving Evaluation of Typical Soil Samples along Qinghai-Tibet Highway

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Abstract: Based on the geological survey data of 167 boreholes along the Qinghai-Tibet Highway, the relationship between frost heaving force and natural density and water content of soil samples was analyzed and evaluated. The results show that the natural density along the line is concentrated from 1.9 g·cm$^{-3}$ to 2.2 g·cm$^{-3}$. The frost heaving force decreases with the increase of the natural density. Frost heaving force is affected by natural density in three stages. The frost heaving force increases with the increase of natural water content, which can be divided into three stages, too. The surface water system is developed and the water content in the shallow layer is relatively large, which makes the frost heaving force reach 37kPa, which is the maximum along the line.

1. Introduction
The Qinghai-Tibet Highway traverses more than 760km of permafrost area, among which the permafrost continuous distribution area is 550km$^2$. Along the Qinghai-Tibet Highway, the permafrost degradation is obvious due to the mutual influence of the construction projects. On the one hand, the degraded frozen soil seriously affects the stability of the constructed project and increases the risk of the proposed project. On the other hand, which is induce great damage to the ecological environment and caused by a variety of hot melt disasters. Such as bridge frost heaving damage, hot melt slump slope instability caused by$^{2,3}$ The number of increasing and the area increases gradually hot melt lake (pond)$^{4}[5,6]$. The settlement of highway subgrade deformation and frost boil$^{[5,6]}$.

At present, scholars have conducted various studies along the Qinghai-Tibet Highway or corridor. Lu Jiahaoo$^{[7]}$ et al. studied the distribution model and variation trend of frozen soil in the corridor. Ma Weij$^{[8]}$ et al. Conducted basic research on the major permafrost projects and their interactions on the Qinghai-Tibet plateau. Niu Fujun$^{[9]}$ and Lin Zhanju$^{[10]}$ et al. studied the impact of permafrost on some projects along the Qinghai-Tibet railway and the impact of thermal and thawing disasters along the Qinghai-Tibet corridor. But up to now there has been no public report on frost heaving of soil along the route.

Through laboratory tests on typical soil samples along the Qinghai-Tibet Highway(From Xidatan fault-line valley – zanga to Ando basin). The relationship between frost heaving force (described below as tangential frost heaving force) and water content and natural density was analyzed. Based on the analysis of a lot of data, the engineering geological conditions of permafrost along the route are summarized. And the frost heaving property is evaluated. The results can provide basic data support for the construction projects along the Qinghai-Tibet Highway.

2. Conditions of the test
In the study area, the Qinghai-Tibet Highway is taken as the baseline. Corresponding to the highway...
The physical and mechanical parameters of soil samples.

The prepared sample ring cannot be completely placed in the sample ring is the original frozen soil sample.

The ground cannot be correctly detected due to the difference of the soil layer between the original soil and the sample when drilling the sample.

The heave force of the soil sample.

Dynamometer evenly stressed. The force displayed when the electronic dynamometer is mounted on the upper surface of the iron piece to make the electronic dynamometer evenly in contact with the expansion permafrost through an electronic dyer, so that the expansion permafrost maintains the original height of the dystomometer and do not invert it upside down.

Test principle: the permafrost is evenly in contact with the expansion permafrost through an electronic dyer, so that the expansion permafrost maintains the original height of the dystomometer reading is the freezing force.

Test process:

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(2) The test process: put the original permafrost soil sample from 1.5 to 2.0 meters obtained from the drill into the specimen ring, and remove the soil sample higher than the specimen ring after melting. Cover the surface cover on the specimen ring with the same area as the specimen ring. The prepared sample is placed in a thermostat box having the same average temperature as the sample taken. Then, an electronic dynamometer is mounted on the upper surface of the iron piece to make the electronic dynamometer evenly stressed. The force displayed when the electronic force count is stable is the frost heave force of the soil sample.

