

Article

# Electrical Resistivity Response to Loess Crack Development and Rainfall Infiltration Recharge Under Wetting–Drying Cycles: Implications for Sustainable Water Management

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## Abstract

Understanding the crack development and rainfall infiltration in loess under wetting–drying cycles is crucial for assessing slope stability and promoting sustainable land management in ecologically vulnerable regions. This study employed a three-dimensional column model ( $\Phi_{24} \times 50$  cm) with 64 buried electrodes to simulate short-term heavy rainfall by changing the light duration (10 h/d and 5 h/d) and using 100 mm rainfall water. Results indicate that dry–wet cycles cause cumulative damage, significantly altering soil infiltration properties. After four cycles, the rainfall infiltration recharge coefficient increased from an initial 0.44% to 45.58%, a more than 100-fold rise. Resistivity imaging revealed a shift in water transport mode: from uniform matrix flow initially to preferential flow dominated by crack networks as cracks developed. During drying, crack zones exhibited high resistivity ( $\rho > 150 \Omega \cdot \text{m}$ ), while water-filled cracks during infiltration showed low resistivity ( $\rho < 50 \Omega \cdot \text{m}$ ). Resistivity is an excellent comprehensive index to quantify multi-field coupling damage, and its change ( $\rho \propto 1/w^{1.86} \times 1/(1 + 0.032 \text{ width})$ ) synchronously responds to water content, crack development and dry–wet process. Low water content ( $w < 15\%$ ) and medium crack width (4–6 mm) are the most sensitive states. Longer illumination (10 h/d) promoted greater crack development and higher infiltration capacity compared to shorter cycles (5 h/d). The developed resistivity–moisture relationship provides a non-destructive monitoring tool for slope moisture dynamics, supporting not only geotechnical stability assessment but also optimized irrigation scheduling and adaptive land-use planning. These insights contribute directly to the sustainable management of soil and water resources in loess landscapes, aligning with sustainability goals in fragile ecosystems.

**Keywords:** electrical resistivity monitoring; loess crack development; rainfall infiltration recharge; wetting–drying cycles; sustainable water management



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## 1. Introduction

The loess is composed of fine-grained soil dominated by wind transport deposition [1]. It is widely distributed in the Loess Plateau and other regions [2]. The soil has high fertility and is suitable for crop growth [3,4]. Due to the collapsibility and looseness of loess itself, it is easy to form a vertical joint and fissure grid under the action of external force [5]. It

is vulnerable to soil erosion and wind erosion, resulting in land degradation [6]. Under the combined influence of climatic conditions and human activities, geological disasters such as soil erosion, collapse, landslides and floods have occurred in the loess area [7]. For this reason, a lot of research has been carried out on the morphological characteristics and preventive measures of loess fissures at home and abroad.

Drying–wetting cycles, as a key climatic and hydrological process [8], significantly drive the development of cracks in loess. In arid and semi-arid regions, intense evaporation causes rapid water loss from the soil surface, leading to shrinkage and cracking [9]. Intermittent rainfall, in turn, subjects the soil to repeated wetting and drying processes [10,11]. This cyclic variation generates uneven stress distribution within the soil, promoting the evolution of cracks from an initial isolated state into a networked and complex system [12].

In terms of mechanical studies, Li et al. [13] systematically summarized crack development patterns in loess under different stress states, highlighting that the widely developed vertical joint system in loess results from the combined action of primary and secondary cracks. Zhang et al. [14] investigated the microstructural evolution of reinforced sea sand through drying–wetting cycle tests, revealing dynamic changes in soil structure during cyclic processes. Mao et al. [15] applied coupled drying–wetting cycle experiments to explore the time-dependent strength and underlying mechanisms of grass–loess composites, providing a theoretical basis for ecological slope protection technologies. Yuan et al. [16] systematically studied the effects of dry density and cycle number on the soil–water characteristic curve of compacted loess and established a corresponding prediction model. Luo et al. [17] focused on the full-process deformation characteristics of slopes under drying–wetting cycles and proposed an innovative analytical method for slope deformation under such conditions.

Collectively, these findings underscore that drying–wetting cycles are a critical factor influencing the engineering properties of soils [18]. Building on this foundation, systematically investigating the evolution of loess cracks under drying–wetting conditions and their impact on rainfall infiltration mechanisms will not only enhance the theoretical understanding of loess hydro-mechanical behavior but also provide practical value for geological disaster prevention and engineering safety in loess regions [19]. Against the backdrop of global climate change, with the increasing frequency of extreme droughts and heavy rainfall events, in-depth research into the mechanisms of drying–wetting effects has become particularly urgent [20].

