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

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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

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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

Table 2

The L_{16} orthogonal array.

Row	Combination of different orders				Slope [°]	Moisture [%]	Flow discharge [L/min]	Freeze-thaw cycles [times]
1	1	1	1	1	3	3	0.3	1
2	1	2	2	2	3	6	0.6	4
3	1	3	3	3	3	9	0.9	7
4	1	4	4	4	3	12	1.2	10
5	2	1	2	3	6	3	0.6	7
6	2	2	1	4	6	6	0.3	10
7	2	3	4	1	6	9	1.2	1
8	2	4	3	2	6	12	0.9	4
9	3	1	3	4	9	3	0.9	10
10	3	2	4	3	9	6	1.2	7
11	3	3	1	2	9	9	0.3	4
12	3	4	2	1	9	12	0.6	1
13	4	1	4	2	12	3	1.2	4
14	4	2	3	1	12	6	0.9	1
15	4	3	2	4	12	9	0.6	10
16	4	4	1	3	12	12	0.3	7

discharge were adjusted according to requirements prior to each experiment which were timed as soon as they started, and were ended when there was a 2 cm depth of eroded soil in each sample box (Zhang et al., 2002). The scoured sediments (Fig. 1 i) were collected by plastic bucket (Fig. 1 j). The wet soil was then oven-dried at 105 °C for 24 h before being weighed, and each experiment was repeated three times for each group.

2.4. Calculations and statistical analysis

An analysis of the signal-to-noise (S/N) ratio is needed in order to evaluate the experimental results obtained by the Taguchi design method. There are three types of S/N ratio analyses that are generally applicable, including the higher-the-better, the nominal-the-better and the lower-the-better. In the study of soil erosion, one of the most important targets is to identify the conditions under which maximum soil erosion would occur (Sadeghi et al., 2012). Therefore, the higher-the-better analysis was used in this study. Simply, S/N ratio of higher-the-better is the ratio of the mean values of the dependent variable to standard deviation. The larger the signal-to-noise ratio is, the smaller the effect of the noise factor based on the concept of Taguchi design method. Thus, the higher-is-better S/N was calculated as follows:

$$\mathrm{S/N} = -10 \times 1\mathrm{g}\left(\frac{1}{\mathrm{N}}\sum_{i=1}^{N}\frac{1}{\mathrm{SDC}_i^2}\right) \tag{1}$$

In this expression, N denoted the number of repetitions under the same experimental conditions, while *SDC* represents measured results, in this case the rate of soil detachment as the result of each flume scour simulation test.

The analysis of means was used to recognize optimal conditions. This was done by first calculating the mean value of the S/N ratio for each factor at a certain order, and then the mean ratios of factor I in order i (M) was calculated (Sadeghi et al., 2012; Zhang et al., 2015) as follows:

$$M_{Factor=f}^{Order=1} = \frac{1}{\mathrm{N}_{fl}}\sum_{j=f}^{\mathrm{N}_{fl}}\left[\left(\frac{\mathrm{S}}{\mathrm{N}}\right)_{Factor=f}^{Order=l}\right]_j \tag{2}$$

In this expression, $M_{Factor\ =\ f}^{Order\ =\ 1}$ referred to the mean of the S/N ratios of factor *f* at order *l*, while N_{fl} denoted the number of appearances of factor *f* in order l. An S/N ratio response table and figure were then obtained, optimal conditions were identified, and a series of confirmation experiments were conducted under these optimal conditions.

The percentage contribution (PC) of each factor was then calculated, as follows:

$$\mathrm{PC} = \frac{\mathrm{SS_F} - (\mathrm{DF} \times \mathrm{V_{Er}})}{\mathrm{SS_T}} \times 100 \tag{3}$$

In this expression, $\mathrm{SS_F}$ refers to the factorial sum of squares, while $\mathrm{SS_T}$ is the total sum of squares, $\mathrm{V_{Er}}$ is the variance of error, and DF is the degrees of freedom. Soil detachment capacity [$\mathrm{g\,m^{-2}\,s^{-1}}$] was then calculated, as follows:

$$SDC = \frac{w_w - w_d}{A \cdot T} \tag{4}$$

In this expression, W_W is the dry weight of soil before testing [g], W_d is the dry weight after testing [g], T is the test duration [s], and A is the sample cross-section area [$\mathrm{m^2}$].

