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Simulation of Morphological Development of Soil Cracks in Yuanmou Dry-hot Valley Region, Southwest China

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Abstract: Soil cracking is an important process influencing water and solutes transport in the Yuanmou Dry-hot Valley region of Southwest China. Studying the morphological development of soil cracks helps to further reveal the close relationship between the soil cracking process and water movement in such semi-arid regions. Here we report regular changes on surface morphology of soil cracks with decreasing water in four different soils (Typ-Ustic Ferrisols, Ver-Ustic Ferrisols, Tru-Ustic Vertisols and Typ-Ustic Vertisols) through simulation experiments. Our results indicate the following: 1) Different soils ultimately have different development degrees of soil cracks, according to their various values of crack area density. Soil cracks in Typ-Ustic Ferrisols can only develop to the feeble degree, while those in the other three soils are capable of developing into the intensive degree, and even into the extremely intensive degree. 2) Soil crack complexity, as expressed by the value of the area-weighted mean of crack fractal dimension (AWMFRAC), is found to continuously decrease as a whole through the whole cracking process in all the studied soils. 3) Soil crack connectivity shows a uniform trend in the studied soils, that is to say, connectivity gradually increases with soil crack development.

Keywords: soil cracks; morphological development; simulation experiment; Yuanmou Dry-hot Valley region; Southwest China

1 Introduction

Soil cracking is a complex process that influences soil properties, plant growth, and the migration of water and solutes in soil (Bandyopadbyay *et al*., 2003; Xiong *et al*., 2006). Soil cracks are closely related to changes in soil structure (Velde, 1999; Bruand *et al*., 2001), infiltration capacity (Liu *et al*., 2003), evaporative loss of soil water (Adams and Hanks, 1964), and the preferential migration of soil solutes. Moreover, they cause deterioration in soil water quality (Adrian *et al*., 2000) and influence many important physical, chemical and biochemical processes in soil (Yoshida and Adachi, 2004). The study of soil cracks has great significance for understanding the processes of soil degradation and underground water pollution as well as for the development of re-vegetation techniques (Xiong *et al*., 2006).

Soil crack morphology determines the migration routes and migration rates of water and solutes based on crack length, tortuosity and other morphological characteristics. These in turn affect the distribution of mass on soil profiles. Hence, the study of morphological development is of importance to the whole study of soil cracking. However, the related studies currently focus on water infiltration (Novak *et al*., 2000; Liu *et al*., 2003; Romkens and Prasad, 2006; Rayhani *et al*., 2007), solute migration (Hendriks *et al*., 1999; Mattews *et al*., 2000; Huang *et al*., 2008), and the effect of tillage practice on

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the soil cracking (Hulugalle and Cooper, 1994; Flowers and Lal, 1999; Bandyopadhyay *et al*., 2003).

Currently, a few studies related to soil crack morphology are found, but these are still in the stage of establishing quantitative indicator systems. For example, Novak (1999) established a quantitative indicator system of soil cracking, including crack porosity on the soil surface, crack porosity and specific internal area of soil density. Vogel *et al*. (2005) took crack area density, length density and Euler number that can describe the connectivity of crack′s network to establish the indicator system. Additionally, Xiong *et al*. (2008) proposed a set of indicators which can reflect both the connectivity and complexity of soil cracks. How to use the quantitative indicators to further reveal the law of morphological development of cracks in different soils is the key to future research on soil cracks.

This paper presents a quantitative study on the law of crack dynamic development of four soils in the Dry-hot Valley region in Southwest China. The aims of the paper are 1) to describe the principles of the development process of soil cracks in a quantitative way and 2) to compare the similarities and differences of cracking processes of the studied soils. The results are expected to be of great help for studying soil water movement, soil degradation and solute migration in the Yuanmou Dry-hot Valley region of Southwest China.

2 Study Area and Soil Conditions

Yuanmou Dry-hot Valley region is an ecologically fragile zone in the mountainous regions of Southwest China and is one of the most difficult areas for re-vegetation in the upper reaches of the Changjiang (Yangtze) River (Yang *et al.,* 2003; Zhang *et al.,* 2003; Xiong *et al.*, 2005). It is located in the upper and middle reaches of the Jinsha River, which is the main tributary of the Changjiang River (Fig. 1). The Yuanmou Dry-hot Valley region extends from 25°23′N to 26°06′N and from 101°35′E to 102°06′E, covering an area of about 2 000 km^2. It has a typical southern subtropical climate, with an average annual temperature of 21.9℃, annual precipitation of 612.8 mm, and annual evaporation of 3 737.3 mm (Yang *et al*., 2003). The zonal soil in the region is the dry-red soil type (classified as Ustic Ferrisols in Chinese Taxonomy) and vertisols are often found on the degraded slopes, with clay content usually reaching above 40% (He *et al.*, 1995). Due to the extremely dry and hot climate, soil cracking is very common on the degraded slopes, especially during dry seasons. Cracks are often found to be more than 1 cm wide and 1 m deep. (He and Huang, 1995). The presence of soil cracks accelerates evaporative water loss and causes plant roots to fracture, resulting in low seedling survival rates and greater difficulty in re-vegetation efforts.

