



# Relationship between soil surface roughness and hydraulic roughness coefficient on sloping farmland

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**Abstract:** The soil surface roughness and hydraulic roughness coefficient are important hydraulic resistance characteristic parameters. Precisely estimating the hydraulic roughness coefficient is important to understanding mechanisms of overland flow. Four tillage practices, including cropland raking, artificial hoeing, artificial digging, and straight slopes, were considered based on the local agricultural conditions to simulate different values of soil surface roughness in the Loess Plateau. The objective of this study was to investigate the relationship between the soil surface roughness and hydraulic roughness coefficient on sloping farmland using artificial rainfall simulation. On a slope with a gradient of 10°, a significant logarithmic function was developed between the soil surface roughness and Manning's roughness coefficient, and an exponential function was derived to describe the relationship between the soil surface roughness and Reynolds number. On the slope with a gradient of 15°, a significant power function was developed to reflect the relationship between the soil surface roughness and Manning's roughness coefficient, and a linear function was derived to relate the soil surface roughness to the Reynolds number. These findings can provide alternative ways to estimate the hydraulic roughness coefficient for different types of soil surface roughness.

**Key words:** soil hydraulics; sloping farmland; soil erosion; soil surface roughness; hydraulic roughness coefficient; Reynolds number; tillage practice

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## 1 Introduction

Soil surface roughness is a critical parameter reflecting soil erosion and runoff processes, and is mainly influenced by soil surface characteristics. Bagnold (1941) first defined and calculated the soil surface roughness. It is always used to describe the surface elevation

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The work was supported by the National Natural Science Foundation of China (Grant No. 40901138), the Project of the State Key Laboratory of Earth Surface Processes and Resource Ecology (Grant No. 2008-KF-05), and the Project of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau (Grant No. 10501-283).

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Received Aug. 20, 2011; accepted Oct. 24, 2011

variation and is a major factor influencing wind and water erosion (Vidal Vázquez et al. 2005). By considering both tillage management and soil erosion (Huang et al. 2001; Darboux et al. 2001; Gómez and Nearing 2005; García Moreno et al. 2008), the soil surface roughness can also be used to investigate runoff generation and sediment deposition (Kamphorst et al. 2000; Merrill et al. 2001; Darboux et al. 2001). During tillage practices, water erosion processes on cultivated lands are often affected by soil micro-relief features. By controlling the volume of water storage of the soil surface, the soil surface roughness indirectly influences the water holding content of the soil surface. A higher degree of soil surface roughness is thought to enhance the infiltration rate of water through the soil surface (Hansen et al. 1999; Kamphorst et al. 2000; Planchon et al. 2001) and reduce overland flow, which in turn reduces the erosive capacity of runoff (Hairsine et al. 1992). The effects of the overall roughness on overland flow depend on the scales of soil erosion and runoff processes. The soil surface roughness impacts rainfall-induced runoff generation and causes sediment deposition in different ways. One important effect is that greater roughness can cause a greater infiltration rate of soil, although this effect tends to diminish due to soil surface sealing as rainfall progresses (Moore and Singer 1990). As we know, a higher level of hydraulic resistance may help to dissipate the water flow energy, soil erosion is lessened with the reduction of runoff due to greater roughness, and then a fraction of the total water flow energy dissipates during sediment transfer (Abrahams and Parsons 1991). Through modification of the clod size distribution, the splashing of raindrops is resisted, and the degree of soil erosion is also reduced (Romkens and Wang 1986). The soil surface roughness affects the drainage pattern adopted in the field, and the catchment scale has a significant influence on the spatial distribution of sediment sources and sinks. Conversely, some of these processes affect the soil surface roughness. Most reports on the soil surface roughness have focused on its mathematical description as well as its changes with rainfall (Bertuzzi et al. 1990). However, because of the practical difficulties in directly obtaining soil micro-relief features (Huang 1998), detailed quantitative information concerning the role of the soil surface roughness in soil erosion processes is under-reported in the literature.

