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硕 士 学 位 论 文

冻融循环和初始土壤含水量对东北黑土区土壤崩解速率的影响

学 科 专 业 水土保持与荒漠化防治

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Effects of Freeze-Thaw Cycles and Initial Soil Water Content on Soil Disintegration Rate in Chinese Mollisol Region

Zoljargal SAINBUYAN

This thesis was completed in State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A & F University, and Sino-US Joint Center of Soil and Water conservation and Environment Protection.

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冻融循环和初始土壤含水量对东北黑土区土壤崩解速率的影响

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本论文在西北农林科技大学水土保持研究所黄土高原土壤侵蚀与旱地农业国家重点实验室完成和“中美水土保持与环境保护联合研究中心”完成。

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ABSTRACT

The Heilongjiang province is the main Mollisol distribution area in China. However, the thickness of Mollisol layer in this region has been declining due to intense agriculture activity, water erosion, wind erosion and freeze-thaw function. The soil disintegration rate is an important index to characterize soil erodibility. During the past decades, studies on soil disintegration have been concentrated on the Loess Plateau, but there is less reports regarding freeze-thaw cycle impacts on the soil disintegration, especially researches on soil disintegration in the Chinese Mollisol region where freeze-thaw cycle occurs frequently within a year is still lacking. Thus, this study collects tested soils from Binxian and Keshan counties in Heilongjiang province, China to measure soil disintegration. The improved indoor soil disintegration experiment method was used to evaluate the effects of freeze-thaw cycles with different initial soil water contents on soil disintegration rate in Chinese Mollisol region. The treatments covers five different times of freeze-thaw cycles (0, 1, 3, 5, and 7), three initial soil water contents (16.5%, 24.8% and 33%), and two tested soil with remolded and undisturbed soil samples. The specific aim of this study quantifies how freeze-thaw cycle and initial soil water content influence on soil disintegration rate in Chinese mollisol region. The results can reveal mechanisms of freeze-thaw effects on soil erodibility and to enhance the understanding of water erosion process and mechanism in this multi-agent erosion area. The main results are as follows:

(1) The Mollisol disintegration rate decreases by 3 times when the initial soil water content increases from 16.5% to 24.8% and soil samples are disintegrated completely within 6 minutes and soil disintegration duration at 16.5% initial soil water content is 5 times shorter than that soil samples at 24.8% and 33.0% initial soil water contents.

(2) The KS soil disintegration rate increases sharply by 3 times when soil experiences one freeze-thaw cycle; when freeze-thaw cycle increases from 5 to 7 times, the soil disintegration rate increases by 2 times; while BX soil disintegration rate increases gradually with an increase of freeze-thaw cycles. The disintegration duration of KS soil is shortened by 64% when soil experiences one freeze-thaw cycle; and then it decreased 95% after seven freeze-thaw cycles;

while the duration of the BX soil disintegration process increases gradually with increase of freeze-thaw cycles. Moreover, the KS soil disintegration rate is 5 times higher than the BX soil disintegration rate when the freeze-thaw cycles increase from 3 to 7 times. Therefore, the KS soil disintegration duration is 10 times shorter than that for the BX soil when the freeze-thaw cycle increases from 0 to 7 times.

(3) The KS soil disintegration rate for undisturbed and remolded soil samples increases five and six times, respectively, when the freeze-thaw cycle increases from 3 to 7; while BX soil disintegration rates for remolded and undisturbed soil samples increase gradually with increases of the freeze-thaw cycles.

(4) The correlation coefficients between the soil disintegration rate for both BX and KS tested soils and the number of freeze-thaw cycles were 0.906 and 0.906, respectively, which is showed that soil disintegration rate has positively correlated with freeze-thaw cycles ($P < 0.05$); while soil disintegration rate for both tested soils has negative correction with the initial soil water content and the correlation coefficients are -0.764 and -0.858, respectively.

KEY WORDS: soil disintegration rate; freeze-thaw cycle; initial soil water content; remolded soil; undisturbed soil; Chinese Mollisol region.

ABBREVIATIONS: DR: Soil disintegration rate; BX: Binxian; KS: Keshan; SWC; Soil water content; F-T cycle: Freeze-thaw cycle

摘 要

黑龙江省是中国黑土的主要分布区。然而由于剧烈的农业活动以及水蚀、风蚀和冻融作用的影响，导致了该地区的黑土层厚度不断降低。土壤崩解速率是表征土壤团聚体稳定性的重要参数。过去几十年间，有关土壤崩解速率的研究主要集中在黄土高原，但缺乏冻融循环对土壤崩解速率的影响研究，特别是在中国东北黑土区冻融循环在春季融雪过程普遍发生，而有关缺乏冻融循环对黑土区土壤崩解速率的影响研究基本为一空白。为此，本研究通过采集中国黑龙江省典型薄层黑土区宾县（BX）和克山县厚层黑土区（KS）原状土和扰动土样品，设计 5 个水平冻融循环次数 (0、1、3、5 和 7 次)和 3 个水平前期土壤含水量（16.5%、24.8% 和 33%）和采用改进的土壤崩解速率测定方法，定量分析了冻融循环和前期土壤含水量对黑土区土壤崩解速率的影响，研究结果可加深对冻融作用影响坡面土壤侵蚀机理的认识。主要研究结论如下：

（1）当初始土壤含水量从 16.5%增加到 24.8%时，土壤崩解速率减少 3 倍；且在初始土壤含水量为 16.5%时，试验土样在 6 min 内完全崩解。与初始土壤含水量为 16.5%的试验土样相比，初始土壤含水量为 24.8%和 33.0%的试验土样发生崩解的时间缩短 5 倍。

（2）经历 1 次冻融循环后，KS 土壤崩解速率增加 3 倍；当冻融循环次数从 5 次增加到 7 次时，其土壤崩解速率增加 2 倍。当冻融循环次数从 0 次增加到 7 次时，BX 土壤崩解速率缓慢增加。同时，经历 1 次冻融循环后，KS 土壤崩解时间减少 64%和 7 次冻融循环后其土壤崩解时间减少 95%。而 BX 土壤崩解时间随着冻融循环次数增加而逐渐增加。当冻融循环次数从 3 次增加到 7 次时，KS 土壤崩解速率比 BX 土壤崩解速率增加 5 倍。当冻融循环次数从 0 次增加到 7 次时，KS 土壤崩解时间比 BX 土壤崩解时间减少 10 倍。

（3）当冻融循环次数从 3 次增加到 7 次时，KS 重塑土与原状土的土壤崩解速率分别增加 6 和 5 倍；而 BX 重塑土与原状土的土壤崩解速率皆随着冻融循环次数增加缓慢增加。

（4）BX 和 KS 土壤崩解速率与冻融循环次数的相关系数分别为 0.906 和 0.906，这表明土壤崩解速率与冻融循环次数呈显著正相关（$P<0.05$）；而 BX 和 KS 土壤崩解速率皆与初始土壤含水量负相关，相关系数分别为-0.764 和-0.858。

关键词：土壤崩解速率；冻融循环；土壤初始含水量；扰动土；原状土；黑土区

缩　写：DR：土壤崩解速率；BX：宾县；KS：克山县；SWC：土壤含水量；F-T cycle：冻融循环

CONTENTS

CHAPTER 1 INTRODUCTION

1.1 Background and Research Importance

1.1.1 Background

The Mollisol is mainly distributed in North America, Eurasia, and South America. The northeast China is a primarily distribution area in Asia (Liu et al., 2012). Mollisol is thick and has a high mineral with the soil surface horizon of mollic epipedon (Soil Survey Staff (SSS), 2010) which is known as fertile and productive soil for farming. The Mollisol in China covers four provinces (Heilongjiang Province, Jilin province, Liaoning Province and the Hulunbeier League of the Inner Mongolian Autonomous Region), with a variety of forms of soil erosion that include water, wind and melted snow erosion, particularly the water erosion on sloping farmlands is the main pattern for soil erosion (Xu et al., 2010). China's Mollisol region in the northeast covers 35.233 million hectors and half of them occur in Heilongjiang province (Kravchenko et al., 2011). The Mollisol in Northeast China, which is rich in organic matter, is considered as one of the most fertile soils as well as the most important food production areas of China (Liu et al., 2010 and 2011; Zhang et al., 2012; Xu et al., 2010). It is also has superior physical and chemical characteristics. The northeast of China contributes approximately 18.9% of food production and 33.1% of national corn production (National Bureau of Statistics of China, 2012).

However, the thickness of Mollisol layer has been declined 16-70 cm (Xiong, 1990; National Soil Survey Office. Soil Taxonomy of China, 1994), and the soil organic matter layer has declined from 6.0% (Xiong, 1990) to 1.98% (National Soil Survey Office. Soil Taxonomy of China, 1994) between 1950s-1980s. Therefore, the layer of mollisol called the effective arable layer has thinned out by 50 percent during the last 5 decades (Feng et al., 2018).

Many studies have characterized erosion types and its impacts in Mollisol region of China (Zhang et al., 2007; An et al., 2012; Lu et al., 2016; Li et al., 2016; Xu et al., 2018; Ouyang et al., 2018). The agricultural transformation has been changing land use types which impacts to soil environment and hydrological condition, and there have been four decades of agricultural development since 1950s (Ouyang et al., 2010). At the same time, soil erosion expands in this region due to extensive agricultural activities. The soil erosion has extended because most croplands are located on long rolling hill-slopes in gentle and hilly areas (Cui et al., 2007).

1.1.2 Research importance

In order to evaluate the severity of soil erosion, the disintegration rate is one of the important parameter for soil erodibility. The soil disintegration refers to the phenomenon of soil dispersion, fragmentation, slumping or weakening of soil immersed in water. Li et al., (2008) calculated the disintegration rate in compacted loess and they reported that initial soil water content and compaction with various residua content affected soil disintegration rate. Many researchers proposed that soil disintegration could influenced by numbers of factors, such as soil organic contents, soil texture, soil crack, and porosity. However, the determination and calculation of the soil disintegration rate has been a weak link in soil erosion research (Yuan et al., 2010), especially in Mollisol region. On the other words, the studies on the soil disintegration commonly considered one factor whether initial soil water content or soil compaction; there are less study regarding impacts of integrated affecting factors on soil disintegration rate. Thus, it is a need to conduct interaction of initial soil water content and freeze-thaw cycle on soil disintegration rate, especially for one of the serious eroded area of Mollisol region in northeast of China in order to reveal mechanisms of freeze-thaw effects on soil erodibility and to enhance our understanding of water erosion process and mechanism in this multi-agent erosion area. Thus, this study will design indoor experiments to quantify how freeze-thaw cycle and initial soil water content influence on Mollisol disintegration rate.

1.2 Literature Review

Based on studies of influencing factors on soil disintegration rate, and soil disintegration process, under the retrieval system of "Web of knowledge"， "Springer link", "Science Direct", "Research Gate", and "Elsevier" were used in order to get a preliminary understanding of the research progress, in this study. The reviews of initial soil water content, freeze-thaw effect, and soil properties influence on soil disintegration rate and soil disintegration process are as follows.

There are several synonyms nomenclatures, such as soil slaking and dispersion, weathering, and soil disintegration, used in soil science (Fig 1-1). Weathering is the process like rocks and minerals breakdown into mini aggregates as soil. Rocks are broken down in three main ways: sedimentary, igneous, and metamorphic. Slaking and dispersion refers to soil structure, especially to structural stability, which is the soil's ability to retain aggregates and pore spaces under various environmental conditions. The slaking is the result when the soil met lack of organic matter (Fig 1-1). Therefore, the rocks disintegrate and crumble at varying rates when exposed to moisture; this process is known as "slaking" (Franklin and Chandra 1972; Wood and Deo 1975; Chapman et al., 1976; Olivier 1979; Franklin 1981; Dick and Shakoor 1992; Dearman 1995; Moon and Beattie 1995; Santi 1998; Koncagul and Santi 1999; and Molina et al., 2011).

The procedure of dispersion is that separation of clay particles from the aggregates when the soil immersed in water. The dispersion defined by soil chemical characteristics. For instance, it namely high levels of exchangeable sodium, even though it can also occurs on non-sodic soils which caused by mechanical disturbance of the soil. Furthermore, slaking and dispersion can occur together.

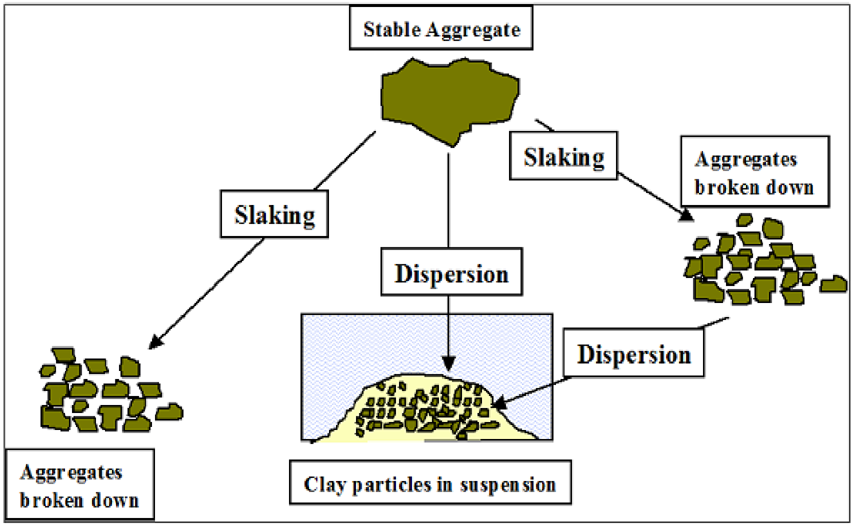


Figure. 1-1 the procedures of the soil physical aggregate breakdown process.

1.2.1 Effects of freeze-thaw cycles and Initial soil water content on soil mechanics

The freeze-thaw erosion factor could be one of the serious erosion type (Zhang et al., 2007). Therefore, the most studies show that greater soil water content during freezing and thawing has been linked to lower soil aggregate stability (Staricka et al., 1995). Aoyama and other scholars have studied that the ice can displace soil particles and separate soil aggregate (Fig 1-2), often disrupting the interlocking of soil grains and changing the soil structure such as void ratio, density, soil fabric, saturated water-holding capacity, and hydraulic conductivity, resulting in decreased soil cohesion and mechanical strength.