Coefficient of Variance (CV) was used to measure the variation of test results and was calculated as follows:

$$\mathrm{CV} = \sigma/\mu \tag{5}$$

In this expression, σ is the standard deviation [$\mathrm{g\,m^{-2}\,s^{-1}}$] and μ is mean values of SDC [$\mathrm{g\,m^{-2}\,s^{-1}}$].

Calculations and application of the Taguchi method were implemented using the Origin 9.0 and Minitab 15 software packages that include submenus for both this method and analysis of variance (ANOVA). The Minitab software package includes a function so that test data from orthogonal design can be used to predict additional sets likely to be generated under other test conditions. Construction of Taguchi design, univariate ANOVA, and predictions were carried out using these submenus.

3. Results

3.1. Conditions for largest SDC

The experimental design used in this study comprised 48 tests each consisted of three replications, as specified by Taguchi design theory. The SDC in each experiment was calculated using Eq. (4) and the mean value and standard deviation are presented in Table 3. Mean SDC in repetitions varied from 5.67 $\mathrm{g\ m^{-2}\,s^{-1}}$ to 686.93 $\mathrm{g\ m^{-2}\,s^{-1}}$ with a mean and standard deviation (SD) of 318.48 ± 221.73 $\mathrm{g\ m^{-2}\,s^{-1}}$ among all 16 tests, respectively, and a coefficient of variation of 0.70. The number of experimental iterations and measurement results were then substituted into Eq. (1) to determine the S/N ratio for each test condition (Table 3), resulted in a mean and SD of 44.82 ± 13.37 and a coefficient of variation of 0.30. According to the specified higher-is-better characteristic of the S/N ratio, SDC was largest in test 13 and smallest in test 1.

Values of the S/N ratio were substituted into Eq. (2), the mean S/N ratio of factor *f* in order *l* was obtained (Table 4). The mean value of the

Fig. 1. Schematic diagram of experimental setups.
a. Metal sampler and thawed soil.
b. Flume and support.
c. Water tank.
d. Flowmeter.
e. The process of soil detachment.

S/N ratio was also determined to be 44.82 ± 6.66 with a coefficient of variation of 0.15. The bold numbers in Table 4 denoted the maximum values of mean S/N ratio for a given factor among the four orders, and thus described conditions for largest soil detachment. Results of this analysis suggested that the conditions for largest soil detachment were at a slope of 12°, moisture of 12%, a flow discharge rate of 1.2 L/min, and ten freeze-thaw cycles. The conditions for smallest soil detachment were a slope 3°, 9% moisture, a flow discharge of 0.3 L/min, and four freeze-thaw cycles. These conditions differ from those of test 13 and 1, respectively.

Table 3
The S/N ratio for each experiment resulted from different combinations of factors and orders.

	Factors				SDC [$g/(m^2 \cdot s)$]		S/N ratios
	Slope [°]	Moisture [%]	Flow discharge [L/min]	Freeze-thaw cycle [times]	Mean values	Standard deviation	
Test 1	3	3	0.3	1	5.67	0.74	14.94
Test 2	3	6	0.6	4	9.67	0.28	19.70
Test 3	3	9	0.9	7	16.85	2.14	24.38
Test 4	3	12	1.2	10	158.97	4.63	44.02
Test 5	6	3	0.6	7	217.40	13.57	46.71
Test 6	6	6	0.3	10	181.32	10.90	45.14
Test 7	6	9	1.2	1	326.71	17.17	50.26
Test 8	6	12	0.9	4	390.50	18.99	51.81
Test 9	9	3	0.9	10	420.21	1.52	52.47
Test 10	9	6	1.2	7	625.33	14.79	55.92
Test 11	9	9	0.3	4	108.30	9.50	40.63
Test 12	9	12	0.6	1	386.32	13.31	51.73
Test 13	12	3	1.2	4	686.93	29.81	56.72
Test 14	12	6	0.9	1	582.87	6.71	55.31
Test 15	12	9	0.6	10	432.13	1.83	52.71
Test 16	12	12	0.3	7	546.43	36.76	54.71

Table 4
Response table for S/N ratios for studied factors and corresponding levels in the study area.