Traditional research methods have primarily relied on laboratory mechanical tests and field surveys to obtain characteristic parameters of loess cracks [21,22]. However, these approaches often struggle to achieve dynamic and non-destructive monitoring of the crack development process. In recent years, geophysical detection methods have been widely applied in the study of loess cracks due to their unique advantages of being non-destructive, efficient, and capable of wide spatial coverage [23]. A significant correlation exists between the resistivity characteristics of loess and its structural parameters [24]. Specifically, resistivity decreases exponentially with increasing water content and is highly sensitive to moisture changes [25]. This physical property provides a theoretical basis for using electrical methods to detect cracks in loess.

In terms of monitoring techniques, Zhao et al. [26] used optical fiber distributed sensors to measure the width of structural cracks, considering the influence of strain redistribution after cracks. Sandric et al. [27] applied high-resolution ground-based photography combined with digital image processing and artificial intelligence algorithms to achieve automatic identification and mapping of crack networks. Zhu et al. [28] utilized 3D laser scanning technology to accurately measure the three-dimensional morphology of cracks and conducted an in-depth analysis of the influence mechanism of crack depth on landslide

development. At the level of advanced technology application, De et al. [29] tested the  $\theta$ - $\rho$  relation model of the clay-textured typhoon hedgehog in tropical conditions by resistivity method, and determined the effect of compaction on this relationship. Du et al. [30] used satellite radar interferometry to monitor regional ground subsidence, indirectly reflecting overall trends in crack development. Cheng et al. [31] applied distributed optical fiber sensing technology to monitor the soil strain field and established a corresponding prediction model. Among these, electrical resistivity tomography (ERT) uses a multi-electrode array system to achieve efficient data collection through automatic electrode switching [32,33]. Combined with advanced inversion algorithms, ERT can reconstruct the three-dimensional resistivity structure of the subsurface, demonstrating significant advantages in monitoring invisible underground cracks.

In engineering applications, Zhang et al. [34] successfully observed the dynamic closure behavior of cracks in loess slopes during rainfall using time-lapse ERT. Bjarn et al. [35], used electrical resistivity tomography (ERT) to evaluate the influence of the Cretaceous aquifer fault zone on groundwater model prediction. Muhammad et al. [36] found a high correlation between resistivity anisotropy characteristics and crack orientation, providing a new technical approach for evaluating crack development direction. These research results demonstrate that geophysical methods, particularly ERT, can effectively overcome the limitations of traditional approaches. They provide strong technical support for the quantitative study and dynamic monitoring of loess cracks, holding significant practical value for geological disaster prevention in loess regions.

Previous studies have examined the evolution of loess cracks and rainfall infiltration. However, for this particular type of soil, the mechanism of its resistivity response remains poorly understood. It is still unclear how the coupling effect of cracks and water influences resistivity during wetting–drying cycles. Therefore, this study integrates resistivity monitoring with practical engineering factors—such as wetting–drying cycles, crack development, and light conditions—to establish a multi-factor analysis framework. This framework aims to reveal the dynamic evolution of loess cracks and their impact on rainfall infiltration, illustrating how cracks promote preferential flow. A quantitative model relating resistivity, crack rate, and water content was developed. This advances the application of geophysical methods in geological disaster prevention and control projects, while also providing a scientific basis for slope stability and ecological restoration in loess regions.

## 2. Materials and Methods

### 2.1. Materials

The experimental soil selected was Malan loess from Ansai District, Yan'an City, Shaanxi Province. This loess has a uniform and loose texture. According to the Geotechnical Engineering Investigation Code (GB50021-2001, 2009 edition) [37], its clay content (particle size < 0.005 mm) exceeds 15%, classifying it as high-clay-content loess and falling into the category of silty clay. The basic physical properties of the soil sample are presented in Table 1.