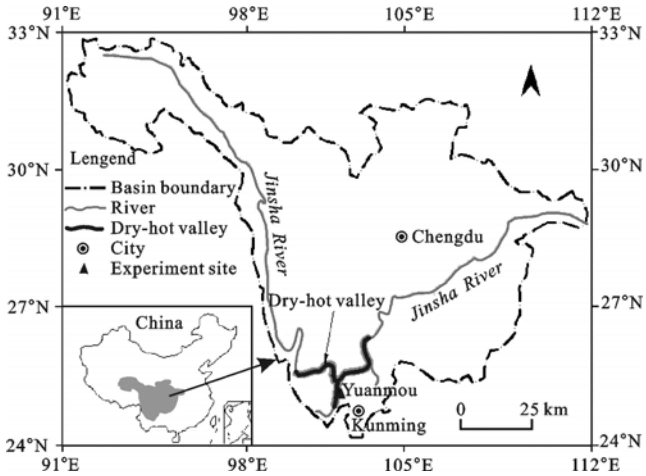


Fig. 1 Location sketch of study area

The studied soils are Typ-Ustic Ferrisols, Ver-Ustic Ferrisols, Tru-Ustic Vertisols and Typ-Ustic Vertisols. Among these, Ver-Ustic Ferrisols are a transition type between Ustic Ferrisols and Ustic Vertisols. Tru-Ustic Vertisols are a special type in vertisols which forms when the Typ-Ustic Vertisols lose both their horizon A and B (He and Huang, 1995). Table 1 lists the basic physic-chemical properties of the studied soils.

3 Methods

3.1 Simulation experiments

All the soil samples were air-dried, sifted through a 2-mm-diameter sieve after being taken from the 0–20 cm depth layer, and then were water-saturated and stirred evenly enough to get paste-like mixtures. The paste then was poured into a plastic pot (its upper diameter is 40 cm, lower diameter is 30 cm, height is 20 cm and upper surface area is 1 250 cm^2), which then was placed under natural sunshine and sun-dried. The four studied soils were taken as the four treatments in the simulation experiment, respectively. There were four replicates in each treatment. The observations on soil

Table 1 Basic physic-chemical property of studied soils

Soil Type	Clay content (%)	Organic matter (g/kg)	Bulk density (Mg/m^3)	pH	Expansion-shrinkage ratio (%)	Texture
Typ-Ustic Ferrisols	32.3	6.81	1.41	5.33	11.5	Loamy clay
Ver-Ustic Ferrisols	36.8	6.17	1.48	7.85	51.3	Loamy clay
Tru-Ustic Vertisols	53.7	2.42	1.56	7.89	61.3	Clay
Typ-Ustic Vertisols	73.1	4.46	1.52	8.74	63.2	Clay

Note: The clay content, organic matter, bulk density and pH were measured by Pipette Method, $K_2Cr_2O_7$ Method, Cutting Ring Method and Electric Potential Method, respectively (Institute of Soil Science, Chinese Academy of Sciences, 1978). The expansion-shrinkage ratio was measured by Soil Expansion-shrinkage Determinator Method (Huang and He, 1995)

water content and soil crack morphological changes started immediately after the soil cracks began to appear in the potted soils. The PR2 moisture meter was applied as the main instrument of soil water observation, and the photographic method (Xiong *et al*., 2008) was used in soil cracks observation. The experiment lasted for 25 days until no obvious morphological changes occurred on the soil surface.

3.2 Image processing

The photographs for soil cracks taken during the development processes were processed using GIS software, including Erdas8.7, ArcView3.2 and ArcGIS9.0. After coordinate correction, digitization, and topological transformation, the perimeter and area of each soil crack were extracted from the processed images (Fig. 2).

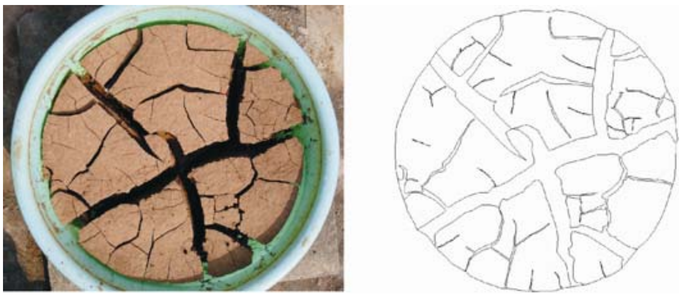


Fig. 2 Original and processed photos for soil cracks

3.3 Calculation methods

The photographs of soil cracks taken in the simulation experiments were processed through the procedures described in Section 3.2, and the values of the morphological indicators were calculated according to the defining equations given below. Statistical analysis was performed to get the regression equations and the dynamic change curve for every morphological indicator.

According to previous works (Xiong *et al*., 2008), soil cracks′ morphology can be described by three criteria: cracks′ morphological intensity, complexity and connectivity. Each criterion has its own quantitative indicator.