Factor	Order	$\left[\left(\frac{S}{N}{}^{l}_{f}\right)\right]_j$				$M_{Factor = f}^{Order = 1}$
		j = 1	j = 2	j = 3	j = 4	
Slope	1	14.94	19.70	24.38	44.02	25.76
	2	46.71	45.14	50.26	51.81	48.48
	3	52.47	55.92	40.63	51.73	50.19
	4	56.72	55.31	52.71	54.71	**54.86**
Moisture	1	14.94	46.71	52.47	56.72	42.71
	2	19.70	45.14	55.92	55.31	44.02
	3	24.38	50.26	40.63	52.71	42.00
	4	44.02	51.81	51.73	54.71	**50.57**
Flow discharge	1	14.94	45.14	40.63	54.71	38.85
	2	19.70	46.71	51.73	52.71	42.71
	3	24.38	51.81	52.47	55.31	45.99
	4	44.02	50.26	55.92	56.72	**51.73**
Freeze-thaw cycle	1	14.94	50.26	51.73	55.31	43.06
	2	19.70	51.81	40.63	56.72	42.22
	3	24.38	46.71	55.92	54.71	45.43
	4	44.02	45.14	52.47	52.71	**48.58**

The boldface figures in Table 4 refer to the maximum value of the mean the S/N ratios.

3.2. *Effect of four factors on SDC*

S/N ratio is the result of reprocessed of test results (Ziegel, 1997). Specifically, a higher S/N ratio was considered to be preferable in this study, while the relationship between this ratio and other factors can influence the response of the SDC (Sadeghi et al., 2012; Zhang et al., 2015). Effects of the main experimental factors (i.e., slope, moisture, flow discharge, and freeze-thaw cycle times) on mean S/N ratios for SDC under Taguchi design were shown in Fig. 2. The S/N ratio of freeze-thaw cycle times and water content remained basically the same (approximately 43), greater than flow discharge (38.85) and slope (25.76) in order 1 of all factors (Fig. 2). However, at order 2, the S/N ratio of the slope was obviously greater than that of other factors, while when these orders reached a maximum for all factors, the order of S/N ratio size was slope > flow discharge > moisture > freeze-thaw cycles. These results demonstrated that SDC exhibited a variable tendency to increase in concert with the orders of the four factors. Results showed that S/N ratio increased as a logarithmic function (6) of slope and was simulated well by the linear function (7) of flow discharge (Fig. 2).

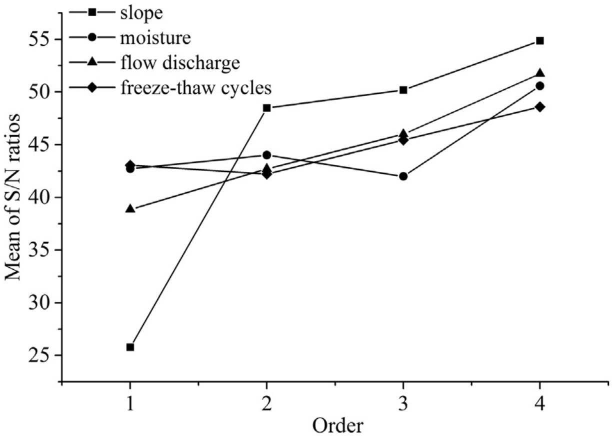

Fig. 2. Effects of slope, antecedent moisture, flow discharge, and freeze-thaw cycles on S/N ratios. Note that factor levels are horizontal coordinates. In the case of slope, the numbers 1–4 refer to 3°, 6°, 9°, and 12° respectively, while for flow discharge these numbers denote 0.3 L/min, 0.6 L/min, 0.9 L/min, and 1.2 L/min respectively. In the case of soil moisture, the numbers 1–4 denote 3%, 6%, 9%, and 12%, respectively, while they refer to 1, 4, 7, and 10 times of freeze-thaw cycles, respectively.

$$S/N = 20.61\ln(S) - 4.73 \qquad R^2 = 0.91 \tag{6}$$

$$S/N = 4.19F + 3.34 \qquad R^2 = 0.98 \tag{7}$$

where S is slope degree and F is flow discharge. The results also showed that SDC decreased initially and then increased in concert with increased in both soil moisture and the number of freeze-thaw cycles.