**Table 1.** The basic physical properties.

| Particle Size (mm) | Content Proportion (%) | Liquid Limit<br>10 mm<br>$W_L$ | Plastic Limit<br>$W_P$ | Plasticity Index<br>$I_P$ | Designation |
|--------------------|------------------------|--------------------------------|------------------------|---------------------------|-------------|
| 0.25–0.075         | 16.2                   | 32.6                           | 19.3                   | 12.5                      | silty clay  |
| 0.075–0.005        | 61.2                   |                                |                        |                           |             |
| <0.005             | 22.6                   |                                |                        |                           |             |

2.2. Experimental Device

Figure 1 shows a schematic diagram of the experimental setup. The equipment consists of four parts: a loess experimental column, a crack observation device, a resistivity acquisition device, and a computer system. A plexiglass column measuring  $\Phi_{24}\text{ cm} \times 50\text{ cm}$  was selected as the soil sample boundary constraint device. Its side wall was precision-designed with a distributed sensor network, arranged as 16 high-purity copper electrodes per row. Four monitoring layers were installed from shallow to bottom depth, maintaining a vertical spacing of 8.3 cm between adjacent layers. The crack observation device includes a high-definition camera and a pan-tilt unit. To minimize the influence of boundary effects on the soil [38,39], a layer of Vaseline was applied to the inner walls of the device prior to soil placement. The resistivity acquisition device consists of the ERT21S signal acquisition unit (developed by Nanjing University), electrodes, and connecting cables. The computer system is equipped with the Particles (Pores) and Crack Analysis System [40] (PCAS) V2.325 for crack identification and the ResIPYv.3.6.2 software for resistivity inversion. Detailed device parameters are listed in Table 2.

Table 2. Detailed device parameters.

| Items              |                    | Parameters                      |
|--------------------|--------------------|---------------------------------|
| Camera             | Brand              | iQOO 12, vivo (Dongguan, China) |
|                    | Maximum resolution | 4500 × 3072 pixel               |
|                    | Field of view      | 180°                            |
| Measuring cylinder | Brand              | Lichen (Xiamen, China)          |
|                    | LT1002             | 0.1 mL                          |
| Mold               | Material           | Dimension                       |
|                    | Plexiglass         | $\Phi_{24} \times 50\text{ cm}$ |
| ERT21              | Brand              | ERT21S (Nanjing, China)         |
|                    | Number             | JZ21-1110                       |

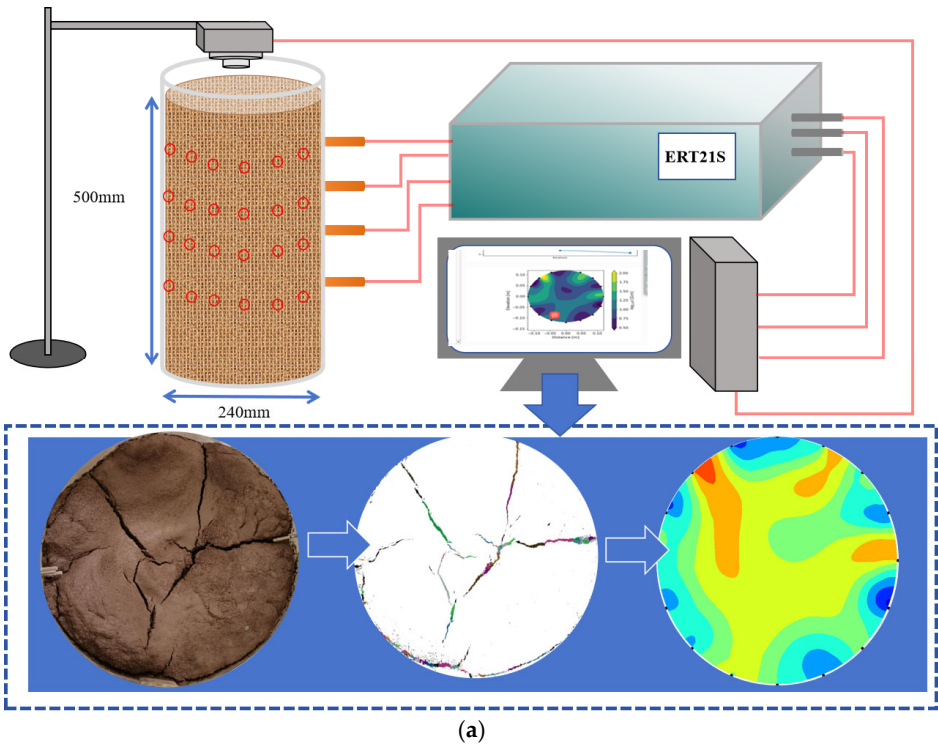


Figure 1. Cont.