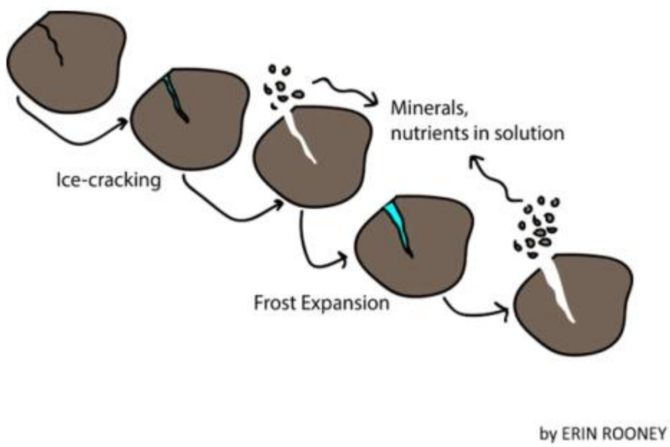


Figure 1-2 the procedures of the frozen soil aggregate dispersion.

Several of studies have been carried out how soil freezing and thawing dynamics have been performed in initial soil water in soil mechanical and physical properties. The soil mechanical properties experimental studies on frozen soil has begun with Zhu (1988). The most common method to study the mechanical properties of freeze-thawed soils is to place wrapped specimens in a thermo-tank that can be controlled by manually adjusting the temperature and the number of F-T (Freeze-thaw) cycles, and the samples undergo F-T cycles without any supplementary water supply (Wang et al., 2007).

Numerous studies conducted on F-T effect with soil organic matter content (Xiao et al., 2019; Han et al., 2018). Therefore, the present studies have investigated that the effects of F-T cycle in conjunction with an available water supply on the mechanical properties of compacted clay soil, during the freezing process. Wang et al., (2010) believed that F-T cycles seriously affected the mechanical properties of undisturbed loess when the soil water content is high. The soil F-T cycles usually affects soil structure, water content, bulk density, and degree of grain interlocking, especially reducing soil strength, temporarily or even longer (Gatto, 1995).

A huge numbers of studies conducted on the strength of frozen soil characteristics (Sayles and Haines, 1974; Bragg and Andersland, 1981; Bourbonnais and Ladanyi, 1985; Wu et al., 1994; Jones, 1981). Some research showed that repetition of F-T cycles can increase total dissolved in soil, so that P in soil owing to damage caused to plant cells, microbial biomass, and/or physical disintegrate of soil aggregates (Matzner and Borken, 2008; White, 1973; Henry, 2007). Han et al., (2018) conducted F-T cycle experiment in laboratory on Mollisol in northeast, China. The study concluded that the release of P in biochar-amended soil by increasing P desorbability by F-T cycle increase, whether the effects of F-T cycles on P release were more likely to mark at saturated moisture levels in a Mollisol.

Qi et al., (2006) reported that the freezing and thawing regimes causes the change in soil physical properties, such as void ratio, density, permeability etc. Numbers of scholars have investigated cause of F-T cycle effects on physical properties (Chamberlain and Gow, 1979; Eigenbrod, 1996; Konrad, 1989; Viklander, 1998). In addition to this, many studies have been conducted on determination of the F-T effects on the soil aggregates (Musa et al., 2016; Angin et al., 2013; Angin and Sari, 2016; Aksakal, 2016; Kok and McCool, 1990; and Lal, 1990). Moreover, the first few cycles has a most influence on the soil mechanical characteristics (Kamei et al., 2012; Lehrschetal, 1991). In terms of reviews of literatures, the freezing and thawing procedure has the effect on the soil properties which causes soil erosion. Furthermore, the F-T cycle and initial soil water content have the combined effect on the soil aggregate stability (Li and Fan, 2014). However, the soil types and test conditions of various researchers are not the same.

The soil disintegration is the phenomenon which is soil dispersed after immersed in water. That phenomenon explained as the cementation within the soil particles is weakened; soil structure becomes shaky with the infiltration of water (Lan, 2013). Hence, the soil disintegration phenomenon within soil slaking due to soil dispersion occurs, therefore caused by weathering and other influential factors. This study was carried out the characteristic of disintegration rate and procedure and the influential factors in specific soil type (Mollisol).

1.2.2 Soil disintegration rate

The soil disintegration studies have begun with Arkin, considered on rock and earth mass disintegration in order to understand increasingly prominent drawbacks of engineering due to disintegration, in 1988. The study was conducted on disintegration on marl which showed the seasonal variation like long, dry summers and short, wet winters are lead to both solution and aggregation of carbonate material. The study found that the chemical disintegration in summer followed by the mechanical disintegration in winter causes progressive weakening of the marl.

Recently, series of researchers have been studied on the disintegration characteristic of granite weathering soil, and influencing factors of the soil disintegration (Zhang, 2013; Groa et al., 2015; Yan et al., 2009; Wu, 2006; Zhou and Li, 2017; Liu et al., 2016). Experiments conducted by Sadisun et al., (2005) showed that the disintegration process of clay-stone is mainly controlled by smectite, and meanwhile an expandable clay mineral, pyrite, a non-clay mineral and calcite, a soluble mineral could affected the disintegration process. Sharma et al., (2017) indicated that a higher slaking index with lower water content and lower initial density were significantly correlated to accelerating mudstone disintegration.

Some studies said that the initial soil water content was an impact on the soil disintegration (Gamble, 1971). Fajardo et al., (2016) carried out a new methodology for evaluate soil disintegration under fast wetting conditions and applied an image recognition algorithm to a set of digital images, taken at regular time intervals of soil aggregates immersed in water. Therefore Zhang et al., (2013) found that initial soil water content significantly correlated with disintegration rate of soil as well as when initial soil water content increases the disintegration rate was decrease. Xiao et al., (2017) focused on slaking and mechanical breakdown as an impact on disintegration and splash erosion. The research focused on slaking and mechanical breakdown as an impact on the soil disintegration and splash erosion. Hence, the slaking rates were more effective than a mechanical disruption on the soil disintegration. Lan et al., (2013) reported that the gas extrusion theory can be used to explain the soil disintegration mechanism.

In the 1960s, Zhu used the results of the hydrostatic disintegration method to propose that the disintegration of soil in still water can be used as an important index to evaluate soil erodibility. In the mid-1990s, Jiang and other scholars to create a simple instrument for determining soil disintegration. According to the rate of soil disintegration, the study was an integral part of the study of soil erosion resistance in the Loess Plateau, which is aimed at soil and water conservation measures. The study was classified loess distribution area into 5 regions by its rate of disintegration. Those were the lowest, very slow, slow, fast, and very fast regions. The calculation formula developed by Jiang, (1995):

$$v = a\frac{l_o - l_t}{t} \tag{1-1}$$

Where v is the volume of the sample disintegrated per unit of time (cm^3 min^{-1}); l_o is the initial reading of the float when the sample is immersed in water or maximum reading at steady state; l_t is float reading at the time of complete disintegration of the soil sample or at 30 m in; t is time that soil sample completely disintegrated and maximum time is 30 minutes; a is volume conversion factor (Jiang et al., 1995).

In recent years, some Chinese scholars have applied ordinary electronic push-pull force gauges (or tension meter) to determine the soil disintegration rate in combination with self-made grids, and evaluated the disintegration rate under different land use types in loess hilly areas, and achieved good results (Li et al., 2007). At the same time, sophisticated soil disintegration rate meters have appeared on the market. The precision soil disintegration rate meter is less expensive in the field of experimental research (Yang et al., 2012). The common method which uses electronic tension-meter overcomes the above shortcomings and is applied more and more in the determination of soil disintegration rate. Li et al., (2007) considered the influence of water content, compactness on soil disintegration, and the corrosion of compacted soil. In 2015, Li et al., has generated a new modified calculation formula for the disintegration rate. Thus, suggested that the three steps of disintegration test as follows: "(1) collecting undisturbed soil samples with plastic film sealing using the square-knife; (2) transpiring soil samples into laboratory, weighting the soil sample, and matting the filter paper, then putting it in a plate with shallow water infiltration of soil from bottom to top, until the soil was saturated; (3) placing saturated soil samples in a hob on stage again after removing gravity water, and weighting soil sample again; (4) removing the square-ring knife gently, putting soil sample in the stage of the tension gauge sheet; (5) its calculation should multiplied by the correction coefficient of k". Therefore, he claimed that the dynamic change of buoyancy in order to calculate disintegration rate (Li et al., 2007).

Li et al., (2018) were carried out in-situ disintegration experimental method on loess soil type. They introduced self-developed disintegration test device for loess. Furthermore, the study reported loess disintegration process, its influencing factor and mechanism, as well as the boundary effect on the loess disintegration process. The results suggested three model parameter k_d and $t_{1/2}$ as an essential theoretical guidance for the research on the dynamic process of loess disintegration. In addition, they found that the initial soil water content and soil structure were influencing factor on the soil disintegration rate.

Some scholars have studied soil disintegration characteristics relation to the gully erosion. They concluded that the soil organic matter, initial soil water content, and the soil particle size distribution were main influencing factors, under different soil types, in order to analyze anti-disintegration rate (K_c). Hence, the soil in the any layer of the collapsing gully were easy to disintegrate in the lower water content (Xia et al., 2018). One of the current studies, Wang, (2019) also focused on loess disintegration characteristics and its influential factors. A novelty of his research was comparison of two kinds of method of disintegration rate test which were in-situ and indoor experiment test on loess soil. The study was also agreed that certain amount of water in soil affected the soil disintegration.

1.2.3 The measurement of soil disintegration rate

Currently, there are two main ways to measure soil disintegration rate; those are the in-situ and the indoor experiment. The in-situ test for soil disintegration rate refers direct observation of undisturbed soil disintegration rate in the field (Wang, 2019). Whereas, the indoor soil disintegration rate experiment conducts in the laboratory which is by using a self-developed experimental device (Jiang et al., 1995).

1.3 Current existing scientific issues

In recent year, numbers of studies in China have conducted on the soil disintegration rate, (Jiang, 1995; Li et al., 2018; Wang, 2019 etc). Previous studies have considered various types of calculation methods, and the influencing factors. Nevertheless, majority of studies have been conducted on a single type soil, particularly on loess soil. Furthermore, the most studies of soil disintegration commonly contributed rock bed sediments, mudstone etc. (Gautam and Shakoor, 2013; Survey, Israel, Jerusalem, and Chemical, 1988; D. Zhang et al., 2013; Zhang et al., 2018). Consequently, impacts of freeze-thaw cycle and initial soil water content on soil disintegration rate is still lack, especially in the Chinese Mollisol region, where freeze-thaw frequently occurs in the snow melting period in Spring. Thus, it is necessary to quantify the impacts of freeze-thaw cycles on soil disintegration rate in Chinese Mollisol region.

CHAPTER 2 RESEARCH CONTENTS AND METHODS

2.1 Research objectives

In view of the existing weakness of the study on the soil disintegration rate in Mollisol region, this study will clarify how initial soil water content and freeze-thaw factors influence on Mollisol disintegration rate, based a set of indoor experiments. The specific objectives of this study are 1) to quantify initial soil water content impacts on Mollisol disintegration rate; 2) to determine freeze-thaw impacts on Mollisol disintegration rate, 3) to analyze soil disturbance effects on Mollisol disintegration rate. The research results can deepen the understanding of mechanisms of freeze-thaw impacts on water erosion and provide scientific support for controlling soil erosion and protection Mollisol resource in China.

2.2 Research Contents

2.2.1 Initial soil water content impact on soil disintegration rate

The improved soil disintegration test method is used to study the effects of different the initial soil water content on Mollisol disintegration rate. The different levels of initial soil water contents such as 16.5%, 24.8%, and 33.0% were designed.

2.2.2 Effects of freeze-thaw cycles on soil disintegration rate

By designing an experiment of indoor disintegration rate, the impacts of different freeze-thaw cycles on soil disintegration rate are evaluated. The designing freeze-thaw cycles are 1, 3, 5, 7 times and no freeze-thaw cycle treatment is taken as control treatment.

2.2.3 Comparison of soil disintegration rate between remolded and undisturbed soils

Soil samples with remolded and undisturbed were used to measure soil disintegration rate. The soil samples were collected from Keshan and Binxian counties in Heilongjiang province.

2.2.4 Correlation between soil disintegration rate and soil properties

The geological statistics is used to analyze relations between soil disintegration rate with soil organic matter and initial soil water content in order to evaluate soil properties impacts on soil disintegration rate.

2.3 Technical routine

The theory and research methods of the soil mechanics and the soil erosion were applied in this study. According to affecting factors of soil disintegration process and rate, set of indoor soil disintegration tests are conducted to quantify effects of initial soil water content, freeze-thaw cycles on soil disintegration process. Moreover, the differences of soil disintegration rate between remolded and undisturbed soil are clarified; finally, correlation between soil disintegration rates with soil properties are analyzed. The technical route is shown in Figure 2-1.