Resistance to overland flow on hill-slopes is commonly expressed with the hydraulic roughness coefficient (Smith et al. 2007). The resistance is affected by such parameters as the flow rate, flow regime, soil concentration, topography, and tillage practices (Parsons et al. 1994; Lawrence 2000; Lane 2005; Asadi et al. 2007; Zhang et al. 2007). Studies show that the hydraulic roughness coefficient varies greatly with such factors as the flow discharge, slope gradient, Reynolds number, and flow velocity (Govers et al. 2000; Hessel et al. 2003). No difference has been found between surface flow and channel flow in the mechanisms of soil particle detachment, sediment transfer, and deposition process (Zhang et al. 2009; Zhang et al. 2010a). Several equations are available to calculate the overland flow velocity from the runoff depth. It is easy to calculate the hydraulic roughness coefficient in a channel using the

Darcy-Weisbach equation and Manning's equation. Most field and laboratory studies on overland flow have produced results consistent with the result from the Darcy-Weisbach equation, while the calculated results of channel flows with Manning's equation have contradicted field studies. Hydrological and soil erosion models have generally been tested with Manning's roughness coefficient, probably for the reason that more Manning's equation results have been provided in the literature. Another reason for the selection of Manning's equation is that overland flow is more or less adopted in the research, while the Darcy-Weisbach equation has been seldom used in streamflow calculation (Hessel et al. 2003).

The soil surface roughness and hydraulic roughness coefficient are important hydraulic resistance characteristic parameters. However, relatively little research has been carried out to relate the hydraulic resistance of the soil surface directly to its micro-topography. Some scientists have conducted preliminary studies to investigate the random roughness and hydraulic roughness coefficient (Sadeghian and Mitchell 1990; Cremers et al. 1996). The random roughness has been simulated with different soil particles, and the hydraulic roughness coefficient is commonly expressed with Manning's roughness coefficient. Manning's equation is one of the most widely used formulas for calculating the overland flow velocity in hydrological and erosion models (Nearing et al. 1989; De Roo et al. 1996; Morgan et al. 1998). The hydraulic roughness coefficient quantifies the comprehensive effect of the soil surface roughness on overland flow. Precise estimation of the hydraulic roughness coefficient is critical to simulation of the processes of overland flow and soil erosion (Zhang et al. 2010b). The objective of this study was to investigate the relationship between the soil surface roughness and hydraulic roughness coefficient through selection of different tillage practices on sloping farmland, and to develop regression equations for estimating the hydraulic roughness coefficient based on the soil surface roughness.

## **2 Material and methods**

### **2.1 Soil and soil box design**

The experiment was conducted at the Soil Erosion Research Laboratory of the Northwest A&F University in Yangling City, Shaanxi Province, China. Loess-derived soil was collected from the Nihegou Watershed in Chunhua County, Shaanxi Province, China. The study area has a long stripe-like shape with a length of 7.8 km (from south to north) and a mean width of 1.2 km (from east to west), and covers an area of about 948 hm<sup>2</sup>. The soil in the study area developed from wind-deposited loessial parent materials, classified as Calcic Cambosols according to the Chinese soil taxonomy (CRGCST 2001). Annual rainfall in this area varies from 500 mm to 700 mm, and the rainfall from July to September accounts for 50% of the total annual rainfall. Four soil boxes with sizes of 5 m × 1 m × 0.5 m were designed for the rainfall simulation. Air-dried top soil was passed through a 10 mm sieve to ensure the consistency of the size of soil particles, and the soil was filled in each soil box with a bottom area of 2.5 m<sup>2</sup>. The filled soil was 40 cm thick, under which was a pea gravel layer with a

thickness of 5 cm at the bottom of the soil box. The soil bulk density was adjusted to  $1.08 \text{ g/cm}^3$ , which is close to natural conditions (Zheng et al. 2009), with the randomization method, so as to ensure homogeneous filling. The soil texture was measured with the pipette method, and the soil bulk density was measured with the sampler method (Liu 1996). The particle size distribution of loess soil is given in Table 1.