Precautions for the test: first of all, keep the level of the sample consistent with the undisturbed soil when drilling the sample. And do not invert it upside down. So as to avoid the frost heave force of the ground cannot be correctly detected due to the difference of the soil layer between the original soil sample. Second, the soil sample of the frozen soil must be in close contact with the inner wall of the sample ring to avoid the small frost heave force measured due to the gap between the soil sample and the sample ring. At last, the height of the soil sample is higher than the sample ring. Since the soil sample placed in the sample ring is the original frozen soil, the volume becomes smaller after melting, and the sample ring cannot be completely filled.

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IOP Conf. Series: Earth and Environmental Science 2019 5th International Conference on Energy Equipment Science and Engineering doi:10.1088/1755-1315/461/1/012062

1.5 2.0 meters.

Apply a layer of Vaseline on the inner wall of the 61.8×20mm ring cutter. And weigh the mass of the ring cutter. Press the knife edge vertically downwards until the soil sample extends out of the ring cutter. Flatten the remaining soil at both ends and take the remaining soil. The natural moisture content was measured. Wipe the outer wall of the ring cutter and weigh the ring cutter and the soil. The natural density of the soil is (Formula 1):

\[ \rho = (m_1 - m_2) \times \nu^{-1} \]

Where: \( m_1 \) is the quality of the ring knife and soil.
\( m_2 \) is the quality of the ring cutter.
\( \nu \) is the volume of the soil.

The natural moisture content of the soil sample was determined by the drying method. Take 30 grams of the sample into the weighing box and cover it. Weigh the wet soil and box, open the lid of the sample, and place it in an oven at a temperature from 100 to 105 degrees celsius for 24 hours. The dried sample was taken out, cooled, and the mass of the box and dry soil was weighed. The natural moisture content of the soil sample is (Formula 2):

\[ w = \frac{m_w}{m_x} \times 100\% \]

Where: \( m_w \) is the mass lost by the soil sample, which is the quality of the water.
\( m_x \) is the quality after drying, which is the quality of the soil particles.

For the determination of frost heave force, Liu Hongyan invented a method for measuring the frozen and expanding force of the tunnel in the cold zone after repeated freeze-thaw damage\(^{[12,13]}\), Chen Weizhi and others studied a low-salt soil salt-frozen expansion determination method\(^{[14]}\). The above method mainly obtains the freezing and expansion force by simulation calculation, the theory is strong, the process is complex. By summarizing the above methods, combined with Guo Chao\(^{[15]}\), Yang Yingzi\(^{[16]}\) and other methods for determining frost heave force and the standard of geotechnical test methods\(^{[17]}\). The following methods are proposed.

(1) Test principle: the permafrost is evenly in contact with the expansion permafrost through an electronic dyer, so that the expansion permafrost maintains the original height of the dystomometer reading is the freezing force.

(2) The test process: put the original permafrost soil sample from 1.5 to 2.0 meters obtained from the drill into the specimen ring, and remove the soil sample higher than the specimen ring after melting. Cover the surface cover on the specimen ring with the same area as the specimen ring. The prepared sample is placed in a thermostat box having the same average temperature as the sample taken. Then, an electronic dynamometer is mounted on the upper surface of the iron piece to make the electronic dynamometer evenly stressed. The force displayed when the electronic force count is stable is the frost heave force of the soil sample.

Precautions for the test: first of all, keep the level of the sample consistent with the undisturbed soil when drilling the sample. And do not invert it upside down. So as to avoid the frost heave force of the ground cannot be correctly detected due to the difference of the soil layer between the original soil sample. Second, the soil sample of the frozen soil must be in close contact with the inner wall of the sample ring to avoid the small frost heave force measured due to the gap between the soil sample and the sample ring. At last, the height of the soil sample is higher than the sample ring. Since the soil sample placed in the sample ring is the original frozen soil, the volume becomes smaller after melting, and the sample ring cannot be completely filled.
3. Analysis of test results

3.1 Physical data analysis
The natural density, natural water content and frost heave data obtained from the test were analyzed by origin software. And the test results are shown in Fig. 1.