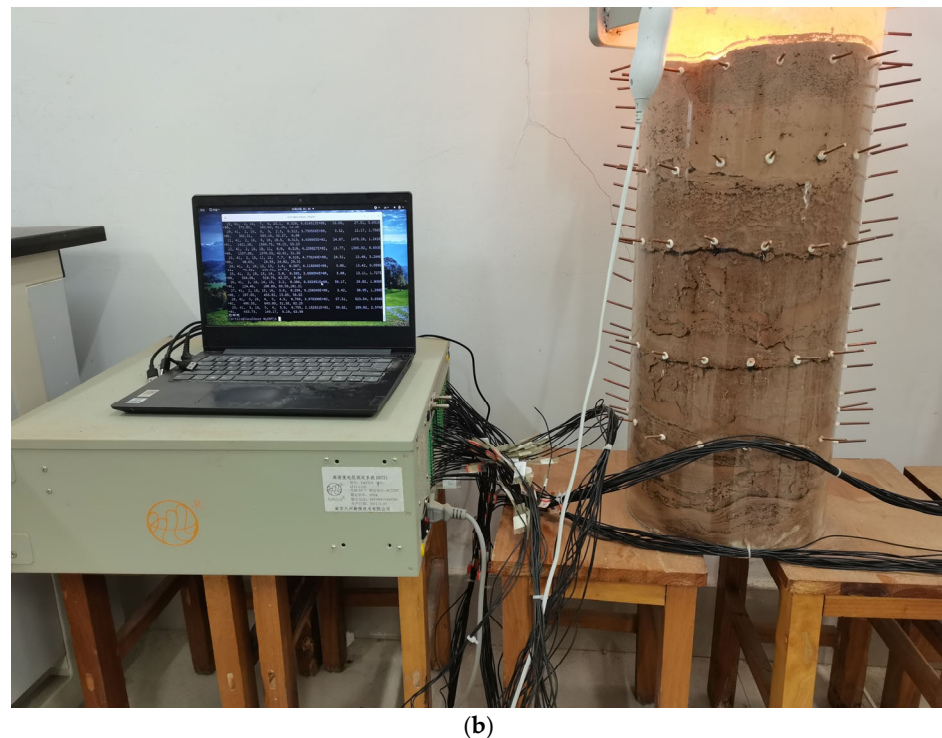


**Figure 1.** Schematic diagram of the experimental setup. ((a) Schematic diagram of experimental setup; The color note: In the schematic diagram, the red circles on the soil column represent the positions of electrode holes (b) Physical image of experimental setup).

### 2.3. Experimental Procedure

#### Step 1 Initial Water Content Measurement

Part of the loess sample was placed into a cutting ring (50 mm diameter, 10 mm height). After trimming and weighing, the sample was oven-dried and weighed again. The measured initial water content was 10%.

#### Step 2 Sample Preparation and Installation

The loess was compacted into a cylindrical device in 5 mm layers, each to a specified mass, until the sample completely covered the first electrode layer. Electrodes were connected to the resistivity monitoring device to track resistivity changes at the initial water content. After compaction, a filter paper was placed over the sample, and water was slowly sprayed to achieve saturation. The calculated saturated water content was 40%. The sample was left for 48 h to allow internal moisture equilibrium. Electrodes were then reconnected to monitor resistivity under saturated conditions.

#### Step 3 Drying–Wetting Cycles

As illustrated in Figure 2, the soil column was placed under an incandescent lamp to accelerate drying. Electrodes remained connected to continuously monitor resistivity, while a high-definition camera periodically captured crack development. An empirical relationship between resistivity and water content was established. Under the initial conditions, the soil moisture content was measured at 10%, corresponding to an air-dried state. Saturation was considered to occur when the moisture content reached 25%. The complete schematic diagram of the dry-wet cycle is shown in Figure 3. Accordingly, one wetting–drying cycle was defined as the process during which the moisture content varied from 10% to 25% and then returned to 10%, with the completion of each cycle marked by the restoration of the initial moisture content (10%). One drying–wetting cycle was defined as the resistivity change in the bottom electrode layer corresponding to water

content variations from 10% (dried) to 25% (rewet) and back to 10%. Cycles were repeated until crack development showed no significant change. Four drying–wetting cycles were conducted, and the entire process was repeated for four parallel experimental sets.

