Review on the Classification of Frozen soil in China

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Abstract. The classification of frozen soil is a key issue in the research of frozen soil. At present, there are many existing frozen soil standards in China which have certain differences. This paper compares the principles of frozen soil classification in the existing domestic standards, summarizes the methods of frozen soil classification on the Qinghai-Tibet Plateau which has a special geographical location, and puts forward reasonable suggestions for the classification of frozen soil.

Keywords: Frozen soil; classification; Qinghai-Tibet Plateau.

1. Introduction

Frozen soil refers to all kinds of rocks and soils below zero centigrade and containing ice. Because of the particularity of frozen soil, its classification has become an important core problem in the study of frozen soil science. Since the 1960s, with the in-depth development of engineering construction in cold regions, some large frozen soil countries, such as China, the former Soviet Union, the United States, Canada, etc., have carried out a lot of research work, and have developed their own frozen soil technical specifications and classification systems in combination with production practices.

In 1973, the classification of frozen soil was proposed for the first time in the Detailed Rules for Railway Survey and Design in Permafrost Regions of the Qinghai-Tibet Plateau jointly. With the further development of research work and the gradual improvement of production technology, the description and classification of frozen soil in China has developed from qualitative to quantitative, and the classification method is transitioning from single indicator to comprehensive indicators. At the same time, due to the distinctiveness of the high altitude geographical location of the Qinghai-Tibet Plateau, some scholars have proposed special classification methods for frozen soil in the Qinghai-Tibet Plateau.

2. Classification of Frozen Soil in Current Specifications

Because of the special properties of frozen soil, the basic principles, methods and indicators of its classification are different in different standards. Seven domestic common standards are selected in the table, including two state standards and five industry standards. The basic principles of classification in the seven standards are summarized in Table 1.

Table 1. Basic Principles of Frozen Soil Classification in Current Codes

Name	Standard Number	Category	Basic principles
Code for Engineering Geological Investigation of Frozen Ground	GB 50324-2014	State Standard	Soil type、Water content、Average frost heaving ratio、Average thaw-settlement coefficient
Code for Design of Soil and Foundation of Building in Frozen Soil Region	JGJ 118-2011	Industry Standard	
Specifications for Design of Foundation of Highway Bridges and Culverts	JTG 3363-2019	Industry Standard	

Code for Rock and Soil Classification of Railway Engineering	TB 10077-2019	Industry Standard	
Code for Investigation of Geotechnical Engineering	GB 50021-2001	State Standard	Soil type、Water content、Average frost heaving ratio
Code for Highway Engineering Geological Investigation	JTG C20-2011	Industry Standard	Soil type、Water content、Volume ice content、Mean annual ground temperature
Code for Geology Investigation of Railway Engineering	TB 10012-2019	Industry Standard	Soil type、Water content、Mean annual ground temperature、Average thaw-settlement coefficient

2.1. Single Indicator of Frozen Soil Classification

In the above specifications, many simple classification methods with single indicator are mentioned, which are summarized as follows:

1) According to the duration of freezing state, it can be divided into permafrost, pereletok and seasonal frozen soil;

2) According to the natural conditions of formation and existence of permafrost, it can be divided into high latitude permafrost and high altitude permafrost;

3) According to the continuous degree of the distribution of permafrost, it can be divided into large areas of permafrost, island thaw zone permafrost and island permafrost;

4) According to the ice content, it can be divided into five types of frozen soil engineering: poor ice content frozen soil、medium ice content frozen soil、rich ice content frozen soil、saturated ice frozen soil and argillaceous ice layer. When the thickness of the ice layer is greater than 25mm and no soil in it, it is named pure ice layer (ICE);

5) According to the volume compression coefficient or total water content, it can be divided into hard frozen soil, plastic frozen soil and loose frozen soil. The volume compression coefficient of hard frozen soil should not be greater than 0.01 MPa^{-1}, the volume compression coefficient of plastic frozen soil should be greater than 0.01 MPa^{-1}, and the total moisture content of loose frozen soil should not be greater than 3%;

6) According to the salinity, it is divided into saline frozen soil. The minimum limit value of salinity of saline frozen soil is 0.1 for coarse grained soil, 0.15 for silt, 0.20 for silty clay, and 0.25 for clay.

