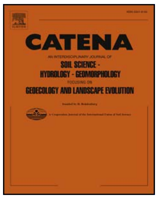
Catena 162 (2018) 100–107

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena



An analysis of soil detachment capacity under freeze-thaw conditions using the Taguchi method

B.Y. Sun[a], J.B. Xiao[a], Z.B. Li[a,b,*], B. Ma[a], L.T. Zhang[b], Y.L. Huang[a], L.F. Bai[b]

[a] *Institute of Soil and Water Conservation, Northwest A & F University, Yangling, Shaanxi 712100, China*
[b] *Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, China*

ARTICLE INFO

Keywords:
Soil erosion
Freeze-thaw
Soil detachment capacity
Taguchi method

ABSTRACT

Soil detachment is one of the most important processes of soil erosion, as it is of great significance for the prevention and treatment of soil erosion in areas subject to seasonal freeze-thaw. However, little research on soil detachment capacity (SDC) during the thawing period has been carried out and this process remains unclear. In order to elucidate the effects of slope, flow discharge and freeze-thaw factors on SDC, the indoor artificial freezing-thawing method was applied in combination with scour to simulate the soil detachment process. Signal-to-noise (S/N) ratio analysis was also used to evaluate the experimental results by applying the Taguchi method. The results showed that SDC increased with the increased of slope and flow discharge. As the number of freeze-thaw cycles and moisture increased, SDC initially decreased and then increased. A maximum soil detachment value was achieved at 12° slope and when moisture was 12%, flow discharge was 1.2 L/min, and there were ten freeze-thaw cycles. Statistical analysis with the help of Taguchi method showed that the percentage contribution of the different factors to SDC occurred in order, slope (76.02% at $p = 0.002$) > flow discharge (13.39% at $p = 0.019$) > soil moisture (6.92% at $p = 0.047$) > the number of freeze-thaw cycles (3.67% at $p = 0.106$), while factors related to hydrodynamic conditions exert a greater influence than those related to freeze-thaw. Finally, the Taguchi and orthogonal analysis methods showed the similar predictive results $R^2 = 0.98$ and $R^2 = 0.97$ respectively. However, the Taguchi method was more accurate than the orthogonal analysis methods due to less relative error 8.98% and 15.11% respectively. These results provided a scientific reference for the study of the mechanisms of soil erosion as well as for the applicability of the Taguchi method.

1. Introduction

Soil erosion has become a key environmental issue globally, restricting the coordinated development of society, economy, and the environment (Ananda and Herath, 2003; Thampapillai and Anderson, 1994; Prosdocimi et al., 2016; Ramos and Martínez-Casasnovas, 2004; Verstraeten et al., 2003). Soil erosion refers to the processes of detachment, entrainment, transport, and deposition of soil particles caused by one, or more, natural or anthropogenic erosive forces (Du et al., 2016). Thus, as an erosive sub-process, soil detachment can be defined as the separation of particles from the matrix at a particular location on the soil surface (Li et al., 2015; Wang et al., 2014; Zhang et al., 2003) and is the first stage of soil erosion. In the case of clear water, maximum soil detachment rate was referred to as soil detachment capacity (SDC) (Li et al., 2015; Nearing et al., 1991) and has been studied in detail over recent decades. Indeed, to study the effects of overland flow on SDC, an extensive series of laboratory and field experiments have been carried out, taking a range of slope and hydraulic parameters into account including flow rate, discharge, slope, flow depth, velocity, friction, and sediment concentration (Cochrane and Flanagan, 1997; Govers et al., 1990; Nearing et al., 1999; Poesen et al., 2003; Zhang et al., 2002). Slope and hydraulic parameters have also been incorporated into a range of representative models for soil erosion which include EUROSEM (Morgan et al., 1998), LISEM (Roo et al., 1996), WEPP (Nearing et al., 1989), EGEM (Woodward, 1999), and CREAMS (Knisel, 2010). Studies to date have suggested that while flow rate is the most accurate parameter for describing SDC, slope and discharge are both more practical and applicable (He et al., 2003).

