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Research and Perspectives on Freeze-thaw Erosion

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Abstract

The main results of freeze-thaw erosion research at home and abroad are introduced. Firstly, the concept of freeze-thaw erosion is discussed and clarified; the research results on the causes of freeze-thaw erosion, classification and grading criteria of erosion intensity, the amount of freeze-thaw erosion and its main influencing factors, freeze-thaw erosion forecasting and prevention of freeze-thaw erosion are introduced and analyzed, and the problems and shortcomings in the research on freeze-thaw erosion are pointed out; finally, the actual situation of freeze-thaw erosion research in China is combined with the future period, and the future, the directions and key areas of freeze-thaw erosion research in China are proposed.

Keywords

Freeze-thaw Erosion; Research Results; Problems; Future Prospects.

1. Introduction

Soil erosion is one of the important environmental problems. Soil erosion is the total process of destruction, denudation, transit and deposition of soil, soil parent material and other ground constituents on the land surface, under the action of external forces such as water, wind, freeze-thaw and gravity. The main types of soil erosion are hydraulic erosion, wind erosion, gravity erosion and freeze-thaw erosion. The first three types of erosion occur in spring, summer and fall, while freeze-thaw erosion occurs in the winter and spring. There are many studies on soil erosion, but the main focus is on hydraulic erosion and wind erosion, especially the study of hydraulic erosion has been very mature. The research on freeze-thaw erosion has lagged behind due to the harsh environment in which erosion occurs, the complexity of the erosion process, and the difficulty of monitoring and experimental simulation.

The area of permafrost in China accounts for about 75% of the national land area, and freeze-thaw erosion is widely distributed. According to the second national soil erosion remote sensing survey, of the total area of 3.56 million km2 of soil erosion in China, 1.268.9 million km2 is covered by freeze-thaw erosion, accounting for 35.6% [1] and 13.36% of the total area of the country, mainly in seven provinces and regions, namely Tibet, Qinghai, Xinjiang, Inner Mongolia, Gansu, Sichuan, Heilongjiang, and the high mountainous areas on and near the Qinghai-Tibet Plateau. The Qinghai-Tibet Plateau and its nearby high mountainous areas are

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the most concentrated and strongly eroded areas.5 Although freeze-thaw erosion is mainly mild and moderate in China, and the intensity of erosion is relatively small, the impact of freeze-thaw erosion on human survival and development has gradually become prominent and has attracted more and more attention. Liu et al [3] explored the main morphological characteristics of freeze-thaw erosion in the gullies of Kebai black soil area in Heilongjiang, and pointed out that the freeze-thaw erosion in the gullies of Kebai black soil area is particularly serious, which can cause the gullies in cultivated land to expand 50-100 cm per year. It has reduced the productivity of the land. Wang [5] evaluated the expression of freeze-thaw erosion and its sand production capacity in the middle reaches of the Yellow River and concluded that the contribution of freeze-thaw erosion to the erosion and sand production in the sandy areas of the middle reaches of the Yellow River is enormous. Xie et al [6] studied the causes, characteristics and control measures of soil erosion in the Sanjiangyuan area, and the results showed that freeze-thaw erosion mainly occurs above 4500 m in elevation, and the area of freeze-thaw erosion is 59,600 km2, accounting for 19.5% of the total area of the area, and the erosion mode of cold weathering denudation and hot thawing slip collapse is the most common. Dong et al [7], Zhang et al [8] and Liu et al [9] showed that freeze-thaw erosion is one of the most important types of soil erosion in Tibetan area and one of the main ecological and environmental problems faced by the area. Freeze-thaw erosion has caused great harm to local production and life, is seriously threatening arable land, grassland resources and buildings such as roads and dams, and has become one of the main factors limiting socio-economic development in Tibet. According to the investigation report of Songliao Committee, in some northeast black soil erosion areas, the rate of soil freezing and thawing erosion has been no less than the soil erosion caused by heavy rainfall. As for the Qinghai-Tibet Plateau, which is the main source of Yangtze River and Yellow River, the area of freeze-thaw erosion reaches 1.04 million km2, which seriously affects the production and life of local people and the development of regional economy. Meanwhile, the products of freeze-thaw erosion have also become one of the main sources of sediment for the Yangtze and Yellow rivers [10]. Therefore, it is of great significance to carry out freeze-thaw erosion research, and there is an urgent need to carry out in-depth research on freeze-thaw erosion mechanism, freeze-thaw erosion quantification, and freeze-thaw erosion environmental benefits, which are of great theoretical value to broaden the research ideas in this field and improve the research framework and discipline system of freeze-thaw erosion. This paper summarizes the previous research results and aims to show the direction for the development of this field.