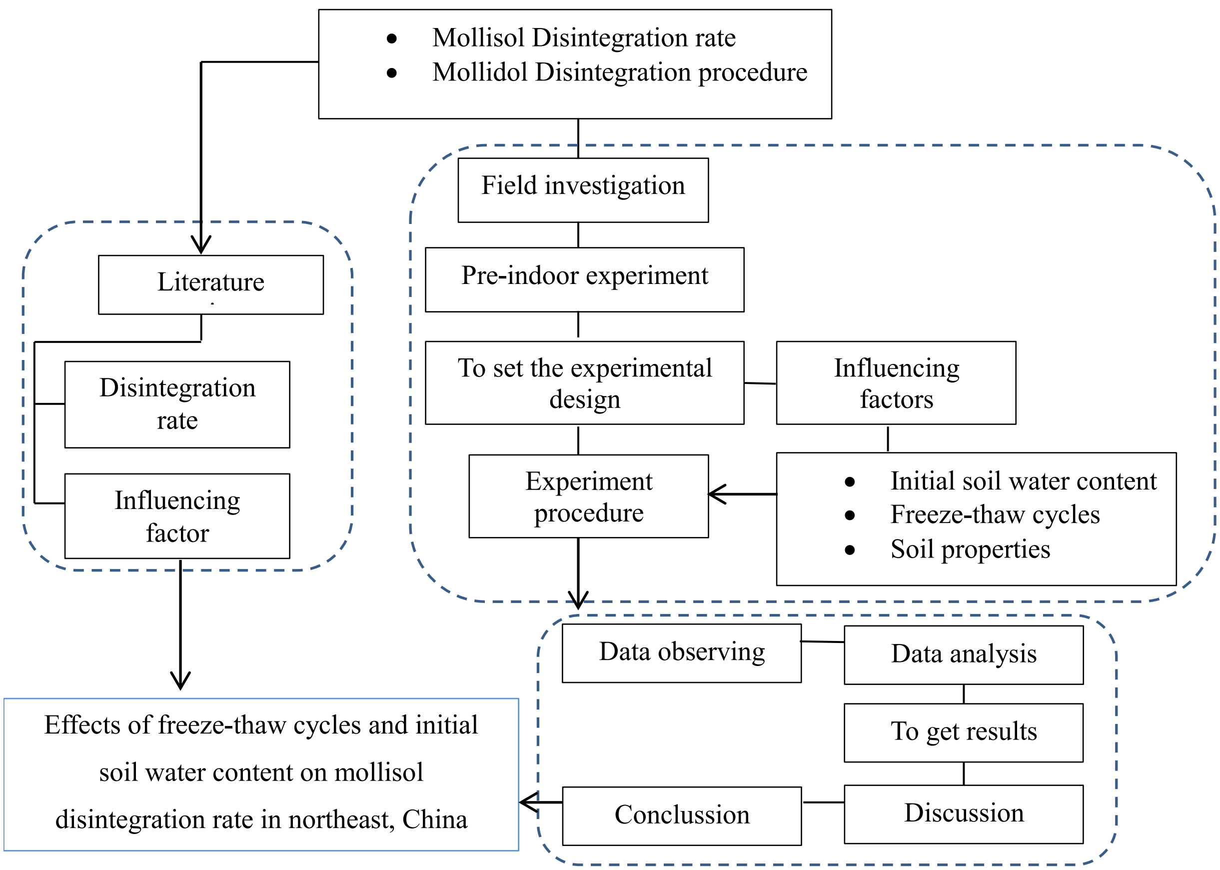


Figure 2-1 Technical routine

2.4 Research methods

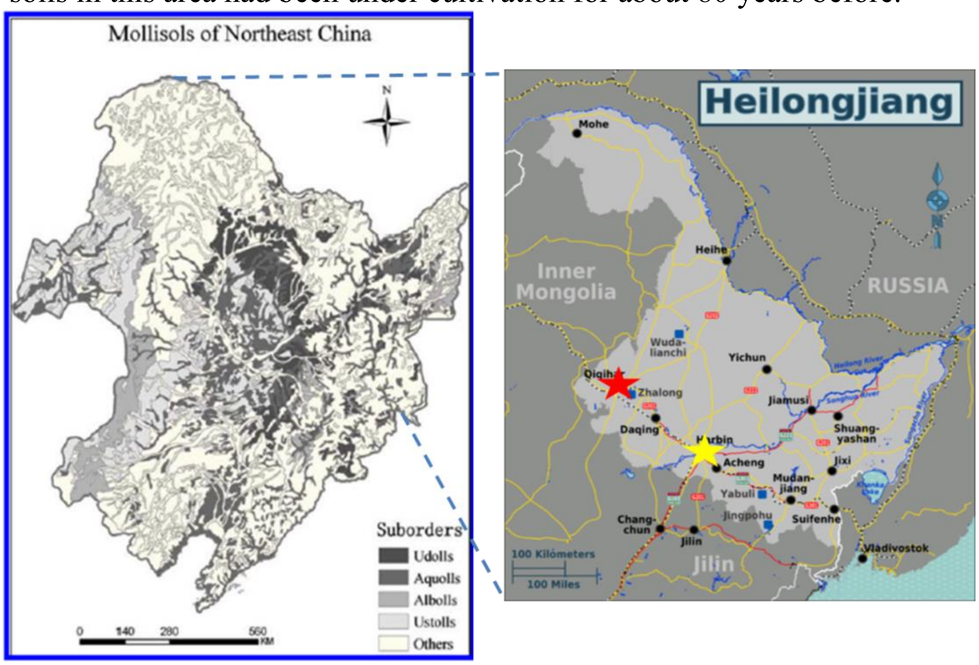
2.4.1 Study site

Chinese Mollisol (Black soil) region in the northeast is the known for its high fertile qualities that is the main grain base, which accounts for one-fifth of China's annual grain yield. The Mollisol in this region is classified as Hapli–Udic Isohumosols in the Chinese Soil Taxonomy (CST), Mollisol (Agriboroll group) in the USDA Soil Taxonomy, or Haplic Phaeozems in the FAO-UNESCO system (NSSO, 1998; Chen et al., 2004; Gao et al., 2015). The total area of mollisol in northeast, China is 35.233 million hectors, which are mainly distributed in Heilongjiang, Jilin and Liaoning provinces and the Inner Mongolia Autonomous Region (Fig 2-2a.). Heilongjiang province is located in Northeast site of China with total land area of 454800 km^2. It borders to Russia to the north and Inner Mongolian Autonomous Region to the northwest. The Climate in Heilongjiang is humid continental and winters are longer, with an average of −31 to −15°C (−24 to 5°F) in January, and summers are short and warm to very warm with an average of 18 to 23 C (64 to 73°F) in July, annual average precipitation is approximately 600 mm, whereas evaporation rate is slow due to low temperature compared with other regions in China. In this region, snow begins to accumulate on November (Zhao et al., 2012). The main crops are maize, soybean, rice and spring wheat.

Two counties in Heilongjiang province were selected for this study. Keshan and Binxian counties are one of the major crop production areas in Heilongjiang province (Fig 2-2b).

The Keshan County (E125° 10 '57' -126° 8 '18'; N47° 50 '51' -48° 33 '47) is located in the hinterland of the Songnen Plain in south of the Five Ridges, Xingan. It belongs to Qigihar city of Heilongjiang Province. The topography inclined 2-6 degrees from northeast to southwest, the highest point was 381.7 meters above sea level, the lowest point was 198.7 meters, the difference between the two places was 183 meters, and the average altitude was 236.9 meters. The Keshan County belongs to the continental monsoon climate in the cold temperate zone. The annual average temperature is 2.4 degrees, the effective accumulated temperature is 2400 degrees, the annual precipitation is 499 millimeters, the frost free period is 122 days, and the rain and heat are the same season. The rainfall is concentrated in 6, 7 and August, and the annual average rainfall is 500 millimeters.

The Binxian County (E127° 24 '41.5'; N45° 45 '8.6')'s landform features of this area are mainly hilly and hilly terrain. The elevation is between 160~220 m and the terrain is relatively gentle. The surface slope of cultivated land is mostly distributed at 1~7 degrees. The slope length can reach hundreds of meters, and the longest is several kilometers. The annual average temperature is 3.9°C degrees, extreme low temperature reaches -33.7°C degrees, and average frost free period is 147 days. The rainy season is concentrated in 6~9 months, accounting for 64.0% of the annual total precipitation. The annual rainfall distribution is uneven (Feng et al., 2018). The soils in this area had been under cultivation for about 80 years before.



a b

Figure 2-2 Distribution area of Mollisol (a. northeast of China; b. Heilongjiang province) (Liu et al., 2012)

2.4.2 Experimental device

The improved indoor soil disintegration rate test method and its calculation formula which developed by Jiang et al., (1995) and Li et al., (2015) are used in this study. The test apparatus (Fig 2-3) includes a fixed frame, a cylinder container, a stencil, and the tension meter HP-50. The test equipment that used in the study is tension meter HP-50, which is records the force (N) of soil sample continuously every di-second, during the measurement. DI water filled in the cylinder container. The wire mesh stencil connected to the tension sensor holds the soil sample. The laptop is connected to tension mete in order to record the force (N) of soil sample, at the same time, the stopwatch records the time. During the experiment, the load-bearing basket is immersed in water and broken debris falls to the bottom of the container through the mesh of the stencil (Fig.2-3).

In addition, a stopwatch, 5×5 cm of the squire knifes (4), a sieve with 2 cm of diameter, 22.1*13.2*5.5 cm dimension of aluminum boxes (30), and the plastic wraps were used in the indoor soil disintegration experiment.

The indoor experiment was carried out in Soil Mechanical properties laboratory of the State Key Laboratory of Soil erosion and Dryland Farming on the Loess Plateau in Yangling, China.

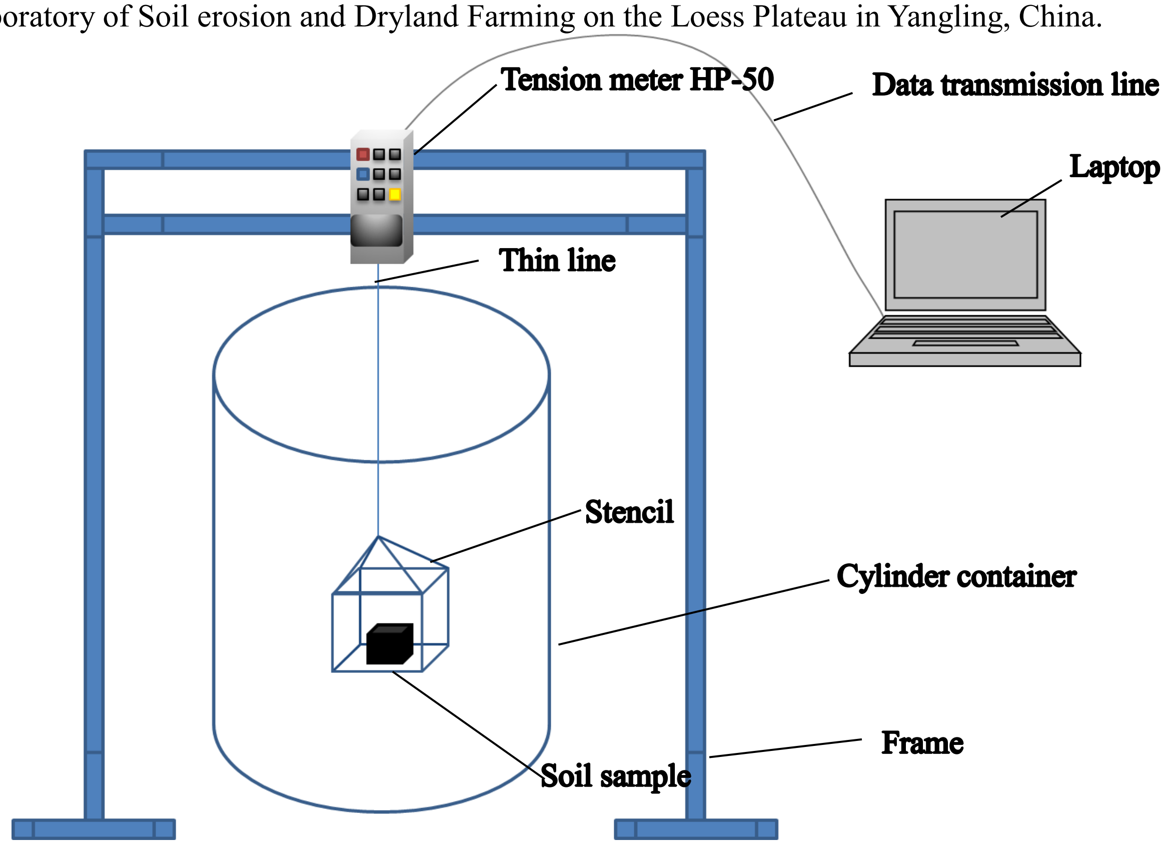


Figure 2-3 Apparatus for soil disintegration test

2.4.3 Experimental Setup

2.4.3.1 Experimental design

Based on the field investigation and review of the previous studies, pre-experiment was carried out in order to plan the experiment procedure and design (Table 2-1). The freezing and thawing durations and times, the target initial soil water content, and the soil preparation was observed during the pre-experiment. Based on the pre-experiment observation experiment design was set. The experiment design includes freeze-thaw cycles with 0 (control), 1, 3 5, 7 times, initial soil water content with 16.5%, 24.8%, 33.0%, and different Mollisol properties from Keshan and Binxian counties in order to analyze the soil disintegration rate and its influencing factors (Table 2-1).

Table 2-1 Experimental design for soil disintegration rate

Factors	Levels
Initial soil water content (%)	3 (16.5, 24.8, 33.0)
Freeze-thaw cycle (times)	5 (0, 1, 3, 5, 7)
Soil structure	2 (Remolded, Undisturbed)
Soil site	2 (KS, BX)

2.4.3.2 Soil sampling

According to the experiment design, the soil samples were collected from 20 cm of the top layer of tillage in early spring and late autumn from the two study sites which are Keshan and Binxian counties of Heilongjiang province, in northeast region of China. Approximately 120 kg of remolded soil samples were collected and stored in 16 aluminum boxes (with 22.1×13.2×5.5 cm dimension), then all aluminum boxes were immediately covered with plastic wrap in order to keep soil natural moisture content. The undisturbed soil samples were collected by ring knife in the field in order to keep the soil natural structure (Fig 2-4), and then were immediately covered with plastic wrap too.

(a) (b)

Figure 2-4 the sampling site (a) and sampling (b)

Then, the soil samples were transported into the State Key Laboratory of Soil erosion and Dryland Farming on the Loess Plateau in Yangling, Shaaxi province of China.

The Keshan Farm ($48^0$06' N, $125^0$83' E), one of the intensive soybean production areas was selected in the study. The freezing period continues from November to June as well as maximum frozen soil goes down into 2.5 m (Jiang X, 2012). In the Binxian County, corn is the main crop that grows between May to September. The soils in this region have been under cultivation approximately 80 years (Feng et al., 2018).

The 29.4% contains of clay, 61.3% contains of silt, and 9.3% of the sand in Keshan (KS) County. The 40.6% contains of clay, 48.7% contains of silt, and 10.7% of sand contains in Binxian (BX) County (Table 2-2).

In addition, the typical soil profile of this region is A–B–C, and A horizon is the surface layer, which has a rich mollic epipedon layer, the result of organic matter to give the soil a darker color than that of the lower horizons. The B horizon is commonly referred as subsoil, and it has a concentration of clay or minerals that are dark gray or brownish due to materials that were leached from the A horizon. The C horizon is parent materials, including Quaternary lacustrine and fluvial sand beds or loess sediments (Sun and Liu, 2001; Gao et al., 2015). The Mollisol bulk density in the crop field is 1.2 g/cm^3 (Table 2-2).

Table 2-2 Soil properties of the tested samples.