The morphological intensity of soil cracks in this paper is the cracking extent expressed by the linear or planar elements of cracks′ morphology. It has two indicators, crack area density (A_c) and crack line density (L_c). The former expresses the soil cracks′ development degrees by planar elements and the latter by linear elements. Their defining equations are the following:

$$A_c = \sum_{i=1}^{n} a_{ci} / A \times 100\% \quad (1)$$

where a_{ci} is the area of crack i, and A is the total surface area of the cracked soil (mm^2).

$$L_c = \sum_{i=1}^{n} P_{ci} / A \quad (2)$$

where P_{ci} is the perimeter of soil crack i (mm).

Soil cracks′ morphological complexity can be quantified by two indicators, area-weighted mean of crack fractal dimension (*AWMFRAC*) and area-weighted mean of crack shape index (*AWMSI*). The former is an effective tool to measure an object′s complexity, of which the value range is between 1 and 2. The more complicated an object is, the greater the value of fractal dimension is

(Chen and Chen, 1998). The latter is used to measure complexity by calculating the deviation degree of an object′s shape to a square which has the same area (Xu, 2002). It gets its minimum value of 1 when all the cracks′ shapes are squares. The more a crack′s shape deviates from a square, the greater the *AWMSI* value is. Their defining equations are listed as the following:

$$AWMFRAC = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[\frac{2\ln\left(0.25P_{cij}\right)}{\ln\left(a_{cij}\right)}\left(\frac{a_{cij}}{A}\right)\right] \Big/ N \quad (3)$$

$$AWMSI = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[\left(\frac{0.25P_{cij}}{\sqrt{a_{cij}}}\right)\left(\frac{a_{cij}}{A}\right)\right] \quad (4)$$

where P_{cij} is the perimeter of crack i in type j (during the image processing, all cracks in the images were divided into four types according to the number of branches they have) (mm), a_{cij} is the area of crack i in type j (mm^2).

Soil cracks′ morphological connectivity can also be quantified by two indicators, index r and index a. The former directly expresses the connectivity of a crack network, while the latter reflects the extent of a crack network formed by the circulation circuits (Xu, 2002). The value of index r is 0 when all the cracks are isolated and unconnected. The greater the value is, the higher the crack′s connectivity is. The value of index a increases with the number of circulation circuit forming in a crack network. A zero value indicates that there is no circulation circuit in the crack network. Their defining equations are listed as the following:

$$r = \frac{L}{L_{max}} = \frac{L}{3(V-2)} \quad (5)$$

$$a = \frac{L - V + 1}{2L - 5} \quad (6)$$

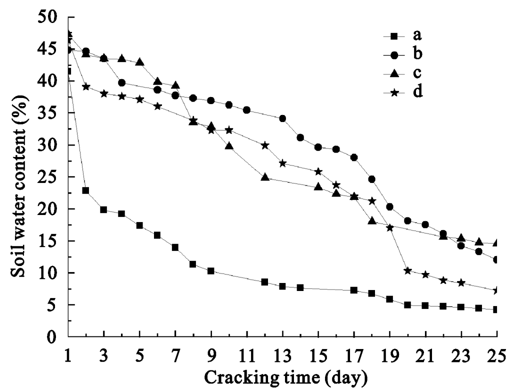
where L is the number of connective sides of soil cracks, V is the number of soil crack nodes, and L_{max} is the maximum possible number of connective sides of soil cracks.

4 Results and Analysis

4.1 Dynamic changes of soil water content

Figure 3 shows the dynamic changes of soil water content through the whole soil cracking process in the studied soils, from which results can be drawn as follows.

The critical point of soil water content (CPSW) at which the soil cracking initiates has a relatively higher value, much different from the common conception that soil cracks can only occur when the soil is in serious drought with very low water content. The results demonstrate that the soil cracking can also initiate when the soil water content is still high. In the simulation experiments, the CPSW is 41.5% for Typ-Ustic Ferrisols, 44.8% for Ver-Ustic Ferrisols, 46.4% for Typ-Ustic Vertisols, and 47.3% for Tru-Ustic Verticsols, all which closely approach their own field moisture capacity.



(a) Typ-Ustic Ferrisols; (b) Ver-Ustic Ferrisols;
(c) Tru-Ustic Vertisols; (d) Typ-Ustic Vertisols

Fig. 3 Changes in soil water content during soil cracking process in studied soils

Firstly, as for the change of soil water content during the cracking process, in Typ-Ustic Ferrisols it manifests itself as first decreasing sharply, then declining much more slowly and finally approaching a stable status, while in the other three soils it decreases slowly and then stabilizes. The change in soil water content in Typ-Ustic Ferrisols is extremely apparent, especially in the early two days of cracking. These days have the greatest amplitude change of 18.7 percentage points, sharply dropping from 41.5% of the first cracking day to 22.8% of the second day. In the other three soils, the soil water change is gentler and their change amplitudes are 0.2, 3.2 and 7.3 percentage points, respectively in the same period. Second, the times when the water contents in all studied soils tend to be stable are different. In Typ-Ustic Ferrisols it is the earliest, beginning to get stable only after ten days. It shows much more slowly in the other soils, reaching a stable status about 20 days later. Finally, there also exists greater differences in the values of soil water contents when soil crack morphology stabilizes (e.g., the value of soil water content after

25-day cracking is 4.2% for Typ-Ustic Ferrisols, 7.2% for Typ-Ustic Vertisols, 12.0% for Ver-Ustic Ferrisols and 14.5% for Tru-Ustic Vertisols). All these demonstrate the greater difference in water holding capacity of the four studied soils.