2. Freeze-thaw Erosion Research Results

2.1. The Concept of Freeze-thaw Erosion

In China, freeze-thaw erosion has not been included in the modern erosion research [11]. At present, scholars at home and abroad do not have a comprehensive and unified understanding of the definition and research scope of freeze-thaw erosion, but from the main development trajectory of freeze-thaw erosion research [11-14], people have become clearer and clearer about its definition and research scope. It is generally believed that freeze-thaw erosion is the whole process of mechanical damage of soil or rock and being carried, migrated and piled up under the action of gravity, etc., due to the phase change of water in soil or rock and the volume change due to the differential expansion and contraction of different minerals of soil or rock in alpine regions as a result of temperature change [15-16], and it is considered that snow erosion is a form of action of freeze-thaw erosion. Most of the freeze-thaw erosion occurs after the soil melts, because in the frozen state, the water in the soil mainly exists in the form of ice, and the linkage between soil grains exists in the form of ice cohesion, and the structure is more stable; when the frozen state of the soil melts, the linkage between the soil rapidly decreases, plus the

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permafrost layer (multi-year permafrost layer) under the seasonal permafrost layer acts as a water barrier, which increases the water content of the soil in the seasonal melting layer. At this time the seasonal layer soils are more susceptible to erosion [17-19]. Soil freezing and thawing is temporally and spatially inconsistent, and when the surface layer of the soil is thawed and the bottom layer is not thawed an impermeable layer is formed and water flows along the intersection surface, which reduces the frictional resistance between the two layers, which may lead to soil erosion even if it is not erosive rainfall [20-21].

2.2. Causes and Classification of Freeze-thaw Erosion

Xie et al [6] and Sun et al [22] summarized the causes of freeze-thaw erosion as two kinds of natural and human factors. Natural factors include: ①temperature including annual average ground temperature and annual difference of ground temperature in the region. Temperature is the decisive factor for freeze-thaw erosion. ②Soil refers to soil texture and soil water content. ③Vegetation retains water in the soil and reduces the annual difference in surface temperature, thus reducing the maximum seasonal thawing (freezing) depth. ④Topography and slope orientation. The type and degree of freeze-thaw erosion are different for different topography; the slope direction is different, and the freeze-thaw erosion is also different for different slope directions, and the depth of freezing (melting) layer is increased for the south slope due to the temperature difference. The human factor refers to the fact that since the establishment of the country, human activities are very frequent, and the logging operation disturbs and destroys the ground surface, which leads to the increase of permafrost temperature difference and permafrost melting, especially in the southern boundary where permafrost is distributed for many years, because the climate is warmer and more suitable for people's survival than in the north, and the population is also more dense, human activities are more frequent, and the possibility of freeze-thaw erosion is greater and the harm is more intense.