Sampling sites	Soil particle composition (%)			Soil organic matter content (g kg^{-1})	Soil bulk density (g cm^{-3})
	Silt (0.002-0.05 mm)	Sand (0.05-2 mm)	Clay (<0.002 mm)		
BX	61.3	9.3	29.4	20.2	1.20
KS	48.7	10.7	40.6	37.0	1.20

2.4.3.3 Experimental procedure

According to the experimental design, the soil samples were pre-prepared. The remolded soil samples were sieved thought 2 cm diameter of sieve after air drying and plant residues are removed. Then remolded soil samples were filled layer by layer (1.5cm×2cm×2cm) in 22.1×13.2×5.5 cm dimension of aluminum boxes. Based on the experimental design, test treatment was randomly selected to achieve the purpose of controlling the test standard deviation and coefficient of variation.

A total of 60 treatments were conducted. Two tested samples can be taken from each soil box, and 30 soil boxes are actually handled. Thirty aluminum boxes of samples were randomly divided into 3 groups of 10 in each group at the one time.

Once aluminum boxes were filled with the soil, the required water (DI water) was added to each assigned soil samples in order to maintain target soil moisture content at 16.5% (SWC), 25% (SWC), and 33% (SWC) respectively (Table 2-1). And then, soil samples were wrapped with plastic film to maintain the target soil moisture content, Afterwards, the samples let stand for 12 h until the soil water in whole box reaches to equilibrium. Some treatments were repeated and double checked after initial data analysis.

The freeze-thaw cycle effects on the soil samples were conducted after adding target water in the soil samples. Then, pre-prepared soil samples were placed in the refrigerator to freeze (-15^{o}C) for 8-12 hours to thaw (8^{o}C) for 8-12 hours. The numbers of freeze-thaw cycles were 0 (control), 1, 3, 5, and 7. When samples were reached the target number of freeze-thaw cycles, soil samples were cut from the aluminum boxes (2 samples from each box) using a disintegration sampling knife (the size of ring cutter is 5 cm×5 cm× 5 cm).

The cutting soil samples were gently placed on the stencil frame. The stencil frame with the soil sample was carefully placed into the cylinder container which filled with DI water. The water temperature was maintained at 17-19ºC degree. Afterwards, the soil disintegration test follows the procedures: 1) click on the software "Start" button, 2) simultaneously record timing with the stopwatch; 3) observe the soil disintegration process until soil samples completely disintegrated.

2.4.3.4 Soil disintegration process

In the presence of water, the soil with the low water content disintegrates rapidly and becomes suspended in the water, this process increases soil erosion. In fact, soil disintegration does not occur in the field as rapidly as in laboratory experiment (Wang, 2019). Many studies have proposed that there be three main stages of soil disintegration process (Jiang, 1995; Wang, 2019):

(1) The soaking stage: This stage represents the soil sample absorbs water, meanwhile begin to break down due to larger air bubbles rapidly overflow from the soil pores, immediately after immersed in DI water. The first stage is the most unstable part of soil disintegration process (Fig. 2-5a). Therefore, under the action of the thrust generated by the bubble expansion, the outlet end particle aggregates of the voids (pores) are likely to break. In addition, gas explosion occurs in the initiate stage of the disintegration process that triggers for the breaking; meanwhile soil sample absorbs water through its surface.

(2)The saturating stage: The soil sample force reaches highest rate, meanwhile the sample size increases. In addition, the soil sample fully saturated and soil pores filled with water (Fig. 2-5b). The stage 2 occurs rapidly, especially when soil sample contains high volume of water.

(3)The fragmentation stage: after the soil sample fully saturated, the soil particles begin to disintegrate constantly from the parent body (Fig. 2-5c). From this stage, some of the big particles begin to breakdown, particularly from the edge of the samples. Therefore, the part of soils from the submerged surface falls into the water when breaking. Afterwards, soil samples were disintegrated completely or reached a stable level of the sample.

The dynamic conditions driven by the soaking, the saturating, and the fragmentation stage were performed in different characteristics in terms of the different levels of influencing factors and treatments. The stage three is the main stage of the disintegration process as well as the disintegration completes in this stage (Fig. 2-5). Therefore elucidating the fragmentation occurs almost throughout the entire disintegration process.

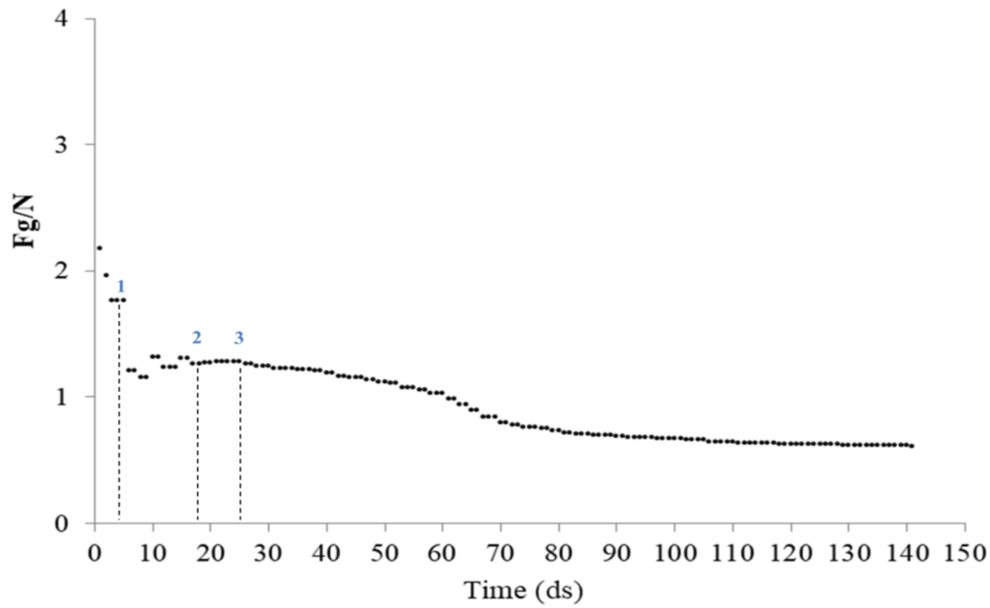


Figure 2-5 Soil disintegration curve (a. 1 soaking stage, b. 2 saturating stage, c 3 fragmentation stage)

2.5 Data analysis

Statistical analysis was performed using IBM SPSS 22.0 in order to one-way analysis of variance (ANOVA) with a least significant difference (LSD) test and correlation analysis to evaluate the significant difference among treatments (SPSS Inc., Chicago, IL, USA) and Excel 2010.

According to the definition, soil disintegration rate can be calculated by the following formula (Li et al., 2015):

$$V_0=\frac{ft_1\text{-}ft_2}{g\Delta t}\left[1+\frac{1}{\rho\text{-}1}\right]\times 2250 \qquad 2\text{-}1$$

Where $V0$: soil disintegration rate (g min^{-1}); $ft1$: $t1$ time rally gauge reading; $ft2$: $t2$ time rally gauge reading; g acceleration of gravity (9.8 m s^{-2}); Δt is disintegration time; $t1$-$t2$. ρ: soil dry density (2.65 g/cm^3). Among them, $1+1/(\rho\text{-}1)$ is the correction coefficient (Zhu et al., 1954; Li et al., 2015).

CHAPTER 3 INITIAL SOIL WATER CONTENT IMPACTS ON SOIL DISINTEGRATION RATE AND PROCESS

3.1 Introduction

The presence of the water in the soil plays important role in the soil strength and mechanical behavior. In many studies initial soil water content was combining effect on soil freeze-thaw erosion. Shusherina and Bobkov, (1978) conclude that the initial soil water content has the effect on the soil mechanical characteristics after freezes. Thus, during the freezing, the pore walls in the soil under pressure due to water in the soil expands, which alters soil physical and mechanical properties (Bing 2009; Hazirbaba and Gullyu, 2010; Liin et al., 2011; Gullu and Khudir, 2014), such as soil conductivity (Konrad, 2000), soil bulk density (Yang et al., 2003), soil volume (Viklander, 1998; Zhang et al., 2007), soil porosity and particle size (Viklander and Eigenbrod 2000; Chepil, 1942), soil water content (Kim and Daniel, 1992), soil strength (Swan and Greene 1998; Formanek et al., 1984; Kok and Mccool, 1990; Qi and Ma, 2006) and so on.

Furthermore, loess disintegration study showed that soil water content influenced on soil mechanical behavior such as strength etc. Consequently, loess disintegrates easily in the water (Rogers et al., 1994; Pye, 1995; Smalley and Rogers, 1996; Zhang and Liu, 2010; Li et al., 2009; Wang et al., 2014; Sun et al., 2016; Peng et al., 2018). Some studies showed that the initial soil water content has a serious impact on the soil disintegration process (Gamble, 1971).

In Chinese Mollisol region, rainfall has significant impact on hillslope erosion (Wen et al., 2015). An et al., (2013) reported that raindrop impact dominated on the soil loss in Mollisol hillslopes. Hence, soil aggregates were easily detached by runoff, and micro aggregates were preferentially transported by raindrop impacts.

Although, there are some results regarding initial soil water content impacting soil mechanics, there are less reports related initial soil water content influencing Mollisol disintegration. Accordingly, indoor experiment is conducted to investigate Mollisol disintegration rate and disintegration process. The aim of the chapter uses two tested soil samples (BX and KS soil) to determine the influence of initial soil water content on Mollisol disintegration rate.

3.2 Materials and Methods

According to the experiment design, 3 different levels of initial soil water content (16.5%, 24.8%, and 33.0%), which represents low, middle, and high soil moisture content were selected (Table 3-1).

Table 3-1 The experimental design of the initial soil water content impact on soil disintegration rate

Tested soils	Initial Soil Water Content (%)	Replication
	16.5	6
KS	24.8	6
	33.0	6
	16.5	6
BX	24.8	6
	33.0	6

The experiment procedures cover as follows: (1) To determine the soil moisture using oven drying method (AS 1289 B1.1-1977). (2) To calculate the required water amount. (3) To measure required water amount by using the high accuracy of scale to achieve the target initial soil water contents (16.5%, 24.7% and 33% SWC). (4) To calculate the soil weight for 22.1×13.2×5.5 cm dimension of aluminum boxes. (5) To tightly fill the aluminum boxes by layer by layer (2, 2 and 1.5 cm). (6) To spray DI water on the top of aluminum boxes with soil samples (Fig 3.1). In addition, the soil samples with the low water content were mixed in advance in order to evenly distribute the water in soil, particularly soil samples in the treatments with the 16.5% of initial soil water content. (7). To cover the soil samples with plastic film in order to maintain the target soil moisture content, (8) Allow the samples stand for 12 h until the water goes down, under constant room temperature (17-20 ^{o}C). (9) Afterwards, soil samples were cut from the aluminum boxes (2 samples from each box) using a disintegration sampling knife (square knife 5 cm×5 cm× 5 cm). (10) The cubic samples were gently placed on the stencil frame. (11) The stencil frame with the soil sample was carefully placed into the cylinder container which filled with DI water. The DI water temperature was maintained at 17-19^{o}C degree. (12) To start measuring soil disintegration rate by click on the software "Start" button, simultaneously recording timing with the stopwatch. (Fig 3-1).

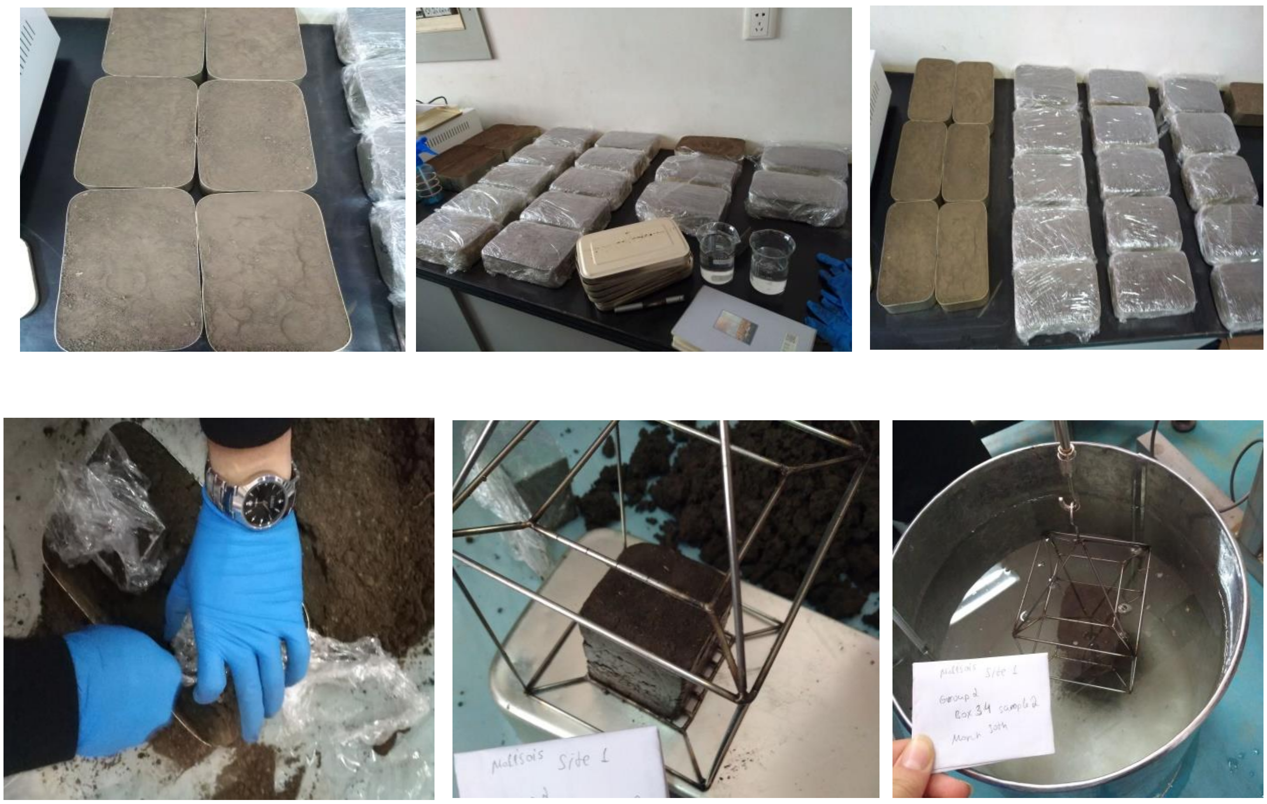


Figure 3-1 The main procedure of measuring soil disintegration rate

3.3 Results

3.3.1 Initial soil water content influence on soil disintegration rate

As Figure 3.2 shows that mollisol disintegration rate tends to decrease with increase of initial soil water content for KS and BX soils (Fig 3-2). The mollisol disintegration rate decreases by 3 times when the initial soil water content increase from 16.5% (0.26 g min^{-1} for KS soil and 0.21 g min^{-1} for BX soil) to 24.8% (0.09 g min^{-1} for KS soil and 0.08 g min^{-1} for BX soil), which indicates that initial soil water content has significant influence on mollisol disintegration rate. Moreover, mollisol disintegration rate also decreases by 1.8 and 1.3 times for KS and BX soils when the initial soil water content increase from 24.8% (0.09 g min^{-1} for KS soil and 0.09 g min^{-1} for BX soil) to 33.0% (0.05 g min^{-1} for KS soil and 0.07 g min^{-1} for BX soil) (Fig 3-2). Compared with change of initial soil water content from 16.5% to 24.8%, the decreasing trend has declined. The soil disintegration rate showed not much difference between KS and BX soil (Fig 3-2a and b).