4.2 Morphological changes of soil cracks

4.2.1 Dynamic changes of soil crack's morphological intensity

Table 2, Fig. 4 and Fig. 5 show the regression equations and dynamic change curves for A_c and L_c with the decrease of soil water content in the studied soils.

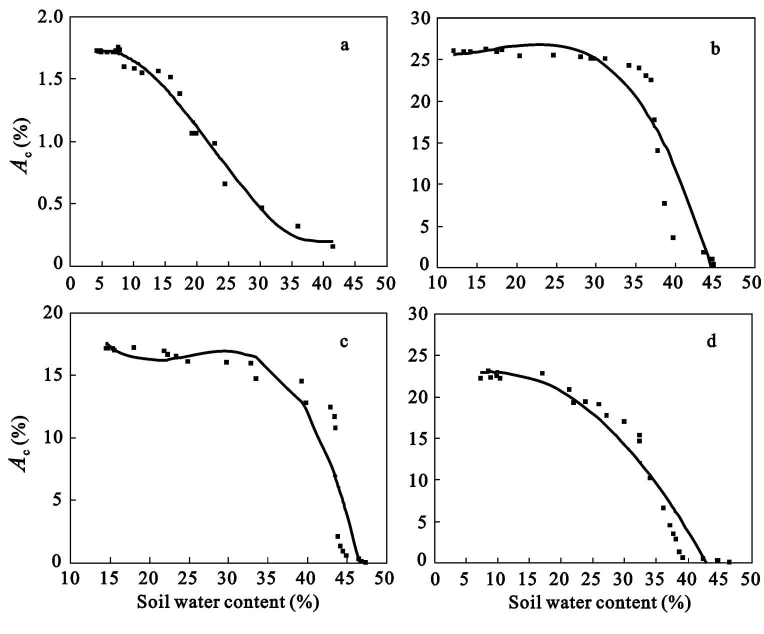
The correlation coefficients of all regression equations listed in Table 2 uniformly reached an extremely significant level, indicating that the two intensity indicators A_c and L_c both have a close negative correlation with the soil water content.

The trend for A_c first increases then stabilizes in the studied soils (except that at the final development stage, A_c slightly increases in Tru-Ustic Vertisols). However, differences are detected between the soil water contents when the A_c value reaches the stable status, the duration of the stable stages and that the final values of A_c. Typ-Ustic Ferrisols begin to reach the stable status at

Table 2 Regression equations for crack intensity indicators in studied soils

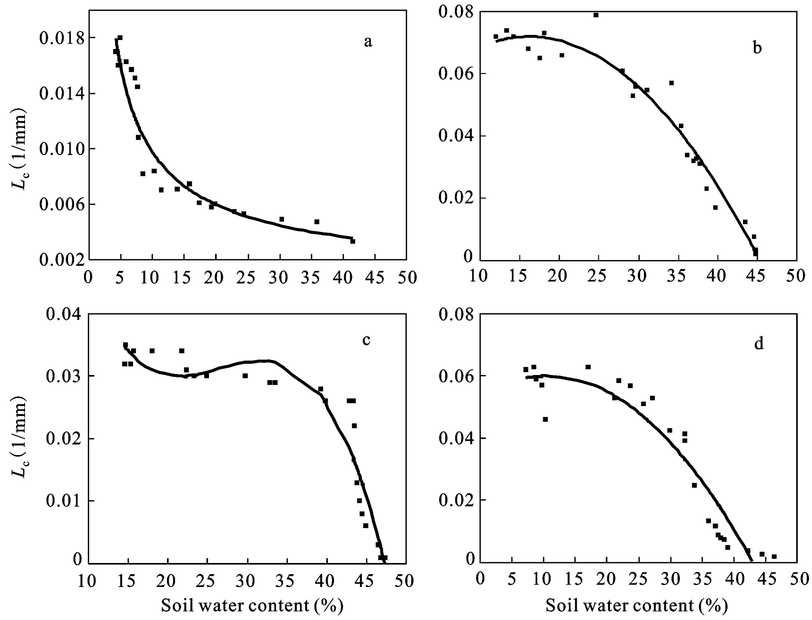
Soil type	Morphological indicator	R	Regression equation	R^2	P
Typ-Ustic Ferrisols	A_c	–0.977**	$Y = 1.601 + 0.049X - 0.00526X^2 + 0.0000078X^3$	0.980	<0.0001
	L_c	–0.837**	$\ln Y = \ln 0.0496 - 0.708X$	0.937	<0.0001
Ver-Ustic Ferrisols	A_c	–0.787**	$Y = 30.862 - 1.136X + 0.0760X^2 - 0.00149X^3$	0.895	<0.0001
	L_c	–0.922**	$Y = 0.0496 + 0.00275X - 0.00000849X^2$	0.952	<0.0001
Tru-Ustic Vertisols	A_c	–0.820**	$Y = 44.123 - 3.533X + 0.145X^2 - 0.00193X^3$	0.863	<0.0001
	L_c	–0.813**	$Y = 0.105 - 0.00902X + 0.000351X^2 - 0.000000439X^3$	0.885	<0.0001
Typ-Ustic Ferrisols	A_c	–0.918**	$Y = 21.335 + 0.371X - 0.0203X^2$	0.921	<0.0001
	L_c	–0.893**	$Y = 0.0537 + 0.00120X - 0.00000568X^2$	0.886	<0.0001