Xie et al [6] classified freeze-thaw erosion into cold weathering denudation, hot thawing slip collapse, freeze-thaw mudflow, and wind-sand dissolution collapse. Li et al [23] divided freeze-thaw erosion into glacial erosion and permafrost erosion. Among them, glacial erosion is further divided into ice avalanche fall, ice bucket valley, small valley glacier and snow erosion depression, etc., and permafrost erosion is further divided into hot melt slip collapse, thaw mud flow and cold weathering, etc. Sun et al [22] divided them into five major categories according to different freeze-thaw erosion camp forces and landforms, namely, soil loss under the action of chilling weathering-gravity (wind); landslides caused by the action of freeze-edge creep flow; subsidence and landslides formed under the action of hot thawing; soil loss under the action of freeze-expansion-gravity (wind); and surface erosion caused by snowmelt runoff. Jing [24] classified freeze-thaw erosion into six categories: snowmelt runoff erosion, gully freeze-thaw erosion, cold thaw rock flow, freeze-thaw wind erosion, freeze-thaw mud flow, and glacial erosion, and described the erosion process and characteristics of each type. According to the temperature conditions of freeze-thaw occurrence, Du et al [25] formulated the annual average temperature less than -1~-2°C as the index to classify the type of freeze-thaw erosion, and combined with other indirect indexes such as vegetation type, altitude, landform part, temperature conditions, and surface composition material to classify the freeze-thaw erosion intensity classification. At present, freeze-thaw erosion is classified into 4 grades, namely, slight erosion, mild erosion, moderate erosion and strong erosion.

2.3. The Relationship between the Amount of Freeze-thaw Erosion and its Main Influencing Factors

Jing et al [26] studied the relationship between freeze-thaw action and soil moisture by field observations and indoor experiments in a typical black soil area in northeast China. The results showed that the freeze-thaw action caused soil moisture migration from the lower part of high soil water potential to the lower part of low soil water potential. The migration of soil moisture

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increases the water content of the frozen layer; the migration of soil moisture reduces the water content of the lower unfrozen layer, and the degree of reduction is influenced by the lower soil water content and the burial depth of shallow groundwater; the migration of soil moisture during freezing causes soil expansion and deformation, and the expansion and deformation of soil is the main factor for the occurrence of soil freeze-thaw erosion. Liu et al [20] conducted an indoor simulated rainfall test under the freeze-thaw conditions of outdoor freezing and indoor surface thawing and lower freezing of northeastern black soil, and studied the erosion characteristics of black soil under different moisture contents, different thawing depths and rainfall conditions during the spring thawing period. The results showed that during the spring thawing period, due to the freeze-thaw effect, the soil on the black soil slope thawed incompletely and had poor infiltration capacity, and the erosion capacity of rainfall was stronger at this time, which led to serious soil erosion on the slope during this period, and the erosion of the soil slope was influenced by the combination of factors such as water content, rainfall intensity and thawing depth, and showed different erosion patterns with the changes of the three. Fan et al [27] studied the effect of thawing depth of near-surface meadow soil during spring thaw on the erosion process of slope surface by rainfall during this period using an outdoor artificial rainfall simulation experiment. The results showed that the soil thawing depth had a large effect on infiltration, flow production, and erosion volume. As the permafrost layer gradually moved downward during the rainfall, the thickness of the thawed soil layer increased, and the flow production and infiltration on the slope surface also went through the process of decreasing and decreasing. For the same rainfall intensity, the smaller the thawing depth, the earlier the initial flow production on the slope surface, the greater the erosion rate in the early stage, and the greater the total erosion volume, but the increase of erosion rate in the late stage of rainfall decreases. With the extension of rainfall time, different degrees of fine channel erosion occurs on the slope surface with different thawing depths. The smaller the thawing depth at the beginning of rainfall, the earlier the development of fine channel erosion during rainfall and the more severe the erosion intensity, and the change of erosion rate during rainfall is also influenced by the degree of fine channel development. Wang [5] discussed the environmental background, mechanism of action and expression of freeze-thaw erosion in the hilly gully area of the middle reaches of the Yellow River, and concluded that the freeze-thaw erosion in the arsenic sandstone area can reach about half of the sand production in the gully, and the maximum can reach about 1/3 of the erosion in the watershed.