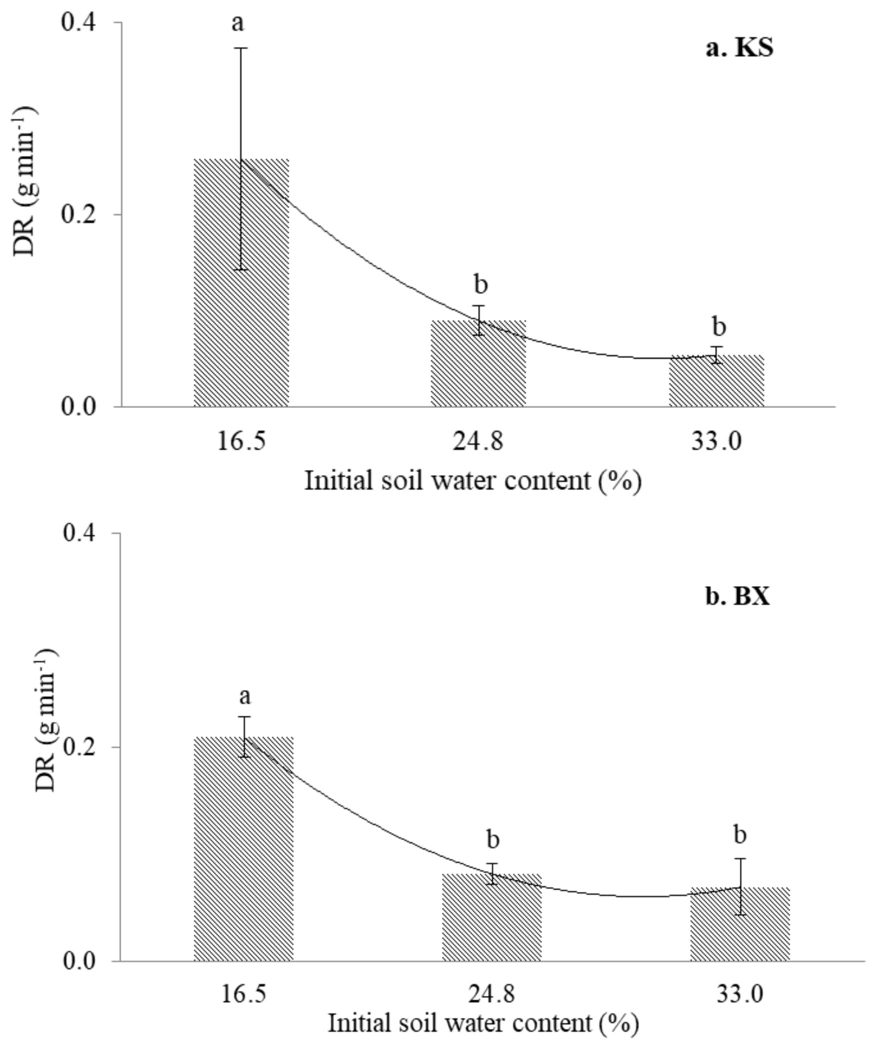


Figure 3-2 Soil disintegration rate of remolded Mollisol sample with different initial soil water contents.

3.3.2 Initial soil water content influence on soil disintegration process

The results showed that increase of the initial soil water content causes the decrease of disintegration process in time (Fig 3-3). The remolded mollisol samples with 16.5% of initial soil water content were completely disintegrated in 5.8 min for KS soil (Fig3-3a) and 5.2 min for BX soil (Fig3-3b). Furthermore, disintegration processes of the mollisol occur gradually, more than 30 minutes when initial soil water content increase from 16.5% to 24.8% and 33.0% and then become stable at the certain point of time (Fig 3-3 and 3-4a, b).

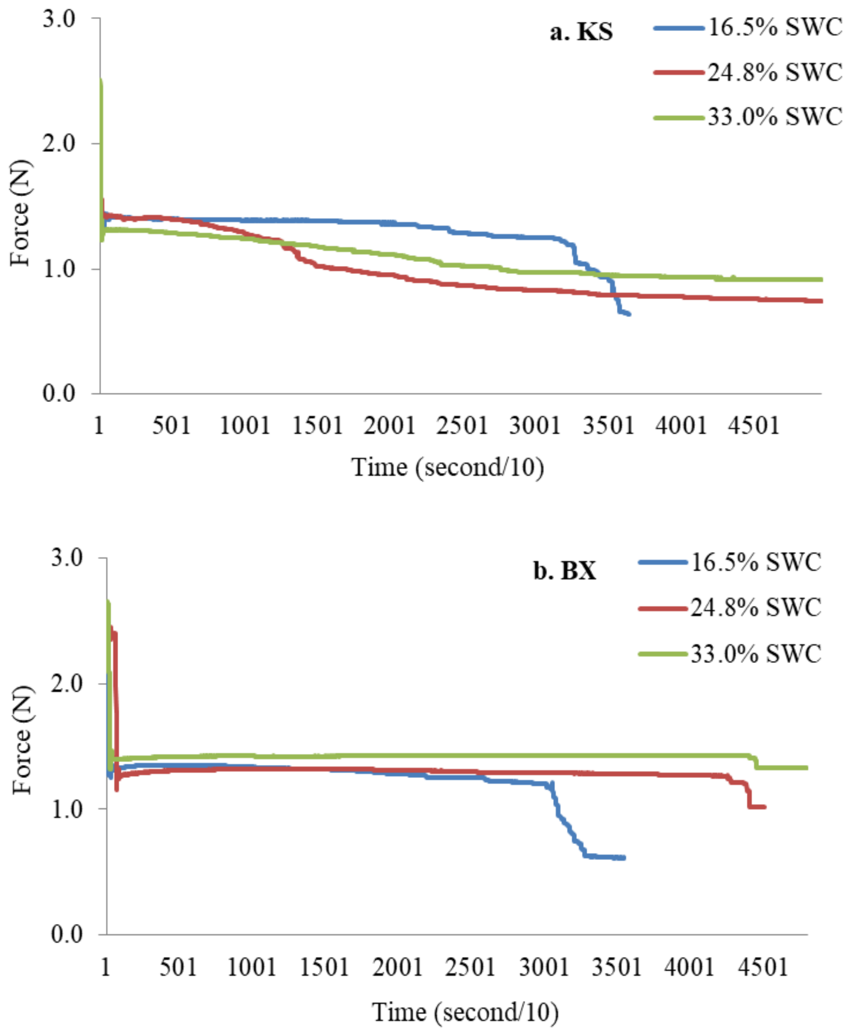


Figure 3-3 The soil disintegration curve with different initial soil water contents.

a1 a2 a3

b1 b2 b3

c1 c2 c3

Figure 3-4 The main soil disintegration process with different initial soil water contents

(a. 33.0% of SWC, b. 24.8% of SWC, c. 16.5% of SWC)

3.4 Discussion

The initial soil water content is an important factor affecting the soil aggregate stability and strength. The trigger for the breaking process is the expansion force or the force generated by the bubble overflow. Thus, soil disintegration mechanism possibly explained by the gas extrusion theory (Lan et al., 2013). When seepage flow occurs in the voids (pores), air bubbles are forced to escape (Li et al., 2018). Therefore, when the soil sample drier there is soil pores filled with the free air. In addition, when the sample immersed in DI water the air bubbles were immediately released from the soil samples, meanwhile sample absorbs water.

The loess disintegration studies indicated that disintegration occurs in the presence of water (Li et al., 2018). Wang, (2019) reported that the water film within the soil particles became condense with the increase of the initial soil water content. Therefore, the study reported that increase of initial soil water content influence on expanding of the clay minerals so that the expansion energy can be released in large quantities. In contrast, the water film in the soil is delicate when the initial soil water content is low. Furthermore, the soil disintegration process triggered by enhance of the soil water absorption. On the other words, soil porosity decreased when the initial soil water content increased.

In addition, speed of disintegration depends on the wetting rate. The studies on loess disintegration rate reports that disintegration occurs rapid when the wide distribution of voids (pores) and joints (fissures) separates. Thus, soil clay content and the soil structure plays an important role on disintegration rate of loess and clay soil (Li et al., 2018). Moreover, other studies have shown that the changes of the initial soil water content impacts on soil disintegration rate and disintegration characteristics (Gamble, 1971). Zhang et al., (2013) reported same result with this study which is soil disintegration rate was decreased with initial soil water content increased.

3.5 Conclusion

Based on the indoor soil disintegration methods, the effect of initial soil content on Mollisol disintegration rate is studied. The conclusions of the chapter are follows:

(1) The mollisol disintegration rate decreases with increase of initial soil water contents for both KS and BX soils. And Mollisol disintegration rate decreases by 3 times when the initial soil water content increases from 16.5% to 24.8%. However, soil disintegration rate showed

insignificant difference when the initial soil water content increased from 24.8% to 33.0%. Moreover, the disintegration rate for the KS soil was slightly higher than that for BX soil.

(2) The soil with the 16.5% is disintegrated completely within 6 minutes and the duration of the disintegration with 16.5% initial soil water content was 5 times shorter than that with 24.8% and 33.0% initial soil water contents. Furthermore, the tested soil disintegration process can be lasted for more than 30 minutes at 24.8% and 33.0% of initial soil water content and then become stable at the certain point of time. Those patterns observed same with both tested KS and BX soils.

CHAPTER 4 EFFECTS OF FREEZE-THAW CYCLES ON SOIL DISINTEGRATION RATE AND PROCESS

4.1 Introduction

The freezing occurs when the air temperature drops below 0° C and the heat lost from the soil surface, under the natural condition (Ferrick and Gatto, 2005). The freeze-thaw phenomenon is closely related to the soil mechanical properties, particularly in seasonally frozen regions. These effects can substantially reduce the strength and bearing capacity of the foundation soil (Aldaood et al., 2014; Kamei et al., 2012; Wang et al., 2007). The freeze-thaw effect is the one of the main erosion type all around the world. There are over thirty seven million km square of frozen soil around the world, which covers 24% of the world land surface. The frozen soil distributes in Russia, Canada, Alaska, Mongolia and China, Norway, the Arctic islands, Greenland and Antarctic (Chang and Liu, 2019). There is approximately 22 percent of the frozen soil occurs in the world. The freezing procedure significantly correlated to some factors such as a surface freezing temperature, freezing depth, freezing duration, and the thickness of the snowfall. In particular, the lower surface temperature (Bai et al., 2012; Wan et al., 2012), deeper freezing depth, longer freezing duration, and wider winter snowfall cause the damage more severe (Chang et al., 2014; Chen et al., 2008).

The Mollisol in northeast China, as ecosystems at mid-high latitudes or high altitudes experienced freeze-thaw processes during winter and early spring when the air temperature fluctuates above and below 0ºC degree. The soil freeze-thaw cycles usually effects on the soil structure, soil bulk density, and degree of grain interlocking, especially reducing soil strength temporarily or even longer (Gatto, 1995). Moreover, the frosts action, extreme cold weather, and the repeated freezing and thawing attribute soil or rock disintegration at high latitudes simply due to low temperatures and repeated freezes. The freeze-thaw effect has an impact on the soil mechanical properties. During the freezing process, the water in the soil freezes and the ice lenses cause to damage of soil structure (Konrad, 1989). Furthermore, northeast China with seasonally frozen soil is relative sensitive to global warming (Fu et al., 2018). Alternating freezing and thawing is one of the critical factors associated with soil structure change and accelerates soil erosion in the Mollisol region of northeast, China (Zhao et al., 2012). The soil biochemical and physicochemical processes is also affected by freeze-thaw cycles in northeast China (Yu X et al., 2011).

The freeze-thaw effect influences on soil structure, particularly it changes soil mechanical properties (Wang et al., 2005). Chang and Liu, (2019) explained the phenomenon of freezing and thawing and fund that the volume of the water expands during the freezing-thawing weakens or loosens the soil aggregates. Therefore, freeze-thaw factor contributes soil or rock disintegration (Thomachot et al., 2005). Thus, aim of this study is to identify freeze-thaw effects on Mollisol disintegration rate and disintegration process.

4.2 Materials and Methods

The soil disintegration test is conducted in the mechanical laboratory of Institute of Soil and Water Conservation. The experimental treatments include five freeze-thaw cycles (0, 1, 3, 5, and 7 times) with 16.5% of initial soil water contents (Table 4-1) and the treatment without freeze-thaw process is taken as control treatment. The stabilized soil samples were subjected to 0 (control). Each experimental treatment has at least six replications.

The ordinary refrigerator with large capacity was used to freeze soil samples. The experimental procedures for measuring soil disintegration under freeze-thaw cycles cover three steps, i.e., 1) sample preparation process; 2) sample preparation process of soil disintegration, 3) soil disintegration test. A more detailed summary of the laboratory procedures for measuring remolded soil disintegration are presented in the following:

(1) Soil sample preparation process: The soil samples were collected from topsoil (0-20 cm) in the maize field in KS and BX countries, Heilongjiang province of China and put in the plastic bags and then brought back to the laboratory. Afterward, all samples are air-dried and then impurities such as crop straw and roots were removed. Later on, soil samples are sieved through a 2 mm mesh.