Note: X represents the soil water content (%), Y represents the morphological indicator. ** indicates that correlation is significant at the 0.01 level. The same hereinafter



(a) Typ-Ustic Ferrisols; (b) Ver-Ustic Ferrisols; (c) Tru-Ustic Vertisols; (d) Typ-Ustic Vertisols

Fig. 4 Dynamic change curves for A_c in studied soils



(a) Typ-Ustic Ferrisols; (b) Ver-Ustic Ferrisols; (c) Tru-Ustic Vertisols; (d) Typ-Ustic Vertisols

Fig. 5 Dynamic change curves for L_c in studied soils

7% of soil water content, and Typ-Ustic Vertisols at 10%. Both have a short and unobvious stable stage, while Ver-Ustic Ferrisols and Tru-Ustic Vertisols stabilize at 32% and 27%, respectively, with a longer and more obvious stable stage. After 25-day cracking, the final A_c values of all soils also have differences. The final A_c value of Typ-Ustic Ferrisols is 1.7%, ranking as the least cracked. Those of the other soils approach the same order of magnitude, ranking as 17.5% for Tru-Ustic Vertisols, 23.6% for Typ-Ustic Vertisols, and 26.1% for Ver-Ustic Ferrisols. According to our latest research results (Xiong *et al.*, 2009), the gradation criteria for the morphological development degrees of soil cracks in Yuanmou Dry-hot Valley region is the following: $A_c \leq 5\%$ for feeble development, $5\% < A_c \leq 10\%$ for slight development, $10\% < A_c \leq 22\%$ for medium development, $22\% < A_c \leq 27\%$ for intensive development, and $A_c > 27\%$ for extremely intensive development. Therefore, in this paper, the ultimate development degrees of soil cracks are feeble development for Typ-Ustic Ferrisols, intensive development for Ver-Ustic Ferrisols, medium development for Tru-Ustic Vertisols and intense development for Typ-Ustic Vertisols.

Similarly with A_c, the changing trends of L_c all first increase and then stabilize (except that the end of the curve of Tru-Ustic Vertisols has a slight rise). Tru-Ustic Vertisols, however, still have relatively higher soil water content (14.5%) in the end, indicating that it still has a greater development potential. The slight rise at the end of the curve might result from the newly occurred cracks. Moreover, what attracts our attention is the difference in the L_c values. The final value of L_c in Typ-Ustic Ferrisols is only 0.018/mm, so small as it is even lower by one order of magnitude than those of the other soils. This might result from the greater difference of Typ-Ustic Ferrisols in soil properties with the other soils, such as soil clay contents and smectite content.

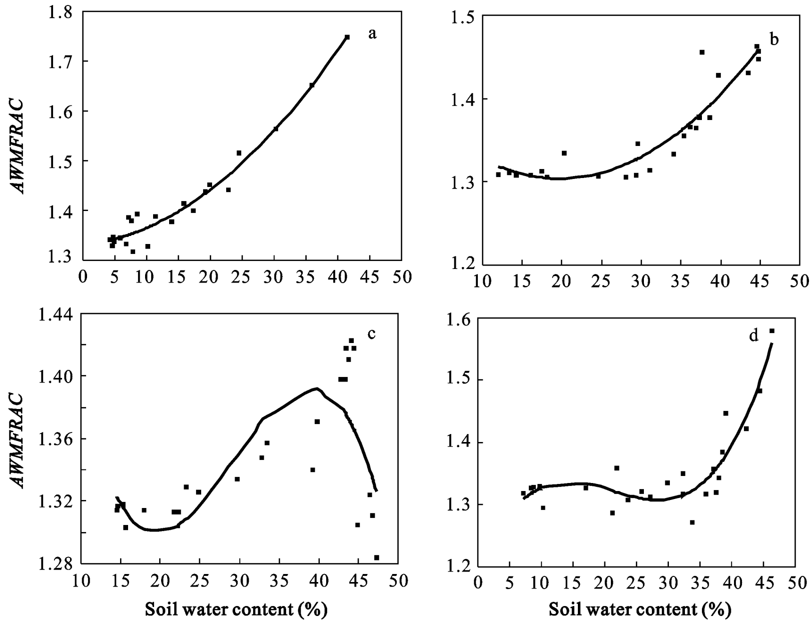
4.2.2 Dynamic changes of soil crack' complexity

Table 3, Fig. 6 and Fig. 7 show the regression equations and dynamic change curves for *AWMFRAC* and *AWMSI* with the decrease of soil water content in the studied soils.