**Table 1** Particle size distribution of loess soil

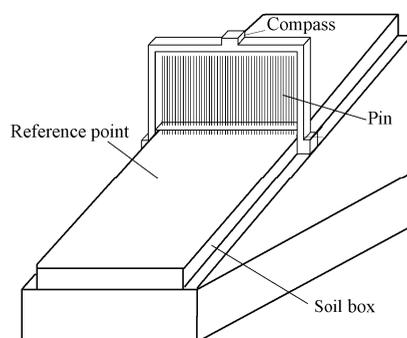
Particle size (mm)	Particle size distribution (%)	Particle size (mm)	Particle size distribution (%)	Particle size (mm)	Particle size distribution (%)
> 0.25	1.01	0.01-0.05	45.85	0.001-0.005	22.66
0.05-0.25	12.56	0.005-0.01	10.75	<0.001	7.17

## 2.2 Rainfall simulation and soil surface roughness measurement

The rainfall simulators used in this study were similar to those described by Zheng et al. (2009). Soil boxes set on  $10^\circ$  and  $15^\circ$  slopes were placed under a rainfall simulator with oscillating nozzles. The rain was designed to fall from a height of 11.5 m, and the effective rainfall area was approximately  $48 \text{ m}^2$ . The constant rainfall intensity and variable rainfall intensities were calibrated before testing. The precipitation uniformity coefficient of the rainfall simulator ranged from 0.80 to 0.92, and the coefficient measured under the experimental conditions was approximately 0.90.

The soil surface roughness was measured with a pin meter, consisting of 51 pins located at 2-cm intervals. The length of the pins was 30 cm (Brough and Jarret 1992). The meter was put on the slope and the lowest point of the slope surface was considered as the reference point. The height of each pin was read manually. The length of the slope was evenly divided into five sections with lengths of one meter. Within each section, the pin meter was used to measure changes in soil surface roughness at 20-cm intervals (moving across the width of the box). A small compass was placed on the top of the pin meter to measure the different slopes (Fig. 1).

The simulated rainfall intensity for each test condition was 1.0 mm/min. Each test was repeated three times for different tillage practices, and each test lasted 40 min according to the rainfall regime of the study area.



**Fig. 1** Sketch of pin meter

## 2.3 Simulation and calculation of soil surface roughness

Four tillage practices were considered based on the local agricultural conditions on the Loess Plateau, including cropland raking, artificial hoeing, artificial digging, and straight slopes. The depth of cropland raking was about 2.5 cm, the depth of artificial hoeing was about 5 cm, the depth of artificial digging was about 7 cm, and the straight slope was relatively smooth. These tillage practices were adopted so that the soil would have different values of soil surface roughness.

Bertuzzi et al. (1990) concluded that the limiting distance (LD) had more of a physical meaning than the random roughness, that it is a function of the horizontal distance between measurement points, and also that it is indirectly related to the height difference between the measurement points (Linden and van Doren 1986). In this study, the soil surface roughness was calculated with LD.

## 2.4 Hydraulic resistance

The hydraulic resistance of the soil surface is characterized by Manning's roughness coefficient  $n$ , which was calculated with Eq. (1):

$$n = \frac{1}{q} h^{5/3} i^{1/2} \quad (1)$$

where  $q$  is the flow rate per unit width ( $\text{m}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ ),  $h$  is the flow depth (m), and  $i$  is the hydraulic slope.

The flow velocity was measured using dye tracing techniques (Luo et al. 2010), and the runoff rate was calculated from the runoff discharge. The Reynolds number is a function of the ratio of the inertial force to viscous force. It can be used to estimate the flow state and describe the characteristics of the soil surface conditions. The Reynolds number ( $Re$ ) was calculated with Eq. (2):

$$Re = \frac{Vh}{\nu} \quad (2)$$

where  $V$  is the mean flow velocity (m/s), and  $\nu$  is the kinematic viscosity of flow ( $\text{m}^2/\text{s}$ ).