The effects of freeze-thaw cycles (0, 1, 5, 10, 15, 20 times) and moisture (6% and 9%) on SDC were shown in Fig. 3. Freeze-thaw cycles and moisture were significant ($p < 0.05$) influenced SDC. The SDC of 6% moisture was significant ($p < 0.05$) > 9% moisture. There were significant difference ($p < 0.01$) between SDC resulted from the first and the fifth freeze-thaw cycle, respectively. SDC reached maximum value after the first freeze-thaw cycle for the two moisture soils. There was no significant ($p > 0.05$) change for SDC when the freeze-thaw cycle more than five times (Fig. 3).

3.3. *The percentage contribution of factors*

The percentage contribution of each factor was determined by substituting SS_F, SS_T, V_{Er}, and DF into Eq. (3). The results of this analysis were shown in Table 5, the significance and percentage

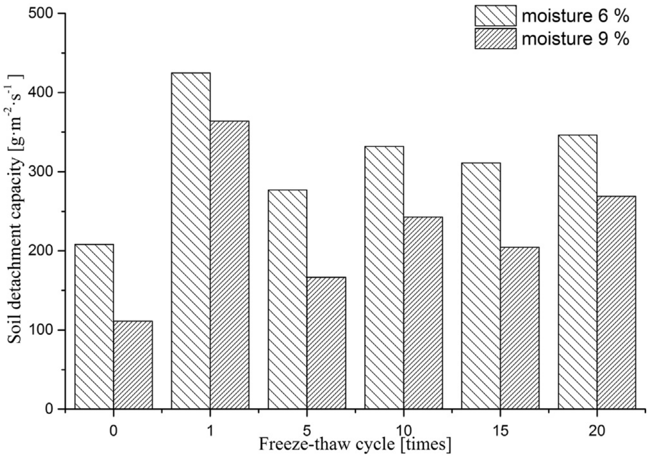

Fig. 3. The relationships of soil detachment capacity (SDC) and freeze-thaw cycles in two conditions of moisture.

contribution of each factor depended on either orthogonal design or use of the Taguchi method. The significant contribution of slope steepness was > 74% according to both statistical methods. This is the largest result in comparison with other factors (Table 5). According to orthogonal design method the contribution of other factors was not significant at $p = 0.05$. However, according to Taguchi method the contribution of the moisture 6.92% and flow discharge 13.39% was significant. The contribution of freeze-thaw cycles was not significant at $p = 0.05$ according to both statistical methods. Generally, the results after Taguchi method were slightly better than results after orthogonal design method (Table 5).

3.4. Prediction of SDC

This function was used to predict the data generated using the Taguchi method, with the S/N ratio under different test conditions considered first and with SDC calculated based on Eq. (1). A scatter plot of predicted versus observed SDCs obtained under Taguchi conditions as well as the orthogonal method was generated (Fig. 4). These data showed that the predicted value is extremely significantly positively correlated with the observed value, with analysis under Taguchi conditions ($R^2 = 0.98$) performed slightly better than the orthogonal method ($R^2 = 0.97$).

