Estimating saturated hydraulic conductivity of soil containing rock fragments with disc infiltrometer

Zhu Yuanjun[1,3], Shao Ming´an[1,2]

(1. *Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing* 100101, *China*;
2. *Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling* 712100, *China*; 3. *Graduate School of Chinese Academy of Sciences, Beijing* 100039, *China*)

Abstract: Simulation experiment was conducteds in soil columns and the effects of rock fragments on soil saturated hydraulic conductivity by disc infiltrometer were analyzed. Results indicate that saturated hydraulic conductivity of soil containing rock fragments can be calculated through nonlinearly regressing steady infiltration rates at different negative water heads. Saturated hydraulic conductivity of soil containing rock fragments is closely correlated to the hydraulic conductivity of soil without rock fragments and the shape coefficient of the rock fragments. And the hydraulic conductivity of soil containing rock fragments decreases exponentially with the increase of rock fragments in the experiment.

Key words: rock fragments; infiltration; soil saturated hydraulic conductivity; shape coefficient
CLC number: S152.7 **Document code**: A **Article ID**: 1002-6819(2006)11-0001-05

Zhu Yuanjun, Shao Ming´an. Estimating saturated hydraulic conductivity of soil containing rock fragments with disc infiltrometer[J]. Transactions of the CSAE, 2006, 22(11): 1- 5. (**in English with Chinese abstract**)

1 Introduction

Infiltration is a main way for the water supply to plants and soil water reservoir in arid and semi-arid regions. Spatial variability of surface soil hydraulic conductivity influences the amount and distribution of infiltration[1]. Nonuniform infiltration leads to the differences for the amount of plant available water stored in the root zone, evaporation from the soil and plant transpiration[2]. The wind-water crisscross zone of the Loess Plateau, situated at arid and semi-arid regions of China, is well known for its intensive soil erosion and fragile ecosystem[3]. Tremendous soil erosion and enrichment of carbonates in soil result in the conglomerations of carbonates covered on top soil. Rock fragments in the soil change surface soil feature and microtopography. Accordingly, infiltration and soil hydraulic conductivity exhibit high spatial variability in Loess Plateau.

In the past decades, many experiments were conducted to investigate infiltration and soil hydraulic conductivity, but few researchers paid attention to the soil containing rock fragments. Rock fragments alter soil configuration and the distribution of soil particles. Soil containing rock fragments often have more macropores in the contacts between soil and rock fragments, which can accelerate water flow and infiltration[4-6]. On the other hand, rock fragments increase the channels of water flow and decrease transect of water infiltration, which lead to the reduction of infiltration[7]. All of these make hydraulic properties of soil containing rock fragments with large variance. Measuring hydraulic conductivity of soil containing rock fragments is time-consumed and complicated. Hence, different methods were put forward to estimate the soil hydraulic conductivity. A linear equation was often used to estimate the soil hydraulic conductivity. In the equation, saturated hydraulic conductivity of soil containing rock fragments could be estimated from saturated hydraulic conductivity of soil without rock fragments and rock fragment content in the soil[8]. But the equation was based on two assumptions as follows: the rock fragments in the soil did not have capability of water absorption and its shape was close to cobblestone, which restricted the application of the equation. Furthermore, soil heterogeneity and the nonuniform distribution of rock fragments in soil depend on the special experimental conditions, and the type, size and position of rock fragments all have great effects on infiltration and hydraulic conductivity[9]. As a result, the knowledge is still poorly understood in this aspect. Additionally, soil containing rock fragments are often

---

Received date: 2005-11- Accepted date: 2006-07-20
Fundation Item: Project supported by the National Natural Science Foundation of China(90502006 and 50479063)

Biographies: Zhu Yuanjun(1978-), male, Ph. D. Candidate at the Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, main research field is soil and water processes in micro-scale, Jia No. 11 Datun Road, Chaoyang District, Beijing 100101. Email: zhuyj.04b@igsnrr.ac.cn

found not only in the wind-water crisscross zone of the Loess Plateau but also in Southwest China and northern stony mountainous areas, information of the soil hydraulic properties is needed urgently for thorough understanding surface processes happened in this kind of soil.

The present experiment aimed to quantify saturated hydraulic conductivity of soil containing rock fragments by disc infiltrometer and to establish a method to estimate saturated hydraulic conductivity of soil containing rock fragments to simplify the measurement.