## 2.5 Statistical analysis

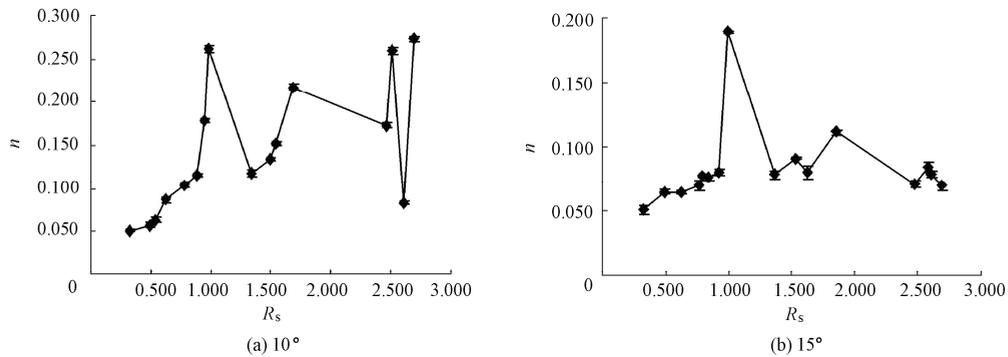
The differences between tillage practices were investigated with one-way analysis of the variance using SPSS 16.0.

## 3 Results and discussion

### 3.1 Soil surface roughness and hydraulic roughness coefficient for different gradients of slopes

The relationship between Manning's roughness coefficient  $n$  and the soil surface roughness  $R_s$  for different slopes is shown in Fig. 2. The hydraulic roughness coefficient of the  $10^\circ$  slope is higher than that of the  $15^\circ$  slope. There is a good correlation between the soil

surface roughness and hydraulic roughness coefficient when the values of the soil surface roughness are less than 1.000. The relationships between the soil surface roughness and hydraulic roughness coefficient become more complicated as the soil surface roughness exceeds 1.000 (Fig. 2).



**Fig. 2** Manning's roughness coefficient and soil surface roughness for different gradients of slopes

Runoff is turbulent ( $Re > 500$ ) with a low soil surface roughness, although the surface flow is uniform. Runoff has a relatively weak shearing and scouring effect on the soil surface. In general, the flow velocity inversely varies with the soil surface roughness. However, with the increase of the soil surface roughness, its effects on the variation of the flow velocity diminish. Furthermore, the shearing effect of runoff on the soil surface and the effect of runoff on soil deterioration increase with the runoff depth, resulting in the occurrence of rills and the decrease of the surface flow. Although the surface flow velocity increases with the gradient of slopes, as to eroding rills, the mean flow velocity does not increase with the gradient of slopes due to an increase in the soil surface roughness and the intensification of soil erosion (Govers 1990; Nearing et al. 1999). Therefore, it was preliminarily inferred that there was a critical state for the  $10^\circ$  and  $15^\circ$  slopes in our study.

### 3.2 Best fit between soil surface roughness and hydraulic roughness coefficient for different gradients of slopes

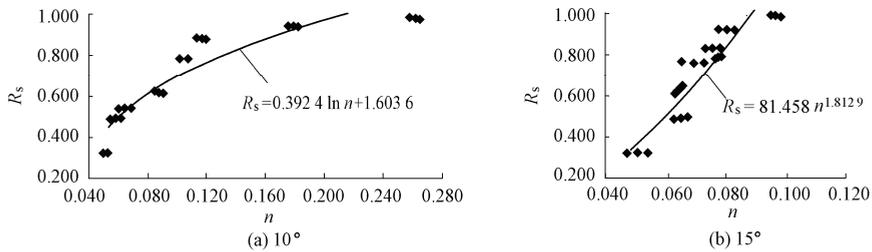
To better understand the relationship between the soil surface roughness and Manning's roughness coefficient, the relationship between the two factors was analyzed for different gradients of slopes, as shown in Fig. 3.