![Fig.1 Relation curve between frost heaving force and natural density &natural moisture content](image)

Figure 1 is a plot of frost heave force versus natural density. It can be seen from the figure that the frost heave force is mainly divided into three stages due to the influence of natural density. First, when the natural density is from 1.6 to 2.1 g·cm⁻³, the frost heave force decreases sharply with the increase of the natural density. This is because when the natural density in this interval, large pores between particles decrease dramatically. Thus, the capillary water migration channel is significantly reduced. So that the rate of frost heave force reduction is higher. Then, the natural density is from 2.1 to 2.35 grams. The reduction of macropores in particles slows down, and the frost heaving force shows a tendency to decrease slowly. Last, when the natural density is from 2.35 to 2.6 g·cm⁻³. At this time, due to the large density of soil. There are only a few micropores and fissures between the particles. And the frost heave force remains essentially unchanged. Overall, the frost heave force of the soil gradually decreases with the increase of natural density. And the natural density is mainly concentrated from 1.9 to 2.2 g·cm⁻³.

Figure 1 is a graph showing that the relationship between frost heave force and natural water content. It can be seen from the figure that the frost heaving force can be divided into three stages due to the influence of natural water content. First, when the natural water content is from 10% to 25%. At this time, the frost heaving force shows a rapid rising trend with the increase of natural water content. Because of the large pores between the soil particles have the ability to store ice molecules. Second, the natural water content is from 25% to 40%, the frost heaving force increases slowly with the increase of water content. At this time, the soil water content becomes active water content gradually. When the water content reaches 40%, enter third stage. At this time, the ice molecules become the main part of the soil. And the soil is dispersed in the ice molecules. Finally, the frost heaving force of the soil tends to the frost heave force of the ice.

3.2 Frost heave evaluation and engineering measures along the line
Treatment of 167 drilled soil samples along the route is obtained from table 1 below (The following are used in the table: S-small frozen soil; D-multiple frozen soil; F-rich frozen soil; B-frozen frozen soil; H-containing soil ice Layer; R-melt zone) [18].
Table 1 Frozen soil evaluation and engineering measures

| Section                  | Drilling No. | Geomorphology unit | Main soil          | Adverse geological phenomena | $T_{cp}/^\circ$C | Groundwater buried deep /m | Frost heaving force /kPa |
|--------------------------|--------------|--------------------|--------------------|-------------------------------|------------------|---------------------------|--------------------------|
| West Great Beach Breaking Valley Kunlun Mountain North Area | 218-269       | Mountain           | Full weathered rock  | Hot melt slump               | 22-25            |                           | 15-21                    |
| Kunlun Mountain Estuary Area | 270-297       | Mountain           | Silty clay         |                               | -1.3             |                           |                          |
| Aqjingang Erba Valley     | 298-321       | Mountain           | Full weathered rock | Hot melt lake                 | 2-10             |                           | 4-8                      |
| Chumar River High Plains  | 322-351       | Mountain           | Silty clay         | Hot melt slump                | 1.5-16           |                           | 10-15                    |
| Cocosili - Five Beams Low Mountain | 352-414       | Tectonic Plains    | Silty clay         | Sand, Hot melt lake           | -0.5             | 1.3-4                      | 26-37                    |
| Beibei River Basin        | 415-476       | Mountain           | Silty clay         | Sand, Hot melt lake           | -1.2             | 14                         |                          |
| Wind volcano low mountain | 477-494       | Mountain depression| Silty clay         | Hot melt slump                | -1.1             | 4-8                        | 5-10                     |
| Uri Basin                 | 495-588       | Mountain           | Full weathered rock| Permafrost Swamp              | -7               | 10-20                      |                          |
| Tuotuo river basin        | 589-668       | Mountain depression| silt               | Hot melt lake                 | -1.9             | 9-13                       | 16-23                    |
| Kaixin Ridge Low Mountain | 669-710       | Mountain           | Fine sand          | Hot melt lake                 | -0.6             | 7-9                        |                          |
| Tongtian river Basin      | 711-736       | Mountain           | Silty clay         | Permafrost Swamp              | -1.2             | 2-10                       |                          |
| Buqi Valley               | 737-796       | Mountain           | Fine sand          | Hot melt lake                 | -1.6             | 4-10                       |                          |
| Hot Springs Fault Basin   | 797-946       | Mountain           | Round gravel       | Hot melt slump                |                   | 0.5-1.5                    | 15-18                    |
| Tangula In the High Mountains | 947-1011      | Mountain           | Fine sand          | Hot melt lake                 |                   | 15                         |                          |
| Zaga Zangbu-Ando Basin    | 1012-1074     | Mountain depression| Fine sand, Silty clay| Permafrost Swamp              | -1.6             | 18-25                      | 13-17                    |
|                          | 1075-1121     |                    |                    |                               | -1.4             | 7-13                       | 15-19                    |
|                          | 1122-1143     |                    |                    |                               | -1               | 6-9                        | 10-14                    |