2 Material and methods

2.1 Experimental material

Experiment was carried out in Shenmu Experiment Station, the state key laboratory of soil erosion and dryland farming on the Loess Plateau. The station was situated at Liudaogou Watershed(38°46′~ 38°51′N, 110°21′~ 110°23′E), a typical wind-water erosion crisscross zone of the Loess Plateau[10]. Intensive soil erosion and eluviations and sedimentation of carbonates made the top soil covered by rock fragments. And the rock fragment content(by weight) in this region changed from 0 to 15%[11].

The infiltration experiment was conducted in soil columns. The columns were 30 cm in length, 30 cm in width, and 50 cm in height. Experimental soil(containing the rock fragments) was sampled at the top 0 ~ 40 cm soil, and soil type was aeolian sandy soil (Table 1). Firstly the soil was through 2 mm sieve to apart the rock fragments. Then the rock fragments were through 2 cm and 7.5 cm sieves, respectively, and 2~ 7.5 cm rock fragments in diameter were selected for experiment. The physical properties of rock fragments were showed in Table 2. The soil and the rock fragments were both air-dried for experiment.

There were eight treatments of soil with rock fragment contents(the mass of rock fragments / the total mass, calculated by air dried mass) as follows: 0, 0.05, 0.10, 0.15, 0.20, 0.30, 0.40, and 0.50, respectively. Soil bulk density controlled at about 1.39 g/cm^3 and soil depth in the columns kept uniform for all soil treatments. Then soil and rock fragments were well mixed on an iron board and loaded into soil columns. Next, soil columns were sealed and kept steady so as to avoid from absorbing atmosphere water. Finally, soil columns were equilibrated for two days.

Table 1 Physical properties of experimetal soil

Depth /cm	Bulk density /g • cm^{-3}	Porosity/%			Silt particles/% (< 0.001 mm)	Physical silt particles/% (< 0.01 mm)
		Non-capillary	Capillary	Total		
0.3~ 5	1.39	19.5	28.5	48.0	9.0	13.9
5~ 40	1.52	11.9	31.3	43.2	9.0	13.9

Table 2 Properties of experimetal rock fragments

Replications	Rock fragment number	Volume /cm^3	Density /g • cm^{-3}	Saturated water content/%	Air drying water content/%
1	26	200	2.16	7.05	0.48
2	21	200	2.07	8.62	0.72
3	38	225	2.08	7.20	0.52

The infiltration was measured by disc infiltrometer. Firstly, soil surface was sanded by 0.5 mm sand so as to airproof the contacts of soil and the infiltrometer base. From the beginning of infiltration, the distance that water column descended was recorded. Infiltration was carried out at three negative water heads (- 15 cm, - 3 cm, and 0). For each soil treatment, the measurement of infiltration lasted for 21 min. During the experiment process, the length of water column was recoded at every 15 s from 0 to 2 min, and every 30 s from 2 to 5 min, and every 60 s from 5 to 21 min.

2.2 Fitting method

Infiltration is highly spatial variability. A little of change in soil texture and soil particle distribution will lead to considerable variance in infiltration. In the simulation experiment, rock fragments easily caused the change of soil uniformity because the size of rock fragment was much more than that of soil particle. Consequently, the infiltration may be different from each soil replication. In order to eliminate or reduce this disadvantage, a nonlinear regression method was used to estimate hydraulic conductivity by fitting steady infiltration rates at three negative water heads[12]. The method was based on the analysis of infiltration process[13, 14]. For unconfined steady infiltration from disc infiltrometer, there was expression

$$q(h) = \pi R^2 K(h) + 4R \cdot \Phi(h) \qquad (1)$$

Where, q is the steady infiltration rate, $\mathrm{cm}^3 \cdot \mathrm{min}^{-1}$; R is the radius of the infiltrometer, cm; h is the water head, cm; $K(h)$ is soil hydraulic conductivity at h water head, $\mathrm{cm} \cdot \mathrm{min}^{-1}$; Φ is the matric flux potential, defined as

$$\Phi(h) = \int K(h) \cdot dh \qquad (2)$$

And K, $K(h)$, and h have the exponential relationship as follows

$$K(h) = K \cdot \exp(\beta \cdot h) \qquad (3)$$

Where, K is soil saturated hydraulic conductivity, $\mathrm{cm} \cdot \mathrm{min}^{-1}$.

Then substituting equation (2) and (3) into (1), the following expression is obtained

$$q(h)/\pi R^2 = K \cdot \exp(\beta \cdot h) + 4K \cdot \exp(\beta \cdot h)/(\pi R \beta) \qquad (4)$$

In the equation (4), parameter β was a constant, which is changeless for the same soil. Unknown parameters β and K could be estimated by infiltration data at two or more water heads[12].