Based on the measured data of the soil surface roughness and hydraulic roughness coefficient obtained through consideration of different tillage practices, the best fit between Manning's roughness coefficient  $n$  and soil surface roughness  $R_s$  for  $R_s < 1.000$  was obtained using the method of regression analysis. The best fit for the  $10^\circ$  slope is a significant logarithmic function, while the best fit for the  $15^\circ$  slope is a power function. They are given as Eqs. (3) and (4), with a significance level less than 0.01.

$$R_s = 0.3924 \ln n + 1.6036 \quad R^2 = 0.8916 \quad (3)$$

$$R_s = 81.458 n^{1.8129} \quad R^2 = 0.8708 \quad (4)$$

where  $R^2$  indicates the coefficient of determination.

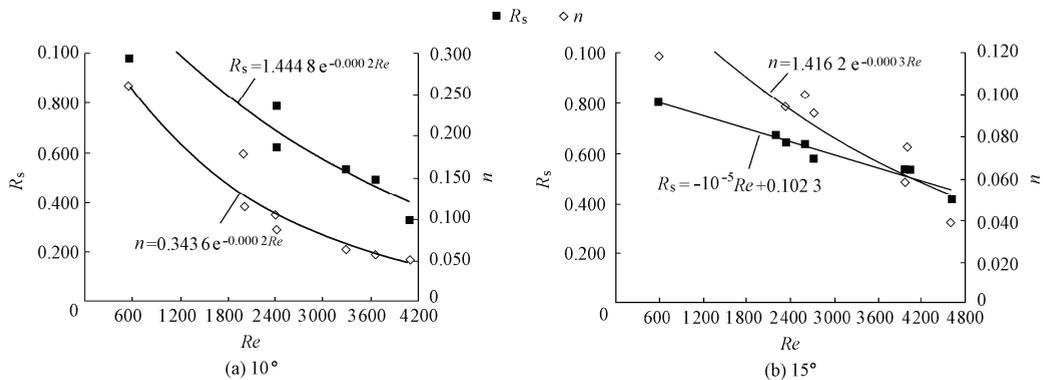


**Fig. 3** Relationships between soil surface roughness and Manning's roughness coefficient for different gradients of slopes under condition of  $R_s < 1.000$

There is a significant difference between Eq. (3) and Eq. (4), showing that the relationships between the soil surface roughness and Manning's roughness coefficient are different for different gradients of slopes. Fig. 3 also shows that the soil surface roughness and Manning's roughness coefficient have consistencies of resistance to overland flow when the values of the soil surface roughness are less than 1.000 for the  $10^\circ$  and  $15^\circ$  slopes.

### 3.3 Relationships between Reynolds number, Manning's roughness coefficient, and soil surface roughness

The relationships between the Reynolds number, Manning's roughness coefficient, and the soil surface roughness for different gradients of slopes are shown in Fig. 4.



**Fig. 4** Relationships between Reynolds number, soil surface roughness, Manning's roughness coefficient, and for different gradients of slopes under condition of  $R_s < 1.000$

The Reynolds number of overland flow varied from 553 to 4098 on the  $10^\circ$  slope, and from 601 to 4590 on the  $15^\circ$  slope. Manning's roughness coefficient decreased with the increase of the Reynolds number for different gradients of slopes (Fig. 4). Exponential relationships were found between Manning's roughness coefficient and the Reynolds number for both slopes. However, Zhang et al. (2010a) showed that there was a power function

between the hydraulic roughness coefficient and the Reynolds number. Hessel et al. (2003) reported that Manning's roughness coefficient increased linearly with the Reynolds number for croplands due to increased soil erosion and soil surface roughness. This discrepancy indicated the influence of the soil surface roughness. Moreover, the results above were also influenced by the soil and experiment conditions.