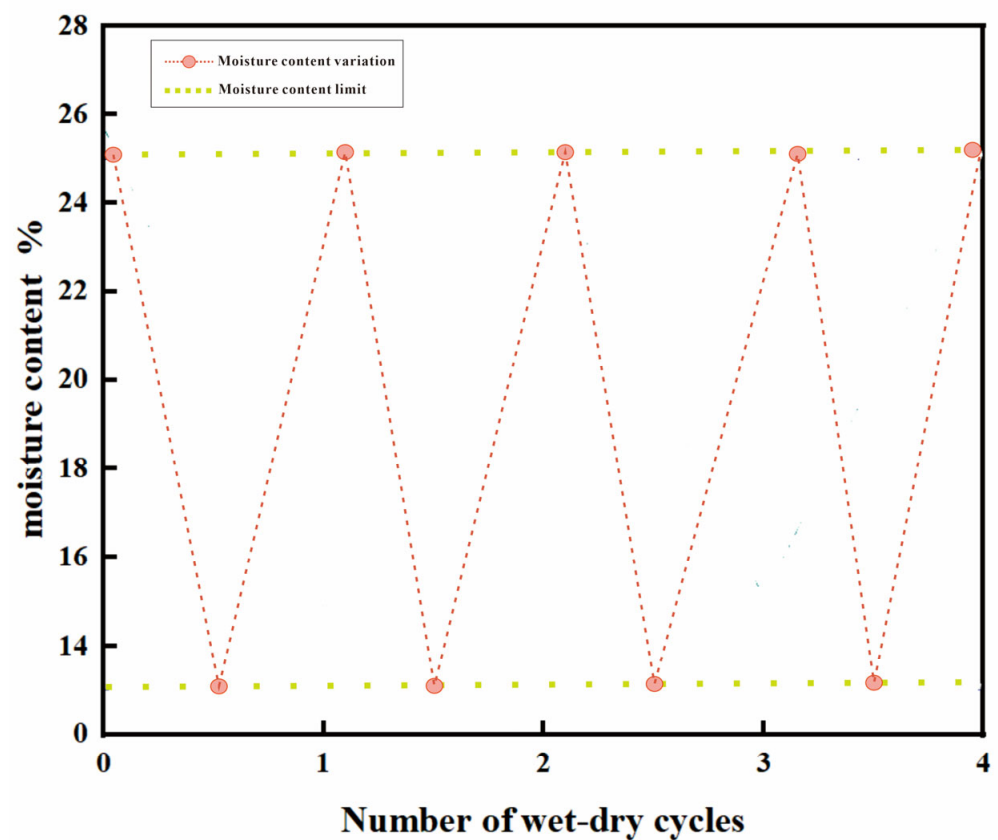


**Figure 2.** Moisture content change diagram of dry–wet cycle.

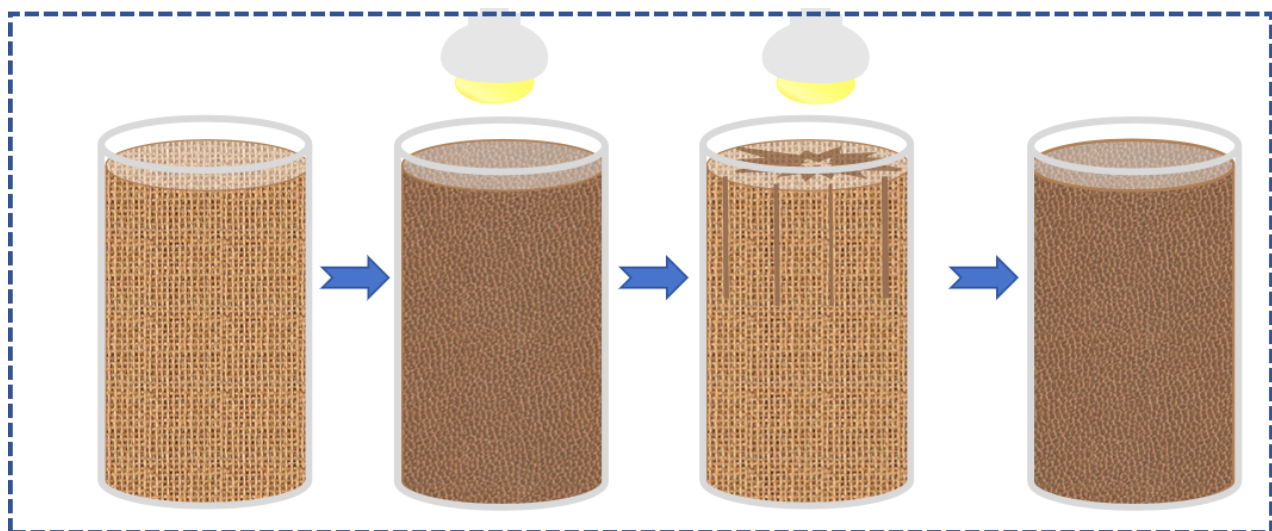


**Figure 3.** Schematic diagram of the dry–wet cycle process. (Color note: The light-colored soil column represents the state of the soil column with a moisture content of 10%, while the dark-colored soil column represents the state of the soil column when the moisture content is 25%).