Parameters β was gained by fitting infiltration rates when rock fragment content was zero. Then it was substituted into equation (4) to estimate the values of soil hydraulic conductivity. The experiment included three replications and the results were the mean of the replications.

3 Results and discussion

3.1 Feasibility of estimating soil saturated hydraulic conductivity by nonlinear regression method

Many methods were put forward to estimate soil saturated hydraulic conductivity in the past. Most of them were time-consumed and parameter-dependent[15-17]. For example, they needed to conduct infiltration experiment at different sites or needed plenty of parameters including soil texture, the initial and final soil water content when infiltration kept steady. However, soil saturated hydraulic conductivity is sensitive to the changes of soil texture and configuration. Infiltration data at different sites would lead to uncertain results. Additionally, the measurements of the initial and final soil water content were difficult in the most of experiments, which would cause the decrease of accuracy. Other methods were presented to eliminate parameters using different disc infiltrometers. But different sizes of infiltrometer would result in the variance of infiltration because of scale effects. All of these increased the variance of infiltration in measurement. The nonlinear regression method could measure infiltration at the same site and only need steady infiltration rates at three water heads[12]. Though the method was based on homogeneous soil, it still exhibited high accuracy in the experiment (adjusted $r^2 \geqslant 0.82$, Table 3).

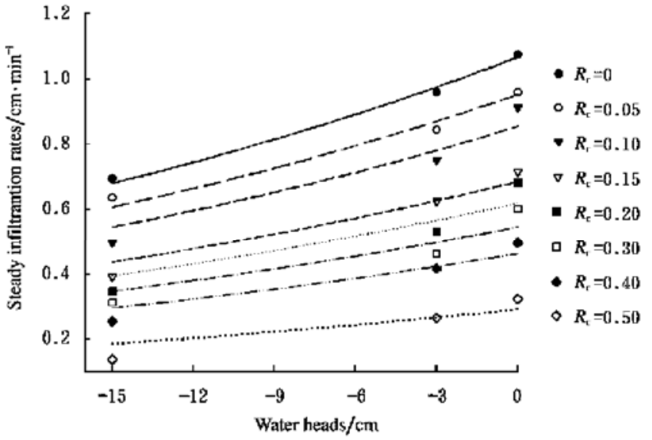
Table 3 Estimated values of K_R by nonlinear method and the adjusted correlation coefficient

R_c /kg·kg^{-1}	0	0.05	0.10	0.15	0.20	0.30	0.40	0.50
K_R /cm·min^{-1}	0.1125	0.1004	0.0901	0.0723	0.0653	0.0575	0.0489	0.0308
Adjusted r^2	0.99	0.97	0.92	0.95	0.87	0.86	0.91	0.82

Notes: K_R is the estimated soil saturated hydraulic conductivity at 0 water head, R_c is rock fragment content.

3.2 Infiltration rates and saturated hydraulic conductivities of the experimental soils

Figure 1 shows the fitting results at three water heads(−15 cm, −3 cm, and 0), respectively by nonlinear regression method in the simulation experiment. Figure 1 shows that the steady infiltration rates of soil containing rock fragments at three water heads decreases with the increase of rock fragment content. And the fitting values of hydraulic conductivities of soil containing rock fragments decreases as well. Furthermore, there are three different change ranges of infiltration rates as follows: 1) when the rock fragment contents are between 0~0.1 kg/kg, the infiltration rates decreases obviously with the increase of rock fragments; 2) infiltration rates decreases slowly when the rock fragment contents change between 0.15~0.4 kg/kg; 3) when the rock fragment content reaches 0.5 kg/kg, the steady infiltration decreases obviously again.



Notes: In the figure the dots were the values of steady infiltration rates measured by disc infiltrometer at three negative water heads (−15 cm, −3cm and 0). The curves were soil hydraulic conductivities fitted by nonlinear regression method

Fig. 1 Fitting curves of soil saturated hydraulic conductivity from steady infiltration rates

Figure 2 reflects the changes of hydraulic conductivities of soil containing rock fragments computed by the method of nonlinear regression. Figure 2 indicates that soil saturated hydraulic conductivity decreases with the increase of rock fragment content because the rock fragments increase the tortuosity of water flow and reduced water transect. In the experiment, the rock fragments were highly irregular, which resulted in large increase of water channels. In this case, water flow in soil was impeded. Consequently, the infiltration decreased with the increase of rock fragments. The relationships between rock fragment content and soil saturated hydraulic conductivity could be expressed by exponential function $K_R = K \cdot \exp(-c \cdot R_c)$ (K_R is saturated hydraulic conductivity of soil containing rock fragments, K is saturated hydraulic conductivity of soil without rock fragments, R_c is rock fragment content($\leqslant 0.5$ kg/kg), and c is shape coefficient of the rock fragments). In the experiment $K = 0.1125$ cm^3/min, $c = 2.42$ (mean radius of rock fragments / mean circularity of rock fragments).