All the correlation coefficients of regression equations between *AWMFRAC* and soil water content reach the significance level, demonstrating that *AWMFRAC* and soil water content have strong correlations in all studied soils. Similarly, *AWMS*I and soil water content are also found to have a close correlation in Typ-Ustic Ferrisols and Tru-Ustic Vertisols, with their correlation coefficients reaching the significance level. However, the correlation coefficients of Ver-Ustic Ferrisols and Typ-Ustic Vertisols both are under the significance level.

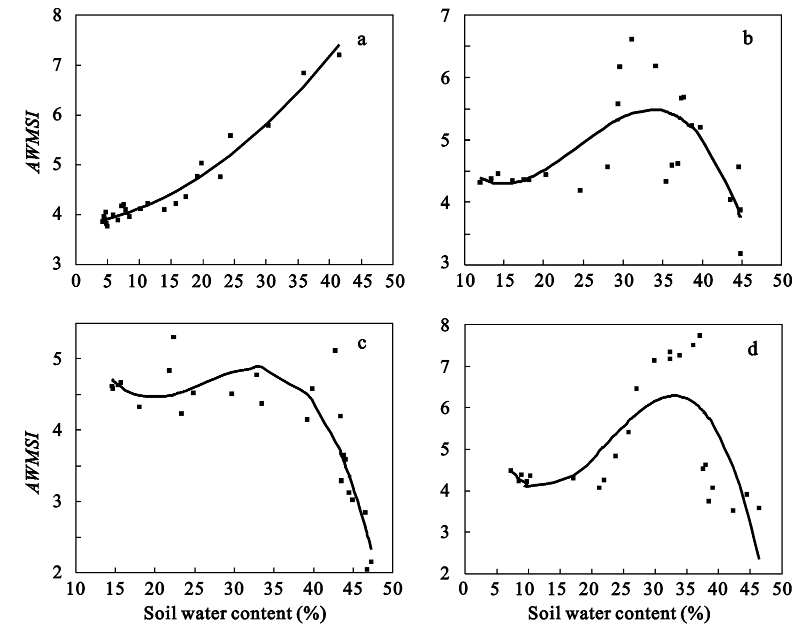
Table 3 Regression equations for crack complexity indicators in studied soils

Soil type	Morphological indicator	R	Regression equation	R^2	P
Typ-Ustic Ferrisols	*AWMFRAC*	0.957**	$Y = 1.331 + 0.00131X + 0.000212X^2$	0.963	<0.0001
	AWMSI	0.958**	$Y = 3.806 + 0.0147X + 0.00174X^2$	0.960	<0.0001
Ver-Ustic Ferrisols	*AWMFRAC*	–0.838**	$Y = 1.399 - 0.00969X + 0.000246X^2$	0.859	<0.0001
	AWMSI	0.079	$Y = 7.730 - 0.539X + 0.0260X^2 - 0.000357X^3$	0.460	0.0015
Tru-Ustic Vertisols	*AWMFRAC*	0.507*	$Y = 1.780 - 0.0587X + 0.00225X^2 - 0.000002567X^3$	0.438	0.0022
	AWMSI	–0.684**	$Y = 10.155 - 0.719X + 0.0290X^2 - 0.000367X^3$	0.754	<0.0001
Typ-Ustic Vertisols	*AWMFRAC*	0.586**	$Y = 1.195 + 0.0239X - 0.00126X^2 + 0.00000198X^3$	0.820	<0.0001
	AWMSI	0.157	$Y = 7.188 - 0.589X + 0.0332X^2 - 0.000490X^3$	0.438	0.0021



(a) Typ-Ustic Ferrisols; (b) Ver-Ustic Ferrisols; (c) Tru-Ustic Vertisols; (d) Typ-Ustic Vertisols

Fig. 6 Dynamic change curves for *AWMFRAC* in studied soils



(a) Typ-Ustic Ferrisols; (b) Ver-Ustic Ferrisols; (c) Tru-Ustic Vertisols; (d) Typ-Ustic Vertisols

Fig. 7 Dynamic change curves for *AWMSI* in studied soils

The changing trends of *AWMFRAC* in all the studied soils except the Tru-Ustic Vertisols, continuously decline with the decrease of soil water content and then tend to keep stable. This indicates that in the soil cracking process, the slim cracks which are more complex occupy the dominant status in the early stage. Then, in the later stages the dominant status is occupied by the wider cracks which are simpler morphologically. During cracking process of Tru-Ustic Vertisols, it's *AWMFRAC* changes can be represented as increase→decrease→increase, indicating that in the latest stage it has an additional process in which the slim cracks occur and gradually occupy the dominant status. In addition, all the *AWMFRAC* values approach 1.3 when they reach stability, though the soil cracks of Typ-Ustic Ferrisols have much higher complexity than the other three soils, with a *AWMSI* value of 1.8 at the initiation of cracking.