In Table 1, the Qinghai-Tibet Highway is mainly weak frost heaving soil, and the frost heaving force is greatly affected by the topography.

The geomorphic unit is mainly mountainous and weathered mudstone. The upper layer is covered with silty clay. The groundwater level is deep, the shallow layer is less frozen soil, water content is lower, resulting in less frost heave. In the high plain of the Chumar River, affected by its topography. The groundwater level is buried shallow, the surface water system is developed, the shallow water content is large, and the type of frozen soil is shallow. For the rich frozen soil, the frost heave force reaches 37 kPa, which is the maximum along the line.

The Beiluhe Basin - Zaga Zangbu-Ando Basin, which spans high mountain areas and basin areas along the route, with a large span and a complex environment. For the basin area, the groundwater level is located in the middle of the high mountainous area and the plain area. The shallow water content is general, the shallow layer is mainly frozen soil, and the main soil is fine sand. So that the frost heaving force is between the high mountain area and the plain.

4. Conclusion

(1) The shallow soil along the line is mainly silty clay, the natural density is concentrated from 1.9 to
2.2 g·cm⁻³. The natural water content is between 10% and 30%, and the frost heave force is from 5kPa to 15kPa. The highest section of the Erhe River reaches the maximum, nearly 40kPa.

(2) The effect of natural density on frost heave force is divided into three stages: First, when the natural density increases from 1.8 to 1.9 g·cm⁻³. It is significantly reduced by the inter-particle macropores and capillary water migration channels. The absolute value of the force is larger, but the rate of decline is faster. Second, the natural density is from 1.9 to 2.2 g·cm⁻³. Due to the dense soil, the rate of macropore reduction in particles slows down, and the downward trend of frost heave force slows down. When the natural density reaches 2.2 g·cm⁻³, it enters third stage. Since the soil enters the compact stage, the frost heave force is basically not affected by the natural density of the soil.

(3) The influence of water content on frost heave force is also divided into three stages: First, when the water content is between 10% and 25%. The frost heave force increases sharply with the increase of water content due to the increase of available frozen water molecules. Second, when the natural water content is from 25% to 40%, the soil water content gradually becomes active water content, and the frost heaving force increases slowly with the increase of water content. Last, when the water content reaches 40%, the soil water content reaches active water content. Ice molecules become the main part of the soil, and the frost heaving force approaches the frost heaving force of the ice molecules.

(4) Along the route can be divided into three typical areas, namely, high mountain, plain area, valley area and so on. High mountain area: deep groundwater, mainly high-temperature frozen soil, prone to frozen soil swamp, less frost heaving force. Plain area: shallow groundwater, low annual average temperature, mostly frozen soil, large frost heaving force, natural balance is easily destroyed and it is prone to hot melt lakes. The nature of the mountain valley is somewhere in between. Measures should be taken actively during construction to reduce the damage of frozen soil environment and avoid extensive changes in hydrogeological conditions.