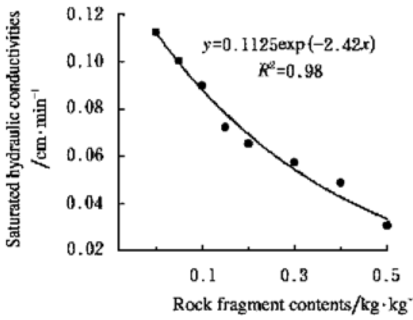


Fig. 2 Changes of saturated hydraulic conductivities (0 water head) of soil containing rock fragment

Generally, the shape coefficient increases with the increase of rock fragment irregularity. The equation was used when the rock fragment content in the soil changed from 0 to 0.5 kg/kg. When the rock fragment content exceeded this value, the experiment was difficult to carry out because soil could not fill with the voids between rock fragments and soil. But it could be speculated that soil saturated hydraulic conductivity increased intensively in this case.

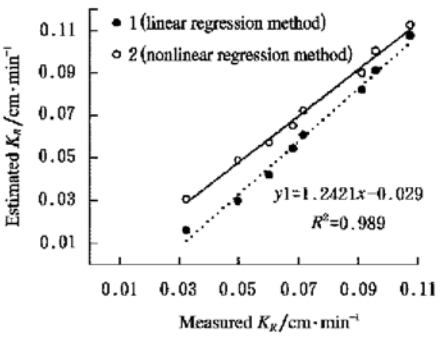
3.3 Accurate test of the estimated soil saturated hydraulic conductivity by nonlinear regression

An equation ($K_R = K \cdot \exp(-c \cdot Rc)$) was established to estimate saturated hydraulic conductivity of soil containing rock fragments in the experiment. From the equation, there was exponential relationship between soil saturated hydraulic conductivity and rock fragment content. There was a linear method to calculate soil saturated hydraulic conductivity[8], as

$$K / K_R = 1 - R_c \tag{5}$$

Where, K_R is saturated hydraulic conductivity of soil containing rock fragments, cm $\cdot$ min^{-1}; K is saturated hydraulic conductivity of soil without rock fragments, cm $\cdot$ min^{-1}; R_c is rock fragment content, kg $\cdot$ kg^{-1}.

In order to test the accuracy of the method obtained in the experiment, the comparison of tow methods is showed in Fig. 3. Results show that nonlinear regression method(method 2) is more accurate than linear regression method(method 1). For the method 2, the ratio of estimated soil saturated hydraulic conductivity to the measured is much closer to 1 and its correlation coefficient is also higher than that in the method 1. Method 1 is accurate at lower rock fragment content but the error increases at higher rock fragment content. When rock fragment content is at high level, the changes of water transect and channels of water flow are nonlinear with the increase of rock fragments and the changes of infiltration are nonlinear as well. Moreover, the method 1 is established on the assumptions as follows: 1) the shape of rock fragments is close to ball, and 2) rock fragments are less water absorption. In fact, the rock fragments presentes in the field are often irregular, and some of them have high capability of water absorption. Hence, the nonlinear relationship between soil saturated hydraulic conductivity and rock fragment content is much closer to the field status.



Note: K_R was saturated hydraulic conductivity of soil containing rock fragments

Fig. 3 Comparison of estimating K_R by two methods

3 Conclusions

The hydraulic conductivity of soil containing rock fragments was investigated by fitting steady infiltration rates at three negative water heads with disc infiltrometer in the simulation experiment. Results indicate that the nonlinear regression method can be used to estimate hydraulic conductivity of soil containing rock fragments and the estimated value is highly accurate. Steady infiltration rate and saturated hydraulic conductivity of soil containing rock fragments both decrease with the increase of rock fragment content in soil. The saturated hydraulic conductivity is dominated by saturated hydraulic conductivity of soil without rock fragments and shape coefficient of rock fragments. The value of saturated hydraulic conductivity decreases exponentially with the increase of rock fragments by the equation.