(2) The sample preparation process of soil disintegration: Soil water content of tested samples is measured to adjust designed target soil water content; (3) According to volume of an aluminum box with 22.3 cm long, 13.2 cm wide and 6.5 cm deep) and soil bulk density (1.20 g/cm^3), tested soil samples were weighted to determine how much soil is need to pack in the aluminum box; c) The aluminum box was packed with tested soil sample by three layers (2, 2 and 1.5 cm) separately, in order to form uniform boundary conditions for all tested samples; d) According to designed initial soil water content, additional deionized water (DI) is added into the aluminum box with packing soils to adjust that soil water content reaches to target soil water content by slow spraying water; then immediately the aluminum box with filled soils was covered by plastic film to eliminate water loss; e) The aluminum box with film cover was placed at overnight (8-12 h) in order that soil water in the whole box reaches to equilibrium; f) The aluminum box with film cover was placed into the refrigerator at -15 °C for 6 to 8 hour to ensure that the whole soil layer is completely frozen; g) After completely frozen, the aluminum box was carefully removed to constant room at 8 °C for 6 to 8 hour to make sure that the whole soil layer is completely melted. Finally, 1-time freeze-thaw cycle was completed. For 3-time freeze-thaw cycles, the above f and g steps were repeated for 3 times; for 5-time freeze-thaw cycles and 7-time freeze-thaw cycles, the above f and g steps were repeated for 5 and 7 times, respectively.

(4) Soil disintegration test: a) For each aluminum box with filling soils after completing required freeze-thaw cycles, two samples for test soil disintegration were cut from the aluminum boxes (2 samples from each box) using a disintegration sampling knife (square knife 5 cm×5 cm×5 cm); b) The cubic samples were gently placed on the stencil frame; c) The stencil frame with the soil sample was carefully placed into the cylinder container which filled with DI water. The DI water temperature was maintained at 17-19^{o}C degree; d) the measurement is run to click on the software “Start” button, simultaneously started timing with the stopwatch (Table 4-1 and Fig 4-1).

Table 4-1 The experiment design for the effects of freeze-thaw cycles on soil disintegration.

Tested soils	Initial soil water content (%)	Freeze-thaw cycles	Freezing temperature (ºC)	Thawing temperature (ºC)	Replications
	16.5	0 (control)			6
	16.5	1			6
KS	16.5	3	-15	8	6
	16.5	5			6
	16.5	7			6
	16.5	0 (control)			6
	16.5	1			6
BX	16.5	3	-15	8	6
	16.5	5			6
	16.5	7			6

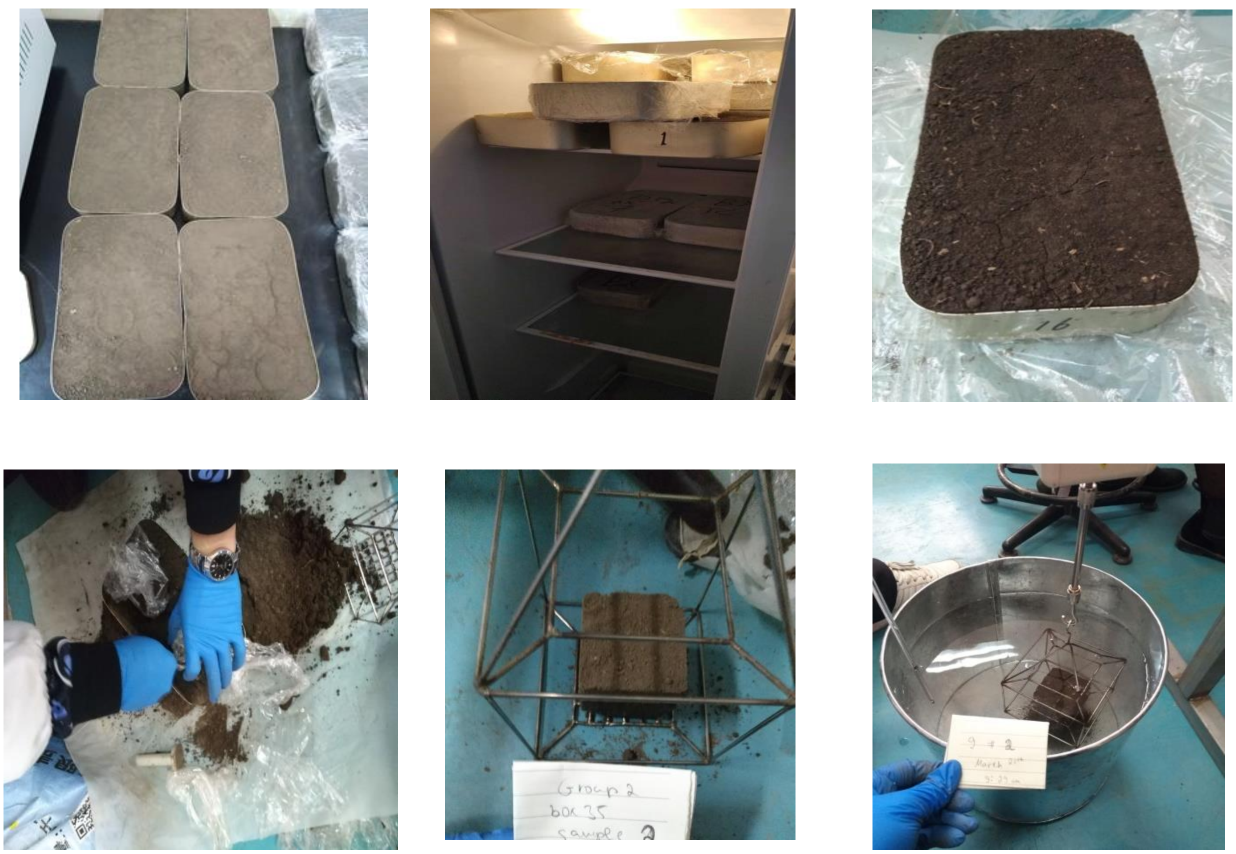


Figure 4-1 The main procedure of testing soil disintegration.

4.3 Results

4.3.1 Freeze-thaw cycle influence on soil disintegration rate

The results showed that the soil disintegration rate increased as numbers of freeze-thaw cycle increased (Fig 4-2). The disintegration rate for the KS soil showed sharp increase with the increase of freeze-thaw cycles and it increases by 3 times when the soil samples experienced one time of freeze-thaw cycle. Moreover, the soil disintegration rate for the KS soil increases by 2 times when freeze-thaw cycles increase from 5 to 7 (Fig 4-2a). Besides, the soil disintegration rate for the BX showed gradual increase with the increase of freeze-thaw cycle.

Compared with BX tested soil, KS soil was about 5 times higher than that for BX soil when the freeze thaw cycle increased from 5 to 7 times, which indicating that soil property has great impacts on soil disintegration rate and procedure.

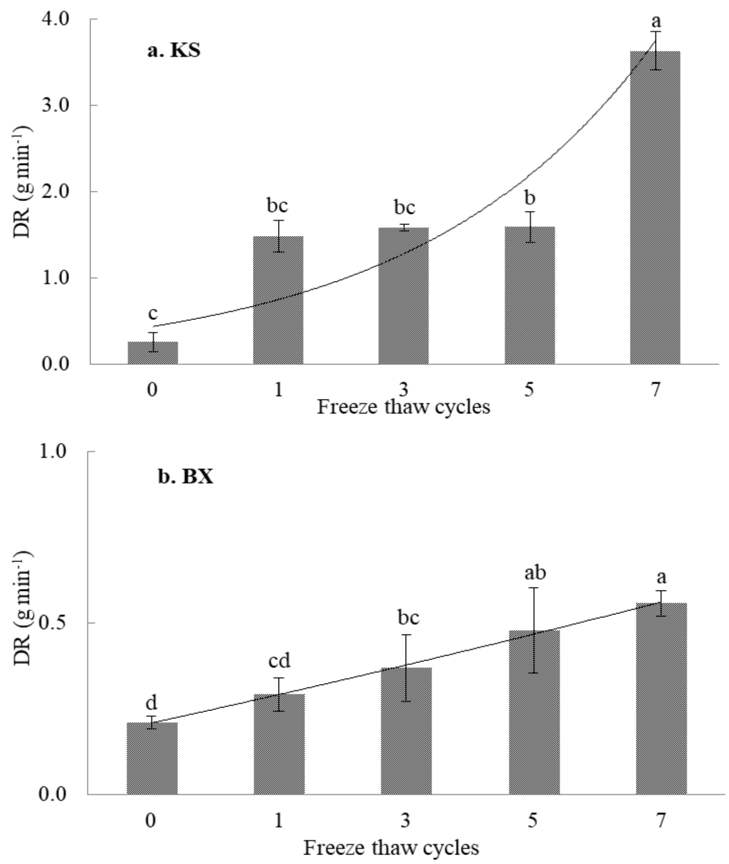


Figure 4-2 The soil disintegration rate of remolded soil sample under different freeze-thaw cycles with 16.5 % of initial soil water content.

4.3.2 Freeze-thaw cycle influence on soil disintegration process

Fig.3 shows that the increasing of freeze-thaw cycles shortens soil disintegration process. In detail, soil disintegration duration of the KS soil shortened by 64% when the soil samples experienced one time of freeze-thaw cycle, and it decreases by 95% after 7 times of freeze-thaw cycles (Fig 4-3a). Furthermore, soil disintegration procedure of BX soil decreases gradually with increase freeze-thaw cycle times (Fig 4-3b). In addition, the soil disintegration duration for the BX soil decreased by 30% when the freeze-thaw cycle increase from 0 (control) to 7 times. Comparing two different tested soils found that soil disintegration duration for KS soil was about 10 times shorter than that for BX soils (Fig 4-3) after seven times of freeze-thaw cycles.

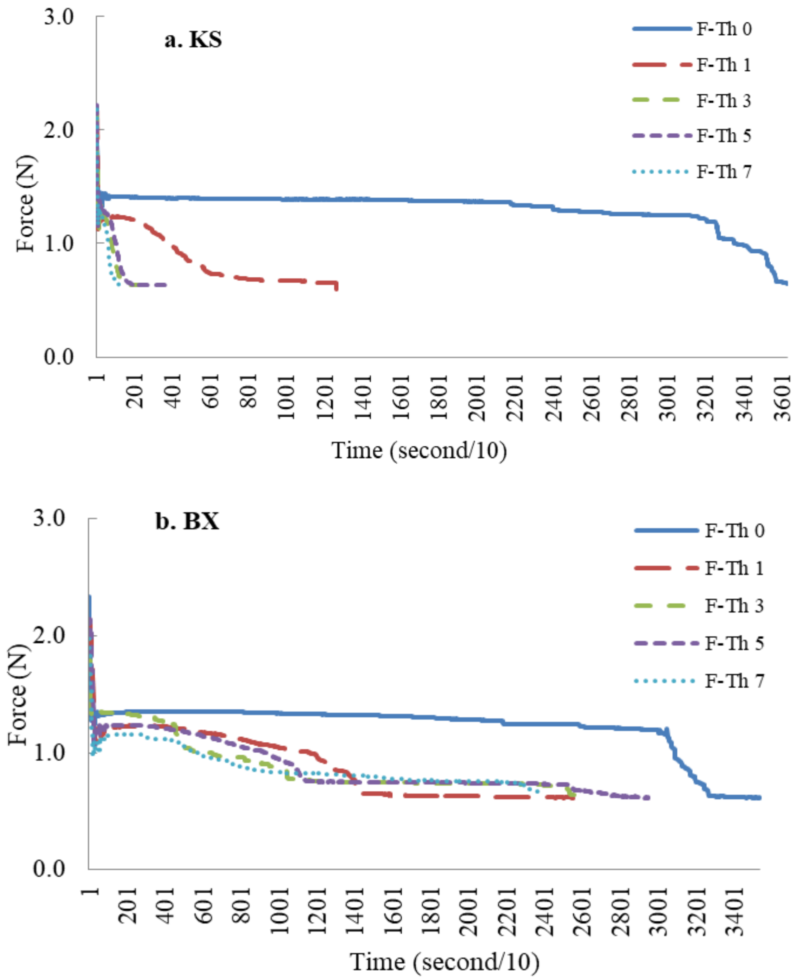


Figure 4-3 Sol disintegration curves of remolded soil samples under different freeze-thaw cycles with 16.5% of initial soil water content.

4.4 Discussion

The frozen soil is made up with solid mineral particles, liquid water that contains unfrozen water and tightly bound water, and water and air vapor (Lai et al., 2009, 2010). The volume of the soil sample increases when the water in the soil freezes; when the thawing procedure occur volume decreases due to consolidation. Some studies have investigated that freeze-thaw process also weakens the soil strength. In this study soil samples were cracked after 3 times of freeze-thaw of cycles. Viklander, (1998) and Yamazaki et al., (2006), were claimed that soil physical properties could possibly affected by freeze-thaw cycles, after soil hydrology impact. Whereas, the freeze-thaw effect is not only factor that influences soil aggregate and pore structure but also wetting-drying and shrinkage-swelling affect soil structure (Bronick and Lal, 2005). Other study also reported that the freeze-thaw effect was the one of the main factor for soil structure (Oztas and Fayetorbay, 2003).

4.5 Conclusion

The chapter designs a set of indoor experiments to investigate the freeze-thaw effects on soil disintegration rate. The main conclusions are follows:

(1) The soil disintegration rate increases with the increasing of freeze-thaw cycles. The soil disintegration rate for KS soil increases sharply by 3 times when soil samples experienced one freeze-thaw cycle. Besides, the soil disintegration rate for the KS soil increases by 2 times when freeze-thaw cycles increase from 5 to 7 times; while the soil disintegration rate for the BX soil increases gradually.

(2) The soil disintegration duration for the KS soil shortened by 64% when soil samples experienced one freeze-thaw cycle, and decreased 95% after 7 times of freeze-thaw cycle; while soil disintegration process for BX soil decreases gradually with increasing of freeze-thaw cycles. Comparing two different tested soils found that soil disintegration duration for KS soil was approximately 10 times shorter than that for BX soil after 7 times of freeze-thaw cycles.

CHAPTER 5 COMPARISON OF SOIL DISINTEGRATION RATE AND PROCEDURE BETWEEN REMOLDED SOIL AND UNDISTURBED SOIL

5.1 Introduction

Soil degradation is the only destructive force on the world soil resource (Parr et al., 1992). Lal, (2001) reported that about 15.1% of the world land was affected by the human-induced degradation, 83.6% of which was reported as soil erosion, and 40.4% of land degradation was occurred in Asia. The human disturbance and cultivation affect soil aggregate stability under various type of land use pattern. Thus, inappropriate land use patterns usually causes unstable aggregate breakdown and produces micro-aggregates which is easily transportable particles during soil erosion process (Zhang et al., 2008).