Research has demonstrated that soil type, aggregate stability, bulk density, soil moisture, freeze-thaw, water tension, and infiltration rate all have a close relationship with SDC (Ghebreiyessus et al., 1994; Khanbilvardi and Rogowski, 1986; Morgan et al., 1998; Nearing et al., 1988; Van Klaveren and McCool, 2010; Zheng et al., 2000). Indeed, previous work has shown that the susceptibility of soil to erosion is two-to-three times higher during the winter-to-spring thawing period than it is throughout the rest of the year (Chow et al., 2000), while other

---

* Corresponding author at: Institute of Soil and Water Conservation, Northwest A & F University, Yangling, Shaanxi 712100, China.
E-mail address: zbli@ms.iswc.ac.cn (Z.B. Li).

https://doi.org/10.1016/j.catena.2017.11.025
Received 28 November 2016; Received in revised form 15 October 2017; Accepted 27 November 2017

studies have demonstrated that temporal variation in soil erodibility (i.e., inherent susceptibility to detachment and transport by rain and runoff) (Ellison, 1945) can result from alternating periods of freeze-thaw (Bajracharya and Lal, 1992; Kirby and Mehuys, 1987; Kok and Mccool, 1990). These results have led to increased levels of interest in understanding how individual factors which determine erodibility (e.g., aggregate stability, cohesion, and the mechanical characteristics of soil) are influenced by frost action (Bryan, 2000; Lehrsch et al., 1991). Most previous studies on the effects of freeze-thaw and soil moisture on aggregate stability have suggested that an increase in the number of freeze-thaw cycles will lead to a decrease in stability (Bajracharya et al., 1998; Bullock et al., 1988; Dagesse et al., 1996; Kværnø and Øygarden, 2006) while the physical and mechanical characteristics of soils change as the result of freeze-thaw cycles (Wang et al., 2007). However, in spite of this previous research, the relationship between freeze–thaw cycles and SDC remains unclear.

For various purposes, some new methods have been successfully introduced in the study of soil erosion in recent years, such as volume replacement method, numerical modeling and remote sensing (Cuomo et al., 2016; Dong et al., 2015; Peter et al., 2014). In order to study the effects of slope, flow discharge and freeze-thaw on SDC, a large number of experiments encompassing the full range of possible factors are required. Thus, in order to reduce the number of required tests, the notion of fractional factorial experiments (FFEs) were developed (Gray, 1988; Ziegel, 1997). The Taguchi method is one kind of FFE matrix that has been widely and successfully applied in order to determine optimal process parameters across a variety of subject areas (Aber et al., 2004; Singaravelu et al., 2009; Zolfaghari et al., 2011). This method has recently been applied in studies on soil erosion and sediments (Sadeghi et al., 2012; Zhang et al., 2015), as it appeared to have utility in understanding the potential factors affecting soil detachment. The Taguchi method was also attractive because it can be used instead of considering numerous experimental combinations which require considerable time and money.

Thus, the aims of this study were to determine and compare the effects of slope, flow discharge, moisture, and freeze-thaw cycles on SDC using the indoor artificial freeze-thaw scour experiments and Taguchi method.

2. Materials and methods

2.1. Test location and soil

Experiments were conducted in the Simulated Rainfall Hall at the Institute of Soil and Water Conservation, Chinese Academy of Sciences. The soil samples used in the tests were collected from the 0–20 cm soil layer in an abandoned cropland. It located in Dalad Banner, Province of Inner Mongolia which was the crisscross region of Hobq Desert and the Loess Plateau (110° 19′ to 110° 36′ E longitude, 39° 55′ to 40° 21′ N latitude). The mechanical composition, bulk density and organic carbon of the soil samples were presented in Table 1. The soil samples were sandy loam based on United States soil textural classification standards. In order to remove stones, grass, and other debris from the soil, the air-dried sample was sieved through a 2 mm mesh.