Infiltration in soil containing rock fragments is a considerably complicated process. When rock fragments in the soil exceeded a certain value, soil cannot fill up the voids between soil and rock fragments, which makes the simulation experiment much difficult in operation. The experimental results only worked well when the rock fragment content changed from 0 to 0.5 kg/kg, and the estimated soil hydraulic conductivity was correct only on this condition.

[References]

[1] Sauer T J, Logsdon S D. Hydraulic and physical properties of stony soils in a small watershed[J]. Soil Sci Soc Am J, 2002, 66: 1947- 1956.

[2] Grayson R B, Western A W, Chiew F H S, et al. Preferred states in spatial soil moisture patterns: local and nonlocal controls[J]. Water Resour Res, 1997, 33: 2897- 2908.

[3] Wang Z L. Analyses of affecting factors of soil erosion and its harms in China[J]. Transactions of the CSAE, 2000, 16(4): 32- 36. (in Chinese)

[4] Grant J W, Struchtemeyer R A. Influence of coarse fraction in two maine potato soils on infiltration, runoff and erosion[J]. Soil Sci Soc Am Proc, 1959, 23: 391- 394.

[5] Jung L. The influence of the stone cover on runoff and erosion on slate soils[J]. Int Assoc Sci Hydrol, 1960, 53: 143- 153.

[6] Simanton J R, Rawitz E, Shirely E D. Effects of rock fragments on erosion of semiarid rangeland soils[M]. In: Erosion and Productivity of Soils Containing Rock Fragments[J]. Soil Sci Soc Am, Special Pub. 13, Madison, WI, 1984, pp. 65- 72.

[7] Dadkhah M, Gifford G F. Influence of vegetation, rock cover and trampling on infiltration rates and sediment production[J]. Water Resourc Bull, 1980, 16: 979- 986.

[8] Brakeneiek D L, Rawls W J, Stephenson G R. Determining the saturated hydraulic conductivity of a soil containing rock fragments[J]. Soil Sci Soc Am J, 1986, 50: 834- 835.

[9] Poesen J, Lavee H. Rock fragments in top soils: significance and processes[J]. Catena, 1994, (23): 1- 28.

[10] Tang K L, Hou Q C, Wang B K, et al. The environment background and administration way of wind-water crisscross region and Shenmu experimental area on the Loess Plateau[A]. Memoir of Northwestern Institute of Soil and Water Conservation, Academia Sinica and Ministry of Water Resources[C]. 1993, (18): 2- 15. (in Chinese)

[11] Jia H Y, Yong S P, Wang F Q. The soil resources in the Shenmu experimental area[A]. Memoir of Northwestern Institute of Soil and Water Conservation, Academia Sinica and Ministry of Water Resources[C]. 1993, (18): 36- 46. (in Chinese)

[12] Logsdon S D, Jaynes D B. Methodology for determining hydraulic conductivity with tension infiltrometers[J]. Soil Sci Soc Am J, 1993, 57: 1426- 1431.

[13] Wooding R A. Steady infiltration from a shallow circular pond[J]. Water Resour Res, 1968, 4: 1259- 1273.

[14] Gardner W R. Some steady-state solutins of the unsaturated moisture flow equation with application to evaporation from a water table[J]. Soil Sci, 1958, 85: 228- 232.

[15] White I, Sully M J. Macroscopic and microscopic capillary length and time scales from field infiltration[J]. Water Resour Res, 1987, 23: 1514- 1522.

[16] Smettem K R J, Clothier B E. Measuring unsaturated sorptivity and hydraulic conductivity using multiple disc permeameters[J]. Soil Sci, 1989, 40: 563- 568.

[17] Reynolds W D, Elrick D E. Determination of hydraulic conductivity using a tension infiltrometer[J]. Soil Sci Soc Am J, 1991, 55: 633- 639.

利用圆盘入渗仪推求含碎石土壤饱和水力传导度

朱元骏[1,3], 邵明安[1,2]

(1. 中国科学院地理科学与资源研究所, 北京 100101;　2. 中国科学院水利部水土保持研究所, 杨凌 712100;
3. 中国科学院研究生院, 北京 100039)

摘　要: 在模拟土柱中, 利用圆盘入渗仪对碎石对土壤饱和水力传导度的影响进行了分析。结果表明: 含碎石土壤饱和水力传导度可以通过对不同负压下土壤稳定入渗速率进行非线性回归获得。含碎石土壤饱和水力传导度与去除碎石后的土壤饱和水力传导度及碎石形状指数密切相关。试验中含碎石土壤的饱和水力传导度随碎石含量的增加而呈指数降低趋势。

关键词: 碎石; 入渗; 土壤饱和水力传导度; 形状指数