2.4. Freeze-thaw Erosion Forecasting Study

The research of freeze-thaw erosion prediction model is the frontier of freeze-thaw erosion research and an effective tool for quantitative research of freeze-thaw erosion process, which is a scientific guide for the rational use of land and soil conservation planning in the freeze-thaw erosion area. International research on freeze-thaw erosion prediction model is represented by the United States and Canada, while China's research in this field is still in the initial stage. Snowmelt erosion has been studied in some foreign countries, such as USLE and RUSLE, which have revised the snowmelt erosion process successively. USLE was revised by adding a winter precipitation sub-factor to the rainfall erosion force factor to consider the role of snowmelt erosion. RUSLE was revised by analyzing the difference between fine gully erosion caused by snowmelt erosion and RUSLE, on the other hand, considers the snowmelt erosion process in the calculation of rainfall erosion force and soil erodibility factor, respectively, by analyzing the difference in erosion ratio between fine gullies due to snowmelt erosion and the effect of repeated freeze-thaw processes on soil erodibility factor. In the WEPP model, on the other hand, one winter subroutine is added for erosion prediction based on the principle of energy balance. Due to the differences in regional natural conditions, in many cases, the generalized physical. Theoretical equations cannot achieve satisfactory results. Therefore, the establishment of regional empirical equations for erosion prediction is necessary. Sharratt et al [28] conducted

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a 4-year observational study of freeze-thaw erosion in a grain-producing region of the northern United States, and quantified various factors and processes that may affect runoff and erosion volumes, and finally established runoff and erosion prediction equations for the region for use in land use and management in the region.

2.5. Freeze-thaw Erosion Control Study

At present, research on freeze-thaw erosion control for soil and water conservation purposes is mainly focused on the control of soil erosion on agricultural land. It has been shown that different tillage practices, the presence or absence of crop residues and the management of crop residues can greatly affect the nature and structure of the soil, the infiltration of surface water and the occurrence and development of freeze-thaw erosion. It has been shown that placing the tillage residues on monopoly furrows and other places for strip mulching can reduce the occurrence of surface runoff and erosion, and help to reduce the depth of soil freezing and increase the permeability of soil; meanwhile, the proper treatment of tillage residues can increase the crop yield to a certain extent.

3. Problems in Freeze-thaw Erosion Studies

3.1. Insufficient in Situ Research

Soil freeze-thaw alternation studies are currently mostly carried out in the laboratory using growth chambers or incubators to cultivate small volumes of soil (homogeneous soil or in situ soil), and field in situ studies are rare, probably because of the difficulty and high cost of controlled experiments in the field, and also probably because of the high degree of soil heterogeneity, which limits the development of field locational studies. Due to the inconsistency of materials in different studies and the differences in research methods, such as the type and physicochemical properties of the studied soils, the differences in sampling time and method, and also some studies did not specify the sampling time or sampling method, these factors are crucial to the study of freeze-thaw alternation effects, which may also be one of the reasons why the results of different freeze-thaw alternation studies are often inconsistent or even contradictory to each other.

3.2. The Mechanism of Freeze-thaw Erosion is Not Well Understood

The freeze-thaw alternation pattern includes the length of the freeze-thaw alternation cycle and the number of alternations. The different time (days to months) and temperature (-7 to -20°C minimum) alternation patterns set in the existing studies are very different from the natural conditions and do not correspond to the real situation of freeze-thaw alternation in the field. The settings of freeze-thaw cycles and frequencies in existing studies also vary, with some studies having freeze-thaw cycles of 1 to 2 days, while most studies have set freeze-thaw cycles of 1 to 2 weeks, and some freeze-thaw cycles lasting only a few hours (generally -4 to 10°C minimum), which may be somewhat similar to the warming of temperatures in early spring; other studies not only have short experimental times, but also have too few freeze-thaw cycles (most studies have In most studies, the number of freeze-thaw cycles is less than 5, which is also difficult to reveal the long-term and cumulative effects of freeze-thaw processes.