As for the changes of *AWMSI*, except the monotone decreasing occurred in Typ-Ustic Ferrisols, the other three soils uniformly first increase then decrease. This indicates that the extent of soil crack morphology deviating from square first increase then decrease. In the early stage of cracking, crack morphology is mainly present with prolate which then become wider and approach squares. Thus, the values of *AWMSI* decrease. In the end, the new slim cracks occur, which finally result in the increase of morphological indicators. Moreover, all the values of *AWMS*I are relatively close, ranging between 2 and 8, indicating that their extent of deviation from squares is also close.

4.2.3 Dynamic changes of soil cracks' connectivity

Table 4 and Fig. 8 show that regression equation and the dynamic changes curves for index *r* and index *a* with soil water content in the studied soils. For Typ-Ustic Ferrisols, due to the number of soil crack nodes and the small connective sides, the values of neither index *r* or index *a* are the same during the whole cracking process. Thus the connectivity of soil cracks in Typ-Ustic Ferrisols is not discussed here. We can conclude the following:

The correlation coefficients in all the equations listed in Table 4 reach the 0.01 level of extreme significance, indicating that both index *r* and index *a* of the three soils have strong negative significant relationships with soil water content.

Table 4 Regression equations for crack connectivity indicators in studied soils

Soil type	Morphological indicator	*R*	Regression equation	R^2	*P*
Ver-Ustic Ferrisols	Index *r*	–0.833**	$Y = 2.065 - 0.0874X + 0.00422X^2 - 0.00000743X^3$	0.847	<0.0001
	Index *a*	–0.910**	$Y = 1.689 + 0.0551X - 0.00210X^2$	0.883	<0.0001
Tru-Ustic Vertisols	Index *r*	–0.815**	$Y = 3.970 - 0.316X + 0.0122X^2 - 0.000154X^3$	0.782	<0.0001
	Index *a*	–0.874**	$Y = 3.588 - 0.231X + 0.00870X^2 - 0.0001154X^3$	0.825	<0.0001
Typ-Ustic Vertisols	Index *r*	–0.942**	$Y = 1.606 + 0.0133X - 0.00197X^2 + 0.00000186X^3$	0.884	<0.0001
	Index *a*	–0.962**	$Y = 1.375 + 0.0992X - 0.00647X^2 + 0.00000794X^3$	0.939	<0.0001

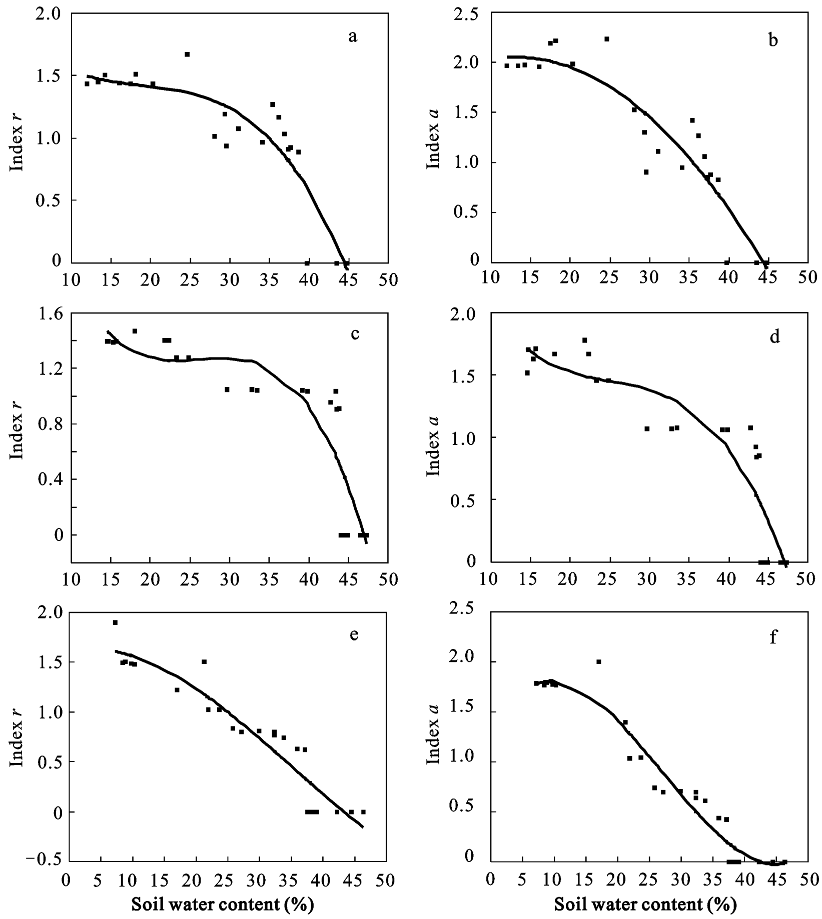
The values of index *r* in the three soils increase with the decrease of soil water content, indicating that the soil crack's connectivity is gradually enhanced during the cracking process. The values of index *r* in all soils uniformly change from 0 when cracking initiates to 1.5 around at the late stage, complying with the cubic equations listed in Table 4.