Based on the measured data of Manning's roughness coefficient and the Reynolds number obtained by adoption of different tillage practices in this study, the best fit of the relationships between Manning's roughness coefficient and the Reynolds number obtained using the method of regression analysis are Eqs. (5) and (6) for the slope gradients of 10° and 15°, with a significance level less than 0.01, under the condition of  $R_s < 1.000$ .

$$n = 0.3436e^{-0.0002Re} \quad R^2 = 0.9265 \quad (5)$$

$$n = 1.4162e^{-0.0003Re} \quad R^2 = 0.7733 \quad (6)$$

Using the same method, we obtained the best fit between the soil surface roughness and Reynolds number under the condition of  $R_s < 1.000$ , with a significance level less than 0.01. For the slope gradient of 10°, there is an exponential relationship between the two factors (Eq. (7)), while for the slope gradient of 15°, there is a linear relationship between the two factors (Eq. (8)), as shown in Fig. 4.

$$R_s = 1.4448e^{-0.0002Re} \quad R^2 = 0.8249 \quad (7)$$

$$R_s = -10^{-5}Re + 0.1023 \quad R^2 = 0.9472 \quad (8)$$

There are also significant differences between Eq. (5) and Eq. (6) as well as Eq. (7) and Eq. (8) for the slope gradients of 10° and 15°, respectively, showing that the relationships are different for different gradients of slopes. The relationships between Manning's roughness coefficient, the soil surface roughness, and the Reynolds number also demonstrate their consistency of resistance to overland flow when the values of the soil surface roughness are less than 1.000 for the 10° and 15° slopes from the perspective of hydraulics.

The value of the hydraulic roughness coefficient is dependent on the interaction between the soil surface and flow velocity only (Wong 1997). Reed et al. (1995) quantified the hydraulic roughness coefficient of a concrete surface under the conditions of steady and non-uniform overland flows. Wong (2002) quantified the hydraulic roughness coefficient of a concrete surface using the time of concentration. However, the results above were evaluated only based on the rising limbs. Various attempts have been made to predict the hydraulic roughness coefficient from measured data of the soil surface coverage, proportion of gravel, flow depth, flow velocity, and Reynolds number using the method of regression analysis (Gilley et al. 1992; Weltz et al. 1992). The flow depth and velocity have typically been recorded within a range of discharges over the soil surface, with the discharge supplied by the trickle flow at the upslope end of the experimental region (Abrahams and Parsons 1991) or by rainfall (Weltz et al. 1992). However, the measurement of flow depths and velocities on rough surfaces is difficult and relatively large measurement errors can be expected. Our results showed that the variation of Manning's roughness coefficient was consistent with that of the soil surface roughness on both

slopes when the soil surface roughness was less than 1.000. This work also showed the consistency between the hydraulic roughness coefficient, soil surface roughness, and Reynolds number, although distinct discrepancies in curve patterns occurred, as shown in Fig. 4. However, it is difficult to estimate Manning's roughness coefficient using the soil surface roughness when the soil surface roughness is larger than 1.000. Zhang et al. (2010b) showed that it is difficult or even impossible to conduct a similar study under the actual overland flow conditions over a hill-slope, because the soil surface roughness is complex and changes quickly with time and space as a result of scouring or deposition.

## 4 Conclusions

This study analyzed the relationship between the soil surface roughness and hydraulic roughness coefficient with the method of regression analysis based on the artificial rainfall simulation. The conclusions are as follows:

(1) For different gradients of slopes, the relationship between the soil surface roughness and the hydraulic roughness coefficient becomes very complicated when the soil surface roughness exceeds 1.000.

(2) For slopes with a gradient of  $10^\circ$ , a significant logarithmic function was developed between the soil surface roughness and the hydraulic roughness coefficient, and a significant power function was developed to reflect the relationship between the soil surface roughness and hydraulic roughness coefficient for the slope with a gradient of  $15^\circ$  when the soil surface roughness was less than 1.000.

(3) An exponential function was derived to describe the relationship between the soil surface roughness and Reynolds number for the slope with a gradient of  $10^\circ$ , and a linear function was derived to relate the soil surface roughness to the Reynolds number for the slope with a gradient of  $15^\circ$  when the soil surface roughness was less than 1.000.

(4) The results have the potential to be applied to soil management and conservation. When the soil surface roughness is less than or equal to 1.000, the models presented in this paper are useful.

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(Edited by Ye SHI)