3.3. Poor Design of Freeze-thaw Alternating Pattern

Freeze-thaw erosion mechanism is the basis for understanding the freeze-thaw erosion process and its dynamics, quantifying the amount of freeze-thaw erosion, and evaluating the environmental effects of freeze-thaw erosion. Some researchers have tried to explain the erosion mechanism from the perspective of freeze-thaw alternation on soil cohesion and soil dispersion force. The rest of the researchers mostly discuss the freeze-thaw erosion mechanism based on the definition of freeze-thaw erosion, i.e., freeze-thaw alternation, which is the erosion

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camp force of freeze-thaw erosion. However, systematic and large-scale experimental studies of similar hydraulic erosion mechanisms have not been reported in the field of freeze-thaw erosion.

4. Future Directions and Priorities of Freeze-thaw Erosion Research in China

China is a country where freeze-thaw erosion is widely distributed and the hazards of freeze-thaw erosion are increasingly highlighted, but there is little research on freeze-thaw erosion in China, so it has become necessary to conduct in-depth and comprehensive research on freeze-thaw erosion. Although freeze-thaw erosion is different from water erosion, wind erosion and other forms of erosion, the research of water erosion, wind erosion and other forms of erosion and the research of glacial permafrost in China have laid a better foundation for the research of freeze-thaw erosion. The authors believe that Chinese research on freeze-thaw erosion in the future should mainly focus on the following aspects.

(1) Research on the mechanism of freeze-thaw erosion. As mentioned above, the study of freeze-thaw erosion mechanism is the basis of freeze-thaw erosion research, so a large number of indoor and field freeze-thaw erosion experiments are needed to clarify the dynamic changes of the freeze-thaw erosion process and its main influencing factors, and the indoor tests and field tests verify each other.

(2) The determination of freeze-thaw erosion modulus and erosion amount. At present, the calculation method of freeze-thaw erosion modulus and freeze-thaw erosion amount is still very immature, which directly affects the quantitative evaluation of freeze-thaw erosion. Therefore, it is necessary to establish a set of calculation formula or prediction model for freeze-thaw erosion modulus or freeze-thaw erosion amount, so that the study of freeze-thaw erosion can be changed from qualitative to quantitative.

(3) Research on freeze-thaw erosion prediction. At present, China already has a good foundation for forecasting models in terms of freeze swelling - thawing amount, freeze - thawing depth, water movement pattern in permafrost and snow cover change trend, snow melt calculation, etc. for the purpose of permafrost research. At the same time, China has more research on forecasting models for water erosion and wind erosion. On this basis, we can further study the change law of soil erodibility under freeze-thaw conditions, the forecast of soil erosion caused by rainfall and snowmelt runoff during the thawing of permafrost, etc.

(4) freeze-thaw erosion prevention and control research. The hazard of freeze-thaw erosion has become an inevitable problem in China, and the research on freeze-thaw erosion prevention and control technology is urgent. Among the factors affecting freeze-thaw erosion, temperature, soil, topography and slope direction are unchangeable factors, while the only two variable factors are vegetation and human activities, so the management of freeze-thaw erosion should also break through from these two aspects. We should select tree and grass species with wide adaptability, strong cold resistance, developed root system and high economic value, and choose suitable engineering measures to prevent or delay the occurrence of freeze-thaw erosion. At present, the prevention and control of freeze-thaw erosion should focus on solving the problem of soil erosion in the northeast black soil area of high grain producing areas and soil erosion in the Qinghai-Tibet Plateau, the source of large rivers. For the prevention and control of freeze-thaw erosion on agricultural land, we can start with tillage methods, crop residue management, and appropriate soil and water conservation projects. For the control of freeze-thaw erosion at the source of large rivers, we should focus on improving vegetation cover.

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