In Chinese Mollisol region, large scale of cultivation and intense soil erosion cause reduction of Mollisol productivity and fertility. Although cultivation activity begins later in northeast China, compared to the other regions of China (Wang et al., 2009), soil greatly is degraded. For example, the national statistics (MWR et al., 2010) reported that black topsoil has thickened 50-80 cm in 1950 and 20-40 cm in 2000.

Some studies have investigated that the stability of the soil aggregates was more stable in its natural structure than that for cultivated soils (Panayiotopulus and Kostopoulou, 1989; Gajici et al., 2010). The soil structure correlated to the plant root growth, water infiltration, porosity gas exchange etc. (Hans, 1996). The soil aggregates are commonly destructed when the soil is tilled or freeze-thaw occurs. The Mollisol in the northeast China have been intensively over several decade (Feng et al., 2018) due to agricultural activities, which causes soil degradation. Hence, the aim of this chapter was to analyze the differences of soil disintegration rates between remolded soil and undisturbed soils in the Chinese Mollisol region.

5.2 Materials and Methods

The tested soil samples were collected from BX and KS too. The experimental treatments include four levels of freeze-thaw cycles (0, 1 and 7 times) with two initial soil water contents (24.8% and 33%) (Table 5-1) and the treatment without freeze-thaw process is taken as the control treatment. Each treatment has at least 4 replications.

Table 5-1. Experimental design for the comparison of soil disintegration rate between remolded soil and undisturbed soil.

Tested soils	Soil structure	Initial Soil water content (%)	Freeze-thaw cycles	Replication
KS	Remolded	24.8	0 (control)	4
			1	
			3	
			7	
		33.0	0	
			1	
			3	
			7	
	Undisturbed	24.8	0	
			1	
			3	
			7	
		33.0	0	
			1	
			3	
			7	
BX	Remolded	24.8	0	4
			1	
			3	
			7	
		33.0	0	
			1	
			3	
			7	
	Undisturbed	24.8	0	
			1	
			3	
			7	
		33.0	0	
			1	
			3	
			7	

The procedures for measuring soil disintegration rate for remolded soil samples are seen in the chapter 4. For the undisturbed soil samples, the procedures for measuring soil disintegration rate are almost the same as procedures for remolded soil samples except that sample preparation process in the field. For undisturbed soil sample preparation, 120 square-knifes with 6.18 cm diameter and 2 cm deep were used to collect soil samples from topsoil (0-20 cm) in the maize field in Keshan and Binxian countries, Heilongjiang province of China and all samples were brought back to laboratory in order that all samples keep their original structure. With 120 ring knifes soils were randomly divided into two groups, one group with 10 ring knifes is used to measure soil water content, other group with 110 knifes is directly used to measure soil disintegration rate without grinding and remolding.

5.3 Results

5.3.1 Comparison of soil disintegration rate between remolded soil and undisturbed soil

The soil disintegration rate between the undisturbed and remolded soil samples showed that soil disintegration rate increases with the increase of freeze-thaw cycle at 24.8% and 33.0% initial soil water contents (Fig 5-2 and 5-3). Furthermore, soil disintegration rate for KS undisturbed soil increases by 5 times (from 0.13 g min^{-1} to 0.68 g min^{-1}), and remolded soil increases by 6 times (from 0.4 g min^{-1} to 2.3 g min^{-1}) (Fig 5-2a and 5-3a) when the freeze-thaw cycle increase from 3 to 7 times; while soil disintegration rate for BX remolded and undisturbed soil increase gradually with the increase of freeze-thaw cycles (Fig 5-2b and 5-3b). In addition, freeze-thaw cycle has insignificant influence on soil disintegration rate for BX undisturbed soil with 33% of initial soil water content (Fig 5-3b).

By comparing soil disintegration rates between the remolded and undisturbed soils, it is found that soil disintegration rates for remolded soils were 4 times higher than those for undisturbed soils, particularly for the KS remolded soil (Fig 5-2a and 5-3a). However, soil disintegration rate for BX undisturbed soil with 24.8% of initial soil water content was 20% higher than that for remolded soil when freeze-thaw cycle changes from 3 and 7 times (Fig 5-2b). Compared with KS undisturbed soil, decreasing trend of soil disintegration rate for BX undisturbed soil is more obvious. The reasons why soil disintegration rate for undisturbed soil is lower than that for remolded soil can been explained as follows: (1) Remolded soil has larger soil bulk density than undisturbed soil. 1.20 g/cm^3 soil bulk density is used to prepare soil disintegration rate test for remolded soil, but for undisturbed soil, soil bulk density in the field is 1.08 g/cm^3. (2) For remolded soil, soil samples for soil disintegration rate test is tilled and it contends less porousness, while for undisturbed soil, soil samples contends more porousness because they are directly collected from the field and maintains their original structure. (3) For remolded soil, soil samples are grounded the sieved through 2 mm mesh, so soil samples for soil disintegration rate test has uniform surface condition; but for undisturbed soil, soil samples for soil disintegration rate test has different soil particle size.

In addition, soil disintegration rate for KS soil was 5 times higher than that for BX soil when the freeze-thaw cycle increases from 3 to 7 times (Fig 5-2 and 5-3).

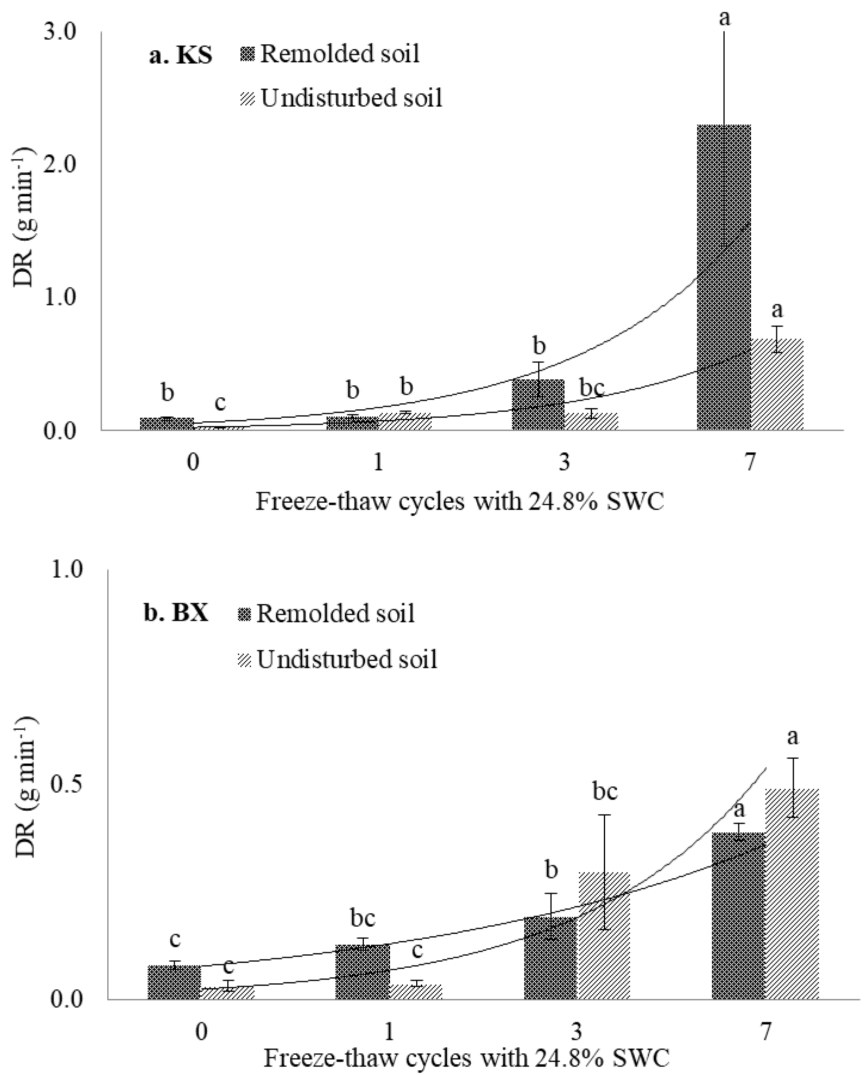


Figure 5-2 The soil disintegration rate of remolded and undisturbed soil samples with different freeze-thaw cycles under 24.8% initial soil water content.

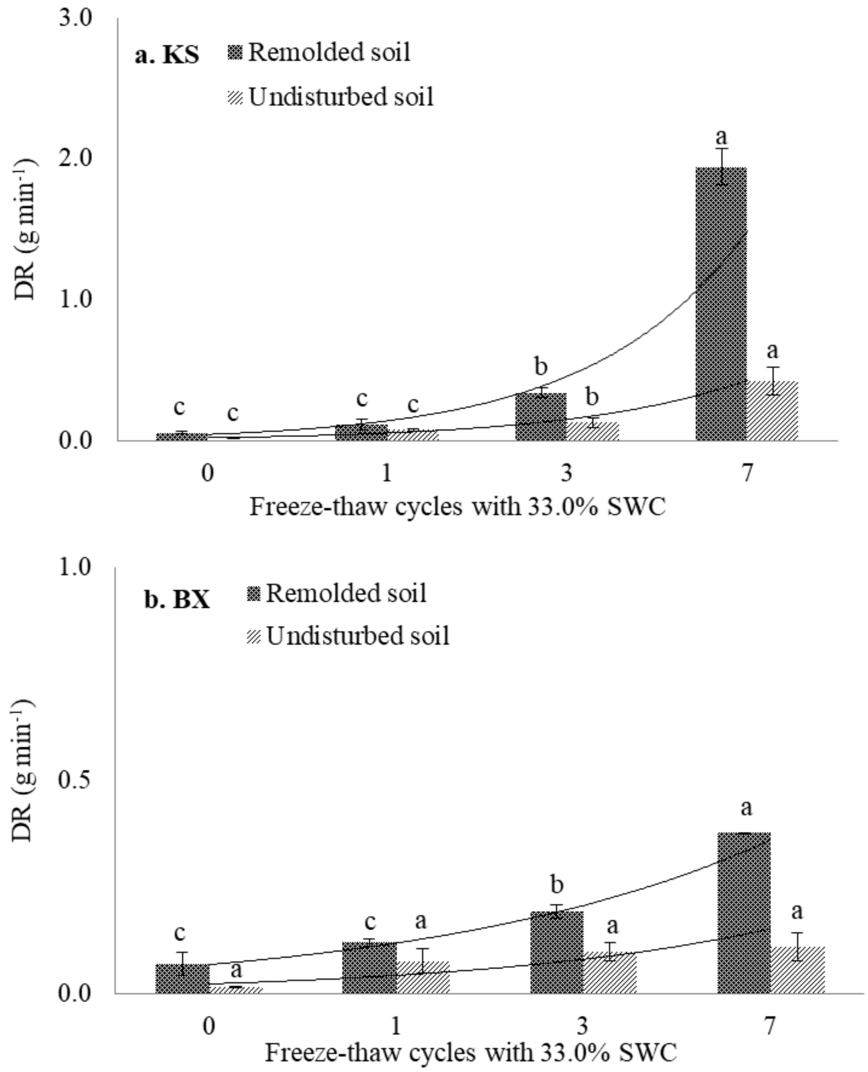


Figure 5-3 The soil disintegration rate of remolded and undisturbed samples with different freeze-thaw cycles under 33% initial soil water content.

5.3.2 Comparison of soil disintegration processes between remolded soil and undisturbed soil

The KS undisturbed soil with 7 times of freeze-thaw cycles under 24.8% initial soil water content was performed shortest duration, among all treatment the duration was 4.2 min (Fig 5-4a). In addition, undisturbed soil began to disintegrate from 1 minute when the freeze-thaw cycle reached 7 times (Fig 5-4 and 5-5). However, for BX soil samples, soil disintegration rate gradually increases for the undisturbed soil after soil samples experienced one time of freeze-thaw cycle during the whole measuring time (more than 30 minutes).

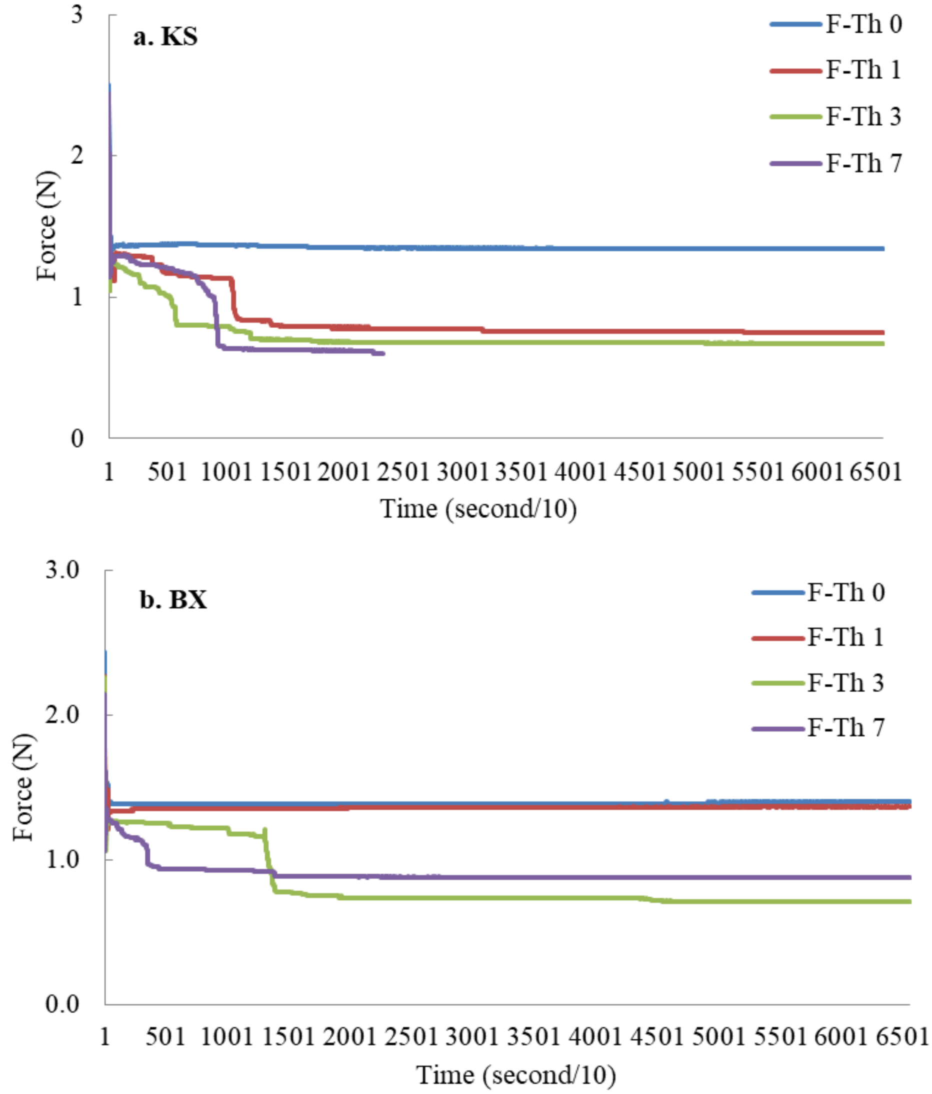


Figure 5-4 Soil disintegration process for undisturbed soil samples under different freeze-thaw cycles with 24.8% Initial soil water content.