References
[1] Ma Wei, Niu Fujun, Mu Yanhu. Basic Research on major permafrost engineering in the Qinghai-Tibet Plateau [J]. Advances in Earth Science,2012,27(11):1185-1191.
[2] Fujun Niu, Guodong Cheng, Wankui Ni, et al. Engineering-related slope failure in permafrost regions of the Qinghai-Tibet Plateau[J]. Cold Regions Science and Technology,2005,42(3):215-225.
[3] Niu Fujun, Cheng Guodong, Lai Yuanning, etc., Study on the instability of hot melt-slip-collapsed slopes in the permafrost area of the Qinghai-Tibet Plateau[J]. Geotechnical Engineering Journal,2004, 26 (3) : 402-406.
[4] Lin Zhanju, Niu Fujun, Xu Zhiying, etc. The development characteristics of the hot melt ditch along the Qinghai-Tibet Railway and its influence on the thermal stability of the roadbed. [J]. Geotechnical Engineering Journal, 2011,33(4):566-573.
[5] Wu Qingbai, Shi Bin, Liu Yongzhi, Study on the interaction between permafrost and highway along the Qinghai-Tibet Highway[J]. Chinese Science :D Series, 2002,46(2):97-105.
[6] Niu Fujun, Lin Zhanju, Lu Jiariolling, etc. Analysis of the factors influencing the subsidence deformation of the transition section of qinghai-Tibet Railway Road Bridge [J]. Geotechnical Engineering Journal, 2011,32 (2) : 372-377.
[7] Lu Jiaxuan, Cheng Hua, Niu Fujun, Lin Zhanju, Liu Hua,The degree of vulnerability of Lake Hotkarst along the Qinghai-Tibet Railway[J]. Disaster,2012,27(04):60-64.
[8] Ma Wei, Liu Ting, Wu Qingbai. Monitoring and analysis of the deformation of the frozen soil road of Qinghai-Tibet Railway[J]. Geotechnical Engineering Journal, 2008(03):571-579.
[9] Niu Fujun, Ma Wei, Wu Qingbai. Thermal stability and major freeze-thaw disasters in the main permafrost roadbed project of Qinghai-Tibet Railway[J]. Journal of Geosciences and Environment, 2011,33(02):196-206.
[10] Lin War, Niu Fujun, Luo Jing, Liu Minghao, Yan Guoan. The hot state of the lake at the bottom of the hot melt lake in the Qinghai-Tibet engineering corridor[J]. Earth Science (Journal of China University of Geosciences), 2015,40(01):179-188.
[11] Lu Jiaxuan, Niu Fujun, Cheng Hua, Lin Zhanju, Liu Hua, Luo Jing, Luo Jing, Qinghai-Tibet Plateau Engineering Corridor Permafrost Distribution Model and Its Changing Trends[J]. Mountain Journal, 2013, 31(02): 226-233.

[12] Geng Ke. Effect of the frozen melting cycle on the frozen expansion force of the tunnel structure in the cold zone[J]. Glacial permafrost, 2013, 35(04): 913-919.

[13] Liu Hongyan, Zhu Fengjin, Zhao Yuxia, Ge Ziwei, Dai Hualong, Xie Tianxuan, Zhou Yuezhi. Measurement method of freezing and swelling force of the tunnel in the cold area after repeated freeze-thaw damage. [P] Beijing: CN109283215A, 2019-01-29.

[14] Chen Weizhi, Li Anhong, Wu Peipei, Xie Yi, Hu Huixing, Liu Gang, Zhang Lin, Zhang Sasha, Li Chugen, Zhou Cheng, Zeng Yonghong, Tang Dia, Zhang Min, Yang Xiangrong, Fu Mingchuan, Li Bogen, Wei Wei Wei. A low-salt soil salt-frozen expansion determination method[P]. Sichuan Province: CN109653184A, 2019-04-19.

[15] Guo Chao, Lu Zhengran, Wang Fengchi, Yu Hongmei. A soil freeze-expansion force measurement device[P]. Liaoning Province: CN207689404U, 2018-08-03.

[16] Yang Yingzi, Xu Dingjie, Xu Yang. A frozen-flat stress detection device and its detection method[P]. Heilongjiang Province: CN109868803A, 2019-06-11.

[17] Ministry of Construction of the People's. GB/T 50123-2019 Standards for geotechnical test methods[S]. Beijing: China Planning Press, 2019.

[18] Ji Yanjun, Jin Huijun, Wang Shang, Zhang Jianmin, Sino-Russian Crude Oil Pipeline (Mohe - Daqing Section) Base Soil Melting Stability Evaluation Study[J]. Journal of Engineering Geology, 2010, 18(02): 241-251.