4. Discussion

The small flume would immediately raise the question of the scaling effects of the experiments. Such as the velocity of flow was may not stable when the flow first touches the soil. The uniform scouring to the soil samples by flow would be influenced by the boundary of flume if the width to depth ratio of flow is too small. It would be concentrated flow as a result of the unstable flow velocity and the influence of the flume boundary on the flow in the process of scour. There is no doubt that the test results may different from the truth in the field and the effects of scale cannot be ignored. Norms and standards of dimension of flume are still not formed in the study of soil detachment especially after freeze-thaw. Although the dimension of flume is small, the sediment deposition could be significantly reduced, the process of soil detachment could be judged accurately and the reliability of test results could be improved by control the appropriate ratio. It has been noted that soil detachment is strongly influenced by slope and flow discharge that can alter erosion energy (Zhang et al., 2002). The results of earlier work in the laboratory also showed that the SDC increased as a linear function of flow discharge (Zhang et al., 2003), a function that was characterized by high correlation coefficients ($R^2 \geq 0.98$) in this study (Eq. (7)). The relationship between SDC and slope transitioned from a power function to a logarithmic one as flow discharge increased (Zhang et al., 2003). The SDC can be simulated effectively using a logarithmic function (Eq. (5), $R^2 = 0.91$) of slope at low flow discharge, perhaps because of the effects of scale and freeze-thaw on soil.

It has also been noted that aggregate stability was a useful index for measuring soil erodibility as this factor was affected by freezing (Bryan, 2000; DíAz-Zorita et al., 2002; Lehrsch et al., 1991). However, the exact impact of freeze-thaw on soil aggregate stability remained debated because of differences between test methods and undisturbed soils. Results from some studies have suggested that aggregate stability might be greatest after two-to-three freeze-thaw cycles because of the precipitation of slightly soluble bonding agents, but will be markedly reduced after six cycles as fracture planes form in aggregates (Lehrsch et al., 1991; Oztas and Fayetorbay, 2003). Aggregate stability appeared to increase almost linearly in a 30% water content loam subject to one-to-five freeze-thaw cycles (Lehrsch, 1998; Lehrsch et al., 1991). This regular variation in aggregate stability was very similar to the effects of freeze-thaw cycle times on the SDC, as shown in Fig. 3. Results showed that freezing and ice formation improve aggregate stability (Perfect et al., 1990) and the soil would be more resistant to water erosion when the number of freeze-thaw cycles is less than four. However, the SDC would increase as the breakdown of macroaggregates increased after four-to-five freeze-thaw cycles (Williams, 1991). Data showed that the effect of soil water content on aggregate stability depended on soil texture, structure, and organic matter content. Aggregate stability has been shown to be inversely proportional to soil water content following freezing because soil drying precipitates the development of cementing or bonding agents (Lehrsch et al., 1991; Lehrsch et al., 1993; Perfect et al., 1990). However, at the same time, aggregate stability would not be affected by the presence of bonding agents when water content is low (Lehrsch et al., 1993). The results of Fig. 2 showed that aggregate stability was greatest at 9% moisture. The SDC underwent incipient decrease and subsequent increase with the increment in the moisture, and the critical moisture for the conversion was 9%.

Previous studies have rarely contrasted the effects of freeze-thaw, slope and flow discharge on the SDC. The results of this study revealed that the effect on the SDC of soil erodibility due to freeze-thaw was greater than the effect of erosion energy due to slope and flow discharge

Table 5
Significance (ANOVA) and percentage contribution of different factors.

Method	Factor	Sum of squares	Degree of freedom	Mean sum of square	F value	Significance	Contribution rate [%]
Orthogonal design	Slope [°]	554,442	3	184,814	29.28	0.010	74.04
	Moisture [%]	53,574	3	17,858	2.83	0.208 (NS)	7.15
	Flow discharge [L/min]	133,044	3	44,348	7.03	0.072 (NS)	17.77
	Freeze-thaw cycle [times]	7746	3	2582	0.41	0.759 (NS)	1.03
Taguchi method	Slope [°]	2025.36	3	675.12	106.45	0.002	76.02
	Moisture [%]	184.43	3	61.48	9.69	0.047	6.92
	Flow discharge [L/min]	356.59	3	118.87	18.74	0.019	13.39
	Freeze-thaw cycle [times]	97.7	3	32.57	5.13	0.106 (NS)	3.67

"NS" - considered as Not Significant value.