7) According to the degree of mud carbonization, it can be divided into peatified frozen soil. The minimum limit of the degree of mud carbonization of gravel soil and sand soil is 3%, and that of silt and clay is 5%.

2.2. Comprehensive Indicator of Frozen Soil Classification

In most frozen soil classifications, frozen soil is not classified by a single indicator, but by the combination of several indicators. Several indicators are as follows.

2.2.1 Granulometric Composition of Soil

The granulometric composition of soil is the most basic factor determining the engineering properties of frozen soil. The types of soil in various specifications are classified as coarse grained soil, coarse sand, medium sand, fine sand, silt, clay, etc.

2.2.2 Water Content and Volume Ice Content

The water content of frozen soil refers to the ratio of the total mass of ice and unfrozen water contained in frozen soil to the mass of dry soil. The volume ice content is the ratio of the volume of ice in the frozen soil to the volume of frozen soil, expressed in percentage. The frozen soil has special engineering properties due to the existence of ice, which also determines the extremely special physical and mechanical properties when the frozen soil melts. According to the ice content, it can be divided into poor ice content frozen soil、medium ice content frozen soil、rich ice content frozen soil、saturated ice frozen soil and argillaceous ice layer.

2.2.3 The frost heaving and thawing settlement characteristics

The frost heaving and thaw-settlement characteristics of frozen soil are the most special engineering properties of frozen soil, and are also the main factors leading to subgrade deformation in permafrost regions.

In 1998, Code for Design of Soil and Foundation of Building in Frozen Soil Region, compiled by Heilongjiang Institute of Low Temperature Science, has the following classification of frost heaving and thaw-settlement of frozen soil which combine with water content on the basis of extensive research on the classification of frozen soil engineering at home and abroad [1], and has been used in many specifications since then, such as the Specifications for Design of Foundation of Highway Bridges and Culverts and Code for Engineering Geological Investigation of Frozen Ground.

Table 2. Classification of Thawing-settlement of Permafrost

Soil type	Water content	Average thaw-settlement coefficient(%)	Thaw-settlement category
Crushed (pebble) stone, gravelly sand, coarse sand and medium sand (the content of particles smaller than 0.075mm is not more than 15%)	$\omega<10$	$\delta_0\le 1$	Non-thaw-settlement
	$\omega\ge 10$	$1<\delta_0\le 3$	Weakly thaw-settlement
Crushed (cobble) stone, gravelly sand, coarse sand and medium sand (the content of particles smaller than 0.075mm is more than 15%)	$\omega<12$	$\delta_0\le 1$	Non-thaw-settlement
	$12\le\omega<15$	$1<\delta_0\le 3$	Weakly thaw-settlement
	$15\le\omega<25$	$3<\delta_0\le 10$	Thaw-settlement
	$\omega\ge 25$	$10<\delta_0\le 25$	Strong thaw-settlement
Fine sand	$\omega<14$	$\delta_0\le 1$	Non-thaw-settlement
	$14\le\omega<18$	$1<\delta_0\le 3$	Weakly thaw-settlement
	$18\le\omega<28$	$3<\delta_0\le 10$	Thaw-settlement
	$\omega\ge 28$	$10<\delta_0\le 25$	Strong thaw-settlement
Silt	$\omega<17$	$\delta_0\le 1$	Non-thaw-settlement
	$17\le\omega<21$	$1<\delta_0\le 3$	Weakly thaw-settlement
	$21\le\omega<32$	$3<\delta_0\le 10$	Thaw-settlement
	$\omega\ge 32$	$10<\delta_0\le 25$	Strong thaw-settlement
Cohesive soil	$\omega\le\omega_p$	$\delta_0\le 1$	Non-thaw-settlement
	$\omega_p<\omega\le\omega_p+4$	$1<\delta_0\le 3$	Weakly thaw-settlement
	$\omega_p+4<\omega\le\omega_p+15$	$3<\delta_0\le 10$	Thaw-settlement
	$\omega_p+15<\omega\le\omega_p+35$	$10<\delta_0\le 25$	Strong thaw-settlement
Argillaceous ice layer	$\omega>\omega_p+35$	$\delta_0>25$	Thaw-settlement

2.2.4 Temperature Conditions

The temperature condition of frozen soil is the most basic condition to determine the survival and development of permafrost, and also the most critical factor to determine the engineering properties of frozen soil.