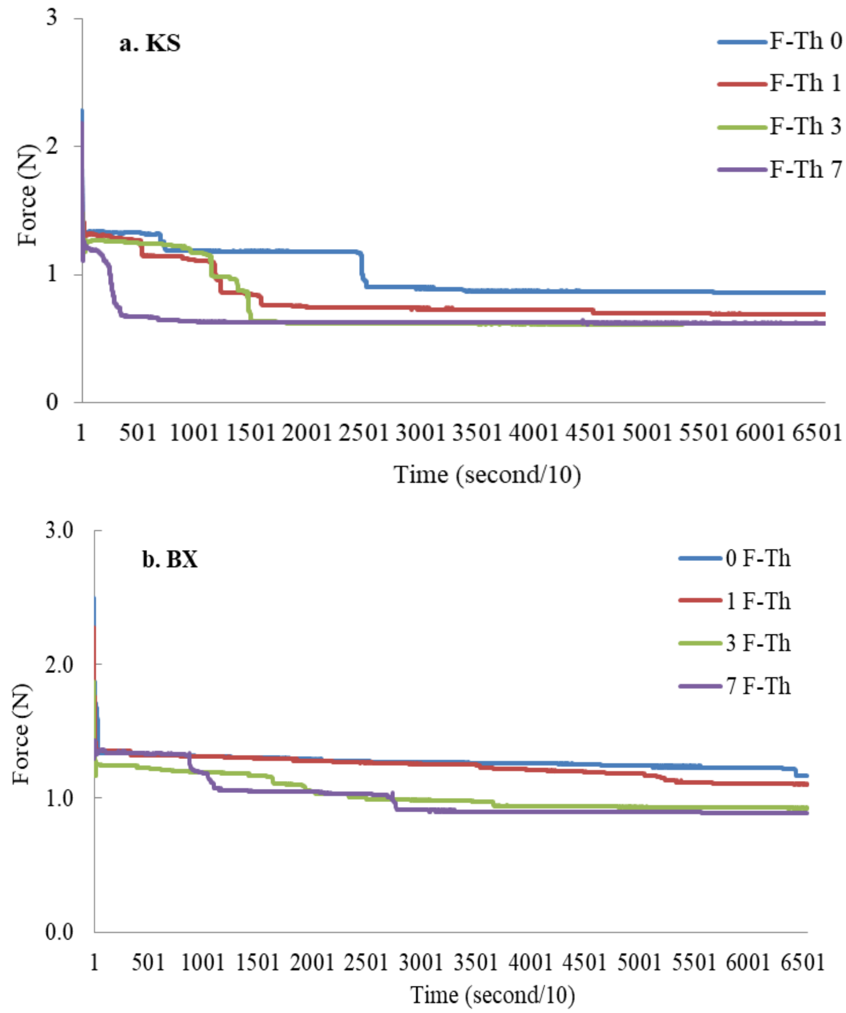


Figure 5-5 Soil disintegration process for undisturbed soil samples under different freeze-thaw cycles with 33% Initial soil water content.

Compared with the BX soil, the KS soil with higher clay content (Table 2-2) showed low disintegration rate in this study. Moreover, the soil samples tend to easily disintegrate in the water with an increase of the numbers of freeze-thaw cycles. This is reason that volume of the water expands during the freezing, which leads to change soil physical properties (Qi et al., 2006). An increase of soil water content also elevates the point of the freeze. Thus, the volume change during the freezing process increases the pressure within the soil porosities and reduces particle cohesion and soil strength, making the soil more erodible (Wang et al., 2007).The some studies claimed that the soil disintegration process occurs only when the disintegration force is greater than the cohesion force of the soil block (Derbyshire et al., 1994; Klukanova and Sajgalik 1994;

Díaz et al., 2007; Kruse et al., 2007; Zhang et al., 2016). For this reason, the more freeze-thaw cycles are, the higher soil disintegration rates are.

5.4 Conclusion

Based on the indoor soil disintegration methods, the comparison of remolded and undisturbed soil disintegration rate was clarified. The conclusions of the chapter are as follows:

(1) The disintegration rate for KS undisturbed soil increases by five times, and remolded soil increases by 6 times when the freeze-thaw cycle increase from 3 to 7 times; while soil disintegration rate for BX remolded and undisturbed soil increases gradually with increasing of the freeze-thaw cycle.

(2) By comparing the remolded soils with undisturbed soils, soil disintegration rate for remolded soils is above 4 times higher than that for undisturbed soils, particularly for the KS remolded soil.

(3) Soil disintegration rate for KS soil is 5 times higher than that for BX soil when the freeze-thaw cycle increases from 3 to 7 times.

(4) The undisturbed soil begins to disintegrate within 1 minute when the freeze-thaw cycle reaches 7 times. However, soil disintegration rate gradually changed for the undisturbed soil after one freeze-thaw cycle during the whole measurement duration (more than 30 minutes).

CHAPTER 6 CORRELATION BETWEEN AFFECTING FACTORS AND SOIL DISINTEGRATION RATE

6.1 Introduction

The northeast China, which is known as the main Mollisol distribution area (National Bureau of Statistics of China, 2012), have been affected intensive soil erosion due to large-scale of the cultivation activities (MWR et al., 2010). Moreover, freeze-thaw erosion also occurs in Mollisol region of China (Yu et al., 2011). The freeze-thaw cycle is not only seasonal phenomenon, it even occurs monthly, daily, and in the dawn. Furthermore, there are numbers of influencing factors which are contributes soil erosion, such as rainfall, temperature, and initial soil water content (Sachs and Sarah, 2017). Thus, soil erosion harms land resource and declines soil productive, which causes reduction of crop production (Wang et., 2009; Oyuang et al., 2018).

Soil disintegration rate is the one of the main indicator (Jiang, 1995) for evaluating soil erosion severity. In other words, high soil disintegration rate indicates that the soil is more dispersed, fragmented and slumped in still water, i.e., soil has less resisting to erosion, which may cause high probability of soil erosion (Li, 2015).

In recent decades, numbers of studies in China have conducted on soil disintegration rate, particularly on loess soil (Jiang, 1995; Li et al., 2018; Wang, 2019). However, there is less information regarding determining affecting factors of soil disintegration rate. Thus, this chapter analyzes corrections between soil disintegration rate and its affecting factors.

6.2 Results

It can be seen that the soil disintegration rate for Mollisol samples is closely related to the number of freeze-thaw cycles, initial soil water content and soil aggregate contents (MWD, mean weight diameter)(Table 6-1 and 6-2). Generally, the affecting factors are also related to each other, which affect the soil disintegration rate too. Correlation analysis showed that there are negative correlations between the soil disintegration rate with soil organic matter content, clay content, especially, there is negatively significant relation between soil disintegration rate with an increase of MWD ($P<0.05$), indicating that soil disintegration rate decreases with an increase of MWD. In contrast, soil disintegration rate has significantly positive correction with freeze-thaw cycles ($P <0.05$). Furthermore, there is significantly negative correlation between soil disintegration rate with initial soil water content ($P <0.05$). The above results prove that soil aggregate, freeze-thaw cycle and initial soil water content are crux factors affecting soil disintegration rate. In addition, the correlation coefficients between soil disintegration rate for the two tested soil with the numbers of freeze-thaw cycles were 0.906 and 0.906, respectively, and the correlation coefficients between the soil disintegration rate for the two soil with the initial soil water content were -0.764 and -0.858, respectively (Table 6-1 and 6-2).

Table 6-1 The correlation between soil disintegration rate with freeze-thaw cycles and soil properties

Tested soil	Variables	DR	F-T cycle	Organic matter content	clay content	MWD
KS	**DR**	1				
	F-T cycle	0.906**	1.000			
	Organic matter content	-0.192	-0.196	1.000		
	clay content	-0.342	-0.381	0.728**	1.000	
	MWD	-0.617**	-0.702**	0.519*	0.845**	1.000
BX	**DR**	1.000				
	F-T cycle	0.906**	1.000			
	Organic matter content	-0.196	-0.192	1.000		
	clay content	-0.381	-0.342	0.728**	1.000	
	MWD	-0.702**	-0.617**	0.519*	0.845**	1.000

Note: * Significant correlation at 0.05 level, ** Significant correlation at 0.01 level.

Table 6-2 The correlation between soil disintegration rate with soil water content and soil properties

Soil properties	Variables	DR	SWC	Organic matter content	clay content	MWD
KS	DR	1.000				
	SWC	-0.764**	1.000			
	Organic matter content	-0.288	-0.142	1.000		
	clay content	-0.309	-0.117	0.998**	1.000	
	MWD	0.647**	-0.867**	0.466*	0.458*	1.000
BX	DR (g min-1)	1.000				
	SWC	-0.858**	1.000			
	Organic matter content	-0.075	-0.142	1.000		
	clay content	-0.080	-0.117	0.998**	1.000	
	MWD	0.831**	-0.867**	0.466*	0.458*	1.000

Note: * Significant correlation at 0.05 level, ** Significant correlation at 0.01 level.

6.3 Conclusion

By analyzing the correlation between soil disintegration rates and affecting factors, main factors affecting soil disintegration rate was identified. The main conclusions are as follows:

(1) The correlation coefficients between the soil disintegration rate for the two tested soils (KS and BX soil) with the number of freeze-thaw cycles were 0.906 and 0.906, respectively, which showed that soil disintegration rate has positively correlated with freeze-thaw cycles ($P < 0.05$).

(2) The correlation coefficients between the soil disintegration rate for the two tested soils (KS and BX soil) with the initial soil water content were -0.764 and -0.858, respectively, indicated that soil disintegration rate has negative correlation with initial soil water content.

(3) There is significant relation between soil disintegration rate with MWD ($P<0.05$), indicating that soil disintegration rate decreases with an increase of MWD.

(4) Soil aggregate, freeze-thaw cycle and initial soil water content are crux factors affecting soil disintegration rate in the Chinese Mollisol region.

CHAPTER 7 CONCLUSIONS AND PERSPECTIVES

7.1 The Main Conclusions

This study has designed a series of indoor experiments to quantify how initial soil water content and freeze-thaw cycles effects on Mollisol disintegration rate and to compare the differences of soil disintegration rate between remolded and undisturbed soil. Thus, the following conclusions are obtained:

(1) The mollisol disintegration rate decreases with increase of initial soil water content and mollisol disintegration rate decrease by 3 times when the initial soil water content increases from 16.5% to 24.8%. However, mollisol disintegration rate showed insignificant difference when the initial soil water content increase from 24.8% to 33.0%. Moreover, the soil disintegration process with the 16.5% initial soil water content is disintegrated completely within 6 minutes and soil disintegration duration with 16.5% initial soil water content was 5 times shorter than that with 24.8% and 33.0% initial soil water contents. Furthermore, disintegration process of the mollisol lasted more than 30 minutes when the initial soil water content increased to 24.8% and 33.0%.

(2) The mollisol disintegration rate increases with an increases of the freeze-thaw cycle. The disintegration rate for KS soil increases sharply by 3 times when soil samples experienced one freeze-thaw cycle. Besides, the disintegration rate for the KS soil increases by 2 times when freeze-thaw cycle increase from 5 to 7 times; while the disintegration rate for the BX soil increases gradually. The disintegration duration of the KS soil shortened by 64% when soil samples experienced one freeze-thaw cycle, and decreased 95% after 7 times of freeze-thaw cycles; while disintegration process for BX soil decreases gradually with increasing of freeze-thaw cycles. Meanwhile, soil disintegration rate for KS soil was 5 times higher than BX soil when the freeze-thaw cycle increases from 3 to 7 times. The disintegration duration for KS soil was approximately 10 times shorter than that for BX soil when the freeze-thaw cycle reached 7 times.

(3) The soil disintegration rate for KS undisturbed soil increases by 5 times, and remolded

soil increases by 6 times when the freeze-thaw cycle increase from 3 to 7 times; while soil disintegration rate for BX remolded and undisturbed soil increase gradually with increasing of the freeze-thaw cycle. Moreover, soil disintegration rate for remolded soils was 4 times higher compared to the undisturbed soils, particularly for the KS remolded soil. Besides, undisturbed soil began to disintegrate within 1 minute when the freeze-thaw cycle reached 7 times. However, disintegration process gradually changed for the undisturbed soil after soil samples experiences one freeze-thaw cycle during the whole measurement duration (more than 30 minutes).

(4) The correlation coefficients between the soil disintegration rate for the two tested soils (KS and BX soil) and the number of freeze-thaw cycles were 0.906 and 0.906, respectively, which showed that soil disintegration rate had positively correlated with freeze-thaw cycles ($P < 0.05$) and soil disintegration rate increases with the increase of freeze-thaw cycle. Meanwhile, the correlation coefficients between the soil disintegration rate for the two tested soils (KS and BX soil) and the initial soil water content were -0.764 and -0.858, respectively, indicated that soil disintegration rate had negative correlation with initial soil water content.

7.2 Perspectives

In order to run the indoor experiment of the soil disintegration rate, the every steps of the experimental procedure should be setup and noted in detail. The proposed disintegration rate indicator reflects prossibility of soil. Furthermore, the calculation formula of soil disintegration rate can be used to predict the disintegration rate for compacted soil. Moreover, soil disintegration rate can be used as an indicator for soil erodibility.

In order to evaluate the soil disintegration rate, this suggests that affecting factors of soil disintegration should be studied in detail and studies on mechanisms of soil disintegration are needed in the near future.

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