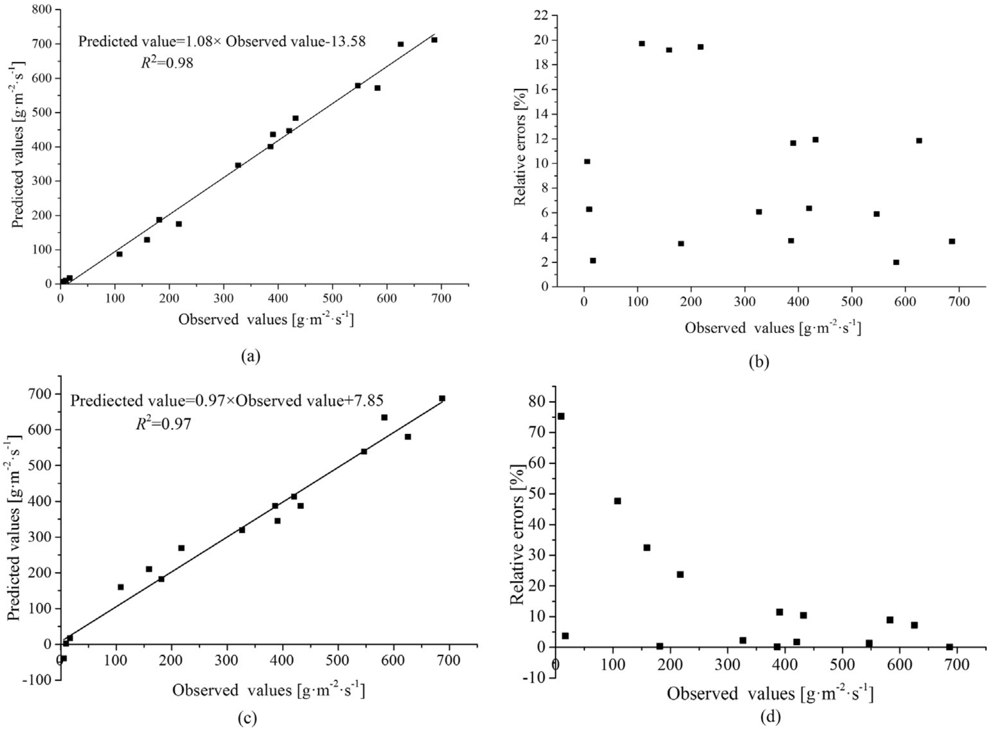

Fig. 4. Observed and predicted SDCs and their relative errors. (a, b) Taguchi method. (c, d) Orthogonal method.
(a) Predicted values from Taguchi method.
(b) Relative errors from Taguchi method.
(c) Predicted values from orthogonal method.
(d) Relative errors from orthogonal method.

when the order of all factors was lowest, especially slope (Fig. 2). Although the SDC increased in concert with flow discharge and slope, in contrast with previous research, our results suggested it was more sensitive to the latter (Nearing et al., 1991). This difference was mainly because the largest designed unit flow discharge (i.e., $0.5 \times 10^{-3}\,m^2\,s^{-1}$) of the semi-arid region in this study was far less than in previous work (i.e., $6.67 \times 10^{-3}\,m^2\,s^{-1}$). And the uniform scouring to the soil samples by flow has been influenced by the boundary of flume because of the width of flume is small. Thus, as the orders of all factors increased, the effect of slope and flow discharge on the SDC gradually became larger than the effect of freeze-thaw, gradually coming to occupy a dominant position, especially in the case of slope. When these orders reached a maximum for all factors, the order of contribution rate was similar to the S/N ratio size (Table 5). The contribution rate of the slope (76.02% based on the Taguchi method) is therefore greater than those of the other three factors, and exerts an extremely significant effect on the SDC when both statistical methods are applied. The significance analyses of flow discharge, moisture, and freeze-thaw cycle times revealed some differences depended on use of either the Taguchi or the Orthogonal design method (Table 5), mainly because the latter employed original data while the former utilized S/N ratio. Soil erosion is a complex process that is influenced by many uncontrollable factors. The S/N ratio was used in order to analyze the experimental results obtained by the Taguchi design method. In the study of soil erosion, S/N ratio analysis was used to identify the conditions of maximum soil erosion would occur (Sadeghi et al., 2012). The S/N ratio of higher-the-better is the ratio of the mean values of SDC to standard deviation. The larger the S/N ratio is, the smaller the effect of the noise factor. Thus, the Taguchi method could effectively reduce the contribution of uncontrollable factors. The error of system as a result of the effect of scale may be able to be reduced by using Taguchi method. Although the contribution rate of flow discharge (13.39% using the Taguchi method) was far less than that of the slope, this also exerted a more significant effect on the SDC. The results of this study also showed that the effect of changes in erosion energy on the SDC were stronger than soil erodibility as a result of design values or the limited impact of freeze-thaw factors. Thus, the contribution rates of moisture (6.92% using the Taguchi method) and freeze-thaw cycle time (3.67% using the Taguchi method) were both low with only the former exerting a significant influence on the SDC when the Taguchi method was used. When slope and flow discharge were excluded, freeze-thaw cycle had significant ($p < 0.05$) influence on SDC (Fig. 3). There were significant difference ($p < 0.01$) between SDC resulted from the first and the fifth freeze-thaw cycle, respectively. Moreover, the SDC of first freeze-thaw cycle was the largest, which was different from the result obtained through Taguchi method. It was because the freeze-thaw factor was masked by other key factors (slope and flow discharge) in determining the complex relationship between SDC and freeze-thaw cycle, according to the framework of Taguchi method. Additionally, SDC seldom changed ($p > 0.05$) when the cycle time exceeded five (Fig. 3), which was the main cause for the inconsistency derived from the analyses using Orthogonal and Taguchi methods, respectively.