With the construction of engineering in permafrost regions and the in-depth study of engineering properties of permafrost, the concept of ground temperature zoning based on annual average ground temperature was introduced into the geological survey of Qinghai-Tibet Railway in 2000. Annual average ground temperature refers to the ground temperature at the depth of zero range of annual ground temperature change. According to the air temperature conditions in the permafrost regions along the Qinghai-Tibet Railway and the ground temperature test in the convenient railway engineering geological survey, the ground temperature at 15 meters is specified as the annual average ground temperature, and the ground temperature is divided into four regions. In the Code for Geology Investigation of Railway Engineering, the permafrost temperature zone is divided based on the ground temperature [2]:

Table 3. Permafrost Geothermal of Permafrost

Permafrost geothermal zonation	Mean annual ground temperature
Stabilization zone	T_{cp}<-2.0
Basic stabilization zone	-2.0≤T_{cp}<-1.0
Instability zone	-1.0≤T_{cp}<-0.5
Extremely unstable zone	T_{cp}≥-0.5

2.2.5 Thermal Stability of Frozen Soil

The thermal stability of frozen soil refers to the sensitivity of the thermal state of any frozen soil to the change of external conditions. The thermal inertia of frozen soil is mainly related to the annual average ground temperature of frozen soil and the ice content of frozen soil. The former determines the thermal capacity of frozen soil, and the latter determines the phase change heat of frozen soil.

In the Code for Highway Engineering Geological Investigation, the water content (volume ice content) is combined with the frozen soil temperature, and the frozen soil is divided into three types: stabilization, basic stabilization and instability [3].

Table 4. Classification of Permafrost in Highway Subgrade

Soil type		Total water content(%)	Volume ice content	Tempera ture	Type
Coarse grained soil	Silty-clay content≤15%	<10	<0.1	Disregar d	Stabilization
	Silty-clay conten＞15%	<12			
	Fine sand	<14			
	Cohesive soil	$<\omega_p$			
Coarse grained soil	Silty-clay content≤15%	10-16	0.1-0.2	0-1	Basic stabilization
	Silty-clay conten＞15%	12-18			
	Fine sand	14-21		<-1	Stabilization
	Cohesive soil	$\omega_p \le \omega_n < \omega_p+7$			
Coarse grained soil	Silty-clay content≤15%	16-25	0.2-0.3	0-1.5	Basic stabilization
	Silty-clay conten＞15%	18-25			
	Fine sand	21-28		<-1.5	Stabilization
	Cohesive soil	$\omega_p+7 \le \omega_n < \omega_p+15$			

Coarse grained soil	Silty-clay content≤15%	25-48	0.3-0.5	0-1	Instability
	Silty-clay conten＞15%	25-48		1	Basic stabilization
	Fine sand	28-45		<-2	Stabilization
	Cohesive soil	$\omega_p+15\le\omega_n<\omega_p+35$			
Coarse grained soil	Silty-clay content≤15%	>48	>0.5	0-1	Instability
	Silty-clay conten＞15%	>48		1	Basic stabilization
	Fine sand	>45		<-2	Stabilization
	Cohesive soil	$>\omega_p+35$			

3. Classification of permafrost in Qinghai-Tibet Plateau

The frozen soil has strong regional characteristics. The Qinghai-Tibet Plateau is the frozen soil region with the highest altitude and the largest area in the middle and low latitudes of the earth. The genesis of frozen soil on the plateau is very complex, which is the historical product of the long-term action of internal and external heat on the surface of the plateau since the late Pleistocene. Due to the control of climatic conditions and the comprehensive influence of terrain and other factors, the plane distribution, underground ice, frozen soil fabric, frozen soil and periglacial phenomena of the plateau frozen soil have obvious regional differences. At the beginning of the research on high altitude frozen soil in China, the naming principle of high latitude frozen soil was also followed. However, with the accumulation of practical data, it is gradually found that this naming principle is not suitable for high altitude permafrost. Therefore, due to the special geographical location of the Qinghai-Tibet Plateau, some scholars have specifically proposed a classification of permafrost in the Qinghai-Tibet Plateau.