Similarly with the change of index *r*, index *a* also has a gradual increasing trend with the decreasing of soil water content, indicating that the extents that the soil crack network forms the circulation circuits are also slowly augmenting. The values of index *a* of the three soils begin at 0 when cracking initiates and finally approaches 20.

5 Discussion

The present paper studied the soil crack morphological development regularity with decreasing soil water, examining the dominant effect of soil water on soil crack development. However, there are still many questions that deserve to be discussed:

(1) What is the critical point of soil water content (CPWC) when soil crack development initiates? Our simulation experiments indicate that soil cracking can also occur even when the water content is still high. In the studied soils, the CPWC values tend to approach the same range and fluctuate around 45%. This conclusion, however, is very different from what we observed *in situ*



(a) and (b) Ver-Ustic Ferrisols; (c) and (d) Tru-Ustic Vertisols; (e) and (f) Typ-Ustic Vertisols

Fig. 8 Dynamic change curves for crack connectivity indicators in studied soils

experiments. The CPWC values obtained in field observations are much lower than those in simulation experiments, e.g., the CPWC value is 14.8% for Typ-Ustic Ferrisols, 19.3% for Tru-Ustic Vertisols and 27.3% for Typ-Ustic Vertisols. The difference in CPWC values probably is a consequence of two factors. On one hand, the soil samples used in simulation experiments were processed by a series of measures, e.g., sieving, water-satisfying and stirring. These measures directly and greatly affect soil structure and soil porosity status (compared with their original state in fields) and thus result in the difference in CPWC values. Moreover, the elimination of some impurities such as gravels, litters, and root residues, which exert a constraining effect on soil cracking also contribute to accelerating the occurrence of soil cracks. These measures might result in the initiation of advance soil cracking. On the other hand, the pots used to hold soil in simulation experiments are relatively smaller in dimension than the actual field conditions. Thus, the consequent edge effect is much more obvious, which is also one of the major factors resulting in a greater CPWC value.

(2) What are the reasons resulting in differences of the degrees of morphological development in the four soils? As we studied in this paper, the soil water content affects the morphological development of soil cracks. We know that different soils have different ultimate development degrees of soil cracks, namely different developmental potentials. For example, the Typ-Ustic Ferrisols can only develop into the feeble development degree range no matter how low the soil water content is, while the other three soils have the potential to develop into extremely intensive degrees. What makes the great difference on soil crack developmental potentials? According to the book of *Soil Physics* (Yao and Cheng, 1983), soil clay content and its mineral types are the two important factors influencing soil expansion and shrinkage. We also notice that the Typ-Ustic Ferrisols, which have the least developmental potential, do have greater differences in clay content than the Tru-Ustic Vertisols

and Typ-Ustic Vertisols; however, it has almost no difference in clay content with the Ver-Ustic Ferrisols, which also have greater developmental potential. However, the analysis results of mineral composition and X-ray diffraction indicate that the smectite content of Typ-Ustic Ferrisols is much lower than those of the other soils. The abundance of the smectite content of Typ-Ustic Ferrisols is evaluated as "little", while the other soils as "much" or "very much". This demonstrates that the smectite contents do have some relationships with the ultimate development degrees of soil cracks. Therefore, the study on quantitatively identifying the contributions of the soil internal factors, e.g., soil clay content, mineral type, and organic matter to soil cracking is still needed in the future. This is expected to give theoretical support and guidance to developing techniques on improving soil cracking quality.

6 Conclusions

Through the simulation experiment study on soil crack morphological changes during their development processes, we reached the following conclusions:

(1) The ultimate development degrees of soil cracks vary from soil to soil, even under the same climate condition. For Typ-Ustic Ferrisols, crack area density (A_c) can only develop into the feeble development degree range no matter how low the soil water content is, while for Ver-Ustic Ferrisols, Tru-Ustic Vertisols and Typ-Ustic Vertisols, their ultimate development degrees can attain the intensive degree, some even the extremely intensive degree of development. With the soil water decreasing, A_c and L_c both increase steadily and then tend to stabilize.

(2) As for the changes on connectivity during the cracking process, a decreasing trend can generally be found when judged by their *AWMFRAC* values because the number of slim cracks is reduced by the advancement of crack development. Nevertheless, the indicator of *AWMSI*, which expresses the extent to which the crack morphology deviates from a square, behaves as irregular changes.

(3) As far as the changes on the soil crack connectivity, with the decline of soil water content gradually becoming sharper, both index *r* and index *a* increase uniformly (except those in Typ-Ustic Ferrisols), indicating that connectivity is also gradually enhanced.

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