To a certain extent, the relative error between observed and predicted values can reflect the forecast effect. All relative prediction errors used the Taguchi method were < 20% (Fig. 3 a, b), with an average value and SD of 8.98 ± 6.16% and a coefficient of variation of 0.69, while relative prediction error using the orthogonal method decreased with an increase in SDC (Fig. 3 c, d). Results showed that this ranged from 0.09% to 75.26%, with an average value and SD of 15.11 ± 21.58% and a coefficient of variation of 1.43. Previous studies have shown that use of orthogonal design and the Taguchi method was more convenient than use of the observed values from the total factor method (Zhang et al., 2015). However, other results have also demonstrated that the predictive power of the Taguchi method was an improvement with respect to that of orthogonal design (Sadeghi et al., 2012). This conclusion is supported here and thus the Taguchi method can be used to effectively predict erosion within a study area given limited experimental conditions and without having to commit to a large amount of work.

5. Conclusions

In this study, the effects of slope, flow discharge, moisture, and freeze-thaw cycles on the detachment capacity of sandy loams were examined using the indoor artificial freeze-thaw and scour experiments. The main conclusions are as follows:

(1) The condition for largest (12° slope, 12% moisture, 1.2 $\mathrm{L\,min^{-1}}$ flow discharge, and 10 times cycle) and smallest (3° slope, 9% moisture, 0.3 $\mathrm{L\,min^{-1}}$ flow discharge, and 4 times cycle) SDC were determined using Taguchi method and differ from those of test 13 and 1, respectively.

(2) SDC was significant positively related to slope and flow discharge that can alter erosion energy. Significant influence of the freeze-thaw cycle on SDC was not effectively detected by using Taguchi method. However, SDC experienced a significant decreasing-increasing trend with the increase in freeze-thaw cycles and moisture when slope and flow discharge were excluded. Specifically, the turning point for the change of the variation tendency was four-five times freeze-thaw cycle and 9% moisture which were mainly because of the variation of aggregate stability.

(3) Freeze-thaw was the most main factor that affects SDC when all factors were lowest values. But as the values of all factors increased the effect of slope and flow discharge on the SDC gradually exceed the effect of freeze-thaw, especially slope. According to Taguchi method, the percentage contribution of slope to SDC was the largest significant (76.02%), followed by the flow discharge (13.39%) and moisture (6.92%), after which freeze-thaw cycle (3.67%) with the smallest not significant.

(4) Given a certain range of different combinations of factors and orders, Taguchi method can thus be used to accurately predict the SDC ($R^2 = 0.98$). The effect of freeze-thaw on the SDC, however, requires further investigation in regions where this process occurs seasonally.

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