Cheng Guodong [4] divided the permafrost of the plateau into upper zone, middle zone and lower zone according to the annual average ground temperature as the main indicator. From the perspective of thermal stability, the upper zone is stable, the lower zone is unstable, and the middle zone is in a transitional position. Then the types are further divided and named according to the stability.

Table 5. Zonation of Permafrost in the Qinghai-Tibet Plateau

Zonation		Mean annual ground temperature(℃)	Permafrost thickness(m)
Upper zonation	Extremely stable	<-5.0	>170
	Stabilization	-3.0--5.0	110-170
Middle zonation	Metastabilization	-1.5--3.0	60-110
	Transition	-0.5--1.5	30-60
Lower zonation	Instability	0.5--0.5	0-30
	Extremely unstable		

According to the ice content of the permafrost and the annual average ground temperature environment, Wu Yunsheng [5] classified the permafrost along the Qinghai Tibet Railway into the following five categories :

Table 6. Engineering Classification of Permafrost along Qinghai-Tibet Plateau Railway

Frozen soil type	$T_{cp}\ge-0.5$	$-1.0<T_{cp}\le-0.5$	$-2.0<T_{cp}\le-1.0$	$T_{cp}<-2.0$
Argillaceous ice layer	I	I	II	III
Saturated ice frozen soil	I	II	III	IV
Rich ice content frozen soil	II	III	IV	IV
Poor、Medium ice content frozen soil	V	V	V	V

Class I refers to the extremely poor engineering geological conditions in frozen soil areas; Class II refers to poor engineering geological conditions of frozen soil; Class III refers to poor engineering geological conditions of frozen soil; Class IV refers to general engineering geological conditions of frozen soil; Class V is of good engineering geological conditions of frozen soil.

Because the climate dryness not only affects the surface temperature and air temperature, but also reflects the water condition, Wang Shaoling [6] proposed to divide the permafrost on the Qinghai Tibet Plateau by dryness. He divided the permafrost into five types: wet, sub wet, semiarid, arid, extremely arid.

Table 7. Classification of Frozen Soil by Dryness Index

	Wet	Sub wet	Semiarid	Arid	Extremely arid
Dryness	<1.0	1.0-1.5	1.6-5.0	5.1-15.0	>15.0
Annual average relative humidity(%)	>65	65-51	50-41	40-30	
Annual temperature range(℃)	<17	17-22	20-26	23-30	>30

Wu Qingbai [7] believed that because of the warming climate and the impact of human activities, the living environment of the frozen soil was seriously disturbed, and the frozen soil changed in a large range. The changes in the frozen soil greatly affected the engineering properties of the frozen soil, destroyed the stability balance under certain temperature, water content, fabric and other conditions, and reduced the stability and durability of the Qinghai-Tibet highway. Considering the engineering stability of the Qinghai-Tibet highway, he combined the annual average ground temperature with the annual average temperature to divide the stability of the permafrost along the Qinghai-Tibet highway into the following 6 zonation:

Table 8. Stability Zonation of Qinghai-Tibet Highway

Zonation		Zonation name	Mean annual ground temperature(℃)	Permafrost thickness(m)	Mean annual air temperature(℃)
I Zonation		Extremely stable zone	-5	>150	<-8.5
II Zonation	II_1	Stabilization zone	-3.0--5.0	100-150	-7.5
	II_2	Basic stabilization zone	-1.5--3.0	60-100	-6.0
	II_3	Basic Stability Transition Zone	-1.0--1.5	40-60	-5.0
III Zonation	III_1	Instability zone	-0.5-1.0	20-40	-4.0
	III_2	Extremely unstable zone	0.5-0.5	0-20	>-2.0

4. Conclusion

The structure and nature of frozen soil are extremely complex. The geological characteristics of frozen soil are the top priority in frozen soil engineering investigation, and also the first-hand data that must be mastered before construction. However, there are so many categories of frozen soil in China, involving construction projects such as buildings, railways and highways. The difference of classification indicators of frozen soil in different standards also brings inconvenience to the practical application of projects, which is easy to cause confusion, and is not conducive to the long-term accumulation of engineering characteristic indicators.

With the promotion of standardization, technical innovation and discovery should be based on scientific and normative systematic research. In the future, frozen soil classification should be more orderly, and a set of strict and logical frozen soil classification standards should be established.

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