2.2. Experimental design

According to field survey, the slope of farmland is < 15°, soil moisture content is between 3% and 15%, and the cyclical phenomenon of thawing during the day and freezing at night generally lasts for one month at the beginning of spring. Thus, using a local standard runoff plot (20 m × 5 m) of maximum runoff to calculate unit flow as the experimental maximum scour flow in the early spring, the design maximum flow was set to 1.2 L/min after correction. This study required 768 tests to be conducted if used full-factorial design, while the design rules of the Taguchi method were applied to the four factors as an alternative. The L_{16} orthogonal array for this study was shown in Table 2. By the Taguchi method, four slope were considered in this study (i.e., 3°, 6°, 9°, and 12°), as well as four soil moistures (i.e., 3%, 6%, 9%, and 12%), flow discharge (i.e., 0.3 L/min, 0.6 L/min, 0.9 L/min, and 1.2 L/min), and freeze-thaw cycles (i.e., 1, 4, 7, and 10 times). Then the slope (9°) and flow discharge (0.9 L/min) were controlled and the process of soil detachment was simulated under different moistures (6%, 9%) and freeze-thaw cycle (0, 1, 5, 10, 15, and 20 times).

2.3. Freeze/thaw and scour simulations

On the basis of field investigations soil bulk density were determined to be 1.35 g cm^{-3} and placed the sieved samples in heat insulated polystyrene boxes (Fig. 1 a, 60 cm in length, 30 cm in width, and 20 cm in depth). Soil samples (Fig. 1 b) were then held at room temperature for 48 h to enable soil moisture to balance before their surfaces were covered with plastic wrap to prevent further evaporation. Samples were then frozen in the refrigerator, at a temperature of − 10 °C maintained for 12 h, before being thawed at room temperature for 12 h at temperatures between 5 °C and 10 °C. This process simulated the natural process of a nightly freeze followed by a daily thaw.

The SDC index was obtained via a flow scouring experiment that utilized a device comprising a water supply tank (Fig. 1 d), flowmeter (Fig. 1 e), steady flow section (Fig. 1 f) and flume (Fig. 1 g). The variation range of test flume for SDC (0.5–22 m in length, 0.05–0.8 m in width) is very large at home and abroad which are mainly in University of Leuven and Beijing Normal University. For this experiment, the length of the acceleration zone must > 1 m which can make the velocity of flow stable and the depth can appropriate for flow discharge (Zhang et al., 2003; Zhang et al., 2002). The length to width ratio of flume should be appropriate which reduces deposition inside the sample (Ciampalini and Torri, 1998). The water supply tank consisted of a 1.5 m constant water head in addition to a flume (100 cm in length, 4 cm in width, and 2 cm in depth) made of organic glass materials. Flowmeter and steady flow section were used to control the scouring flow and adjust scour flow stability, respectively. For each experiment, a soil sample was cut vertically out of the polystyrene box with a partially-blade metal box (Fig. 1 c, 20 cm in length, 4 cm in width, and 3 cm in depth), placed on an aluminum plate with holes, and then sealed with plastic wrap to prevent further disturbance. The soil sample on the aluminum plate was then placed into a water tank with 2 cm depth for 12 h so that water could infiltrate from the bottom of the metal soil box to the top to reach saturation. The water was removed by gravity from the metal box and then placed in the flume (Fig. 1 h), with its surface flush with the flume bed (Wang et al., 2016). Slope and flow

Table 1
Soil samples mechanical composition and properties.

Soil type	Mechanical composition [%]			Bulk density [g/cm^3]	Organic carbon [g/kg]
	Clay (< 0.002 mm)	Silt (0.002–0.05 mm)	Sand (0.05–2 mm)		
Sandy loam	10.25	38.63	51.12	1.35	3.26