The spiral copper electrodes were employed, with colloidal material injected into each electrode and the surrounding soil pores to ensure secure fixation. The four-electrode Wenner array configuration was adopted for resistivity measurement, which effectively minimizes errors resulting from localized poor contact.

#### Step 4 Rainfall infiltration coefficient measurement and calculation

Water equivalent to 100 mm rainfall was added manually at the end of each drying–wetting cycle. The water infiltrated from the soil surface. Under laboratory conditions, short-term extreme rainfall was simulated to promote rapid soil infiltration. Effluent from the bottom of the soil column was collected into a graduated cylinder. The time and volume of effluent were recorded. This procedure was repeated for four cycles in total.

For a more comprehensive investigation, four parallel replicate groups were included in the experiment. Each replicate group experienced four complete wetting–drying cycles. Two different lighting durations were applied across groups to examine their effects. Data from all experimental runs were combined to generate a comprehensive dataset.

#### 2.4. Crack Parameter Extraction Method

This study applied systematic digital image processing techniques to quantitatively characterize the crack network developed in loess during drying–wetting cycles. The specific procedure is shown in Figure 4. First, the core analysis tool used was the (PCAS) V2.325, an independent software developed by Nanjing University. Based on advanced image recognition algorithms, PCAS enables accurate extraction of crack geometric features. During the preprocessing stage, original crack images collected by the high-definition camera were cropped into circular areas with a radius of 1500 pixels. This step eliminated boundary effects and ensured analysis area consistency.

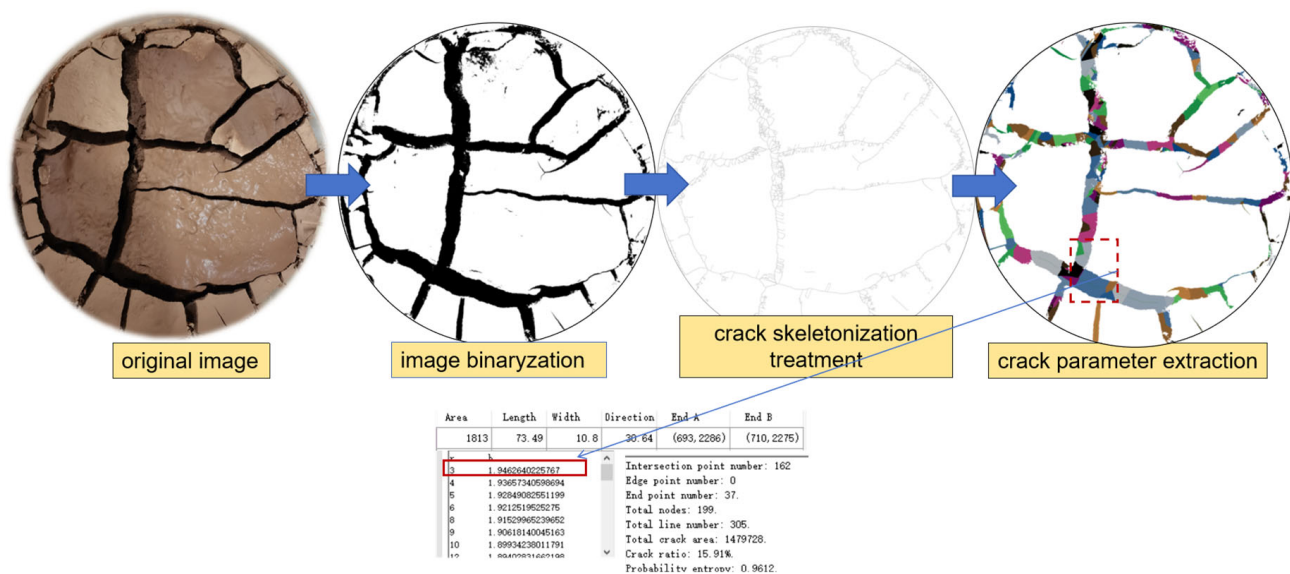


**Figure 4.** Crack parameter extraction diagram.

The cropped images underwent binarization. An optimal threshold segmentation method separated cracks from the soil matrix, producing black-and-white binary images. A skeletonization algorithm was then applied to extract the centerlines of the crack network. Key parameters such as crack width, crack area, and surface crack ratio were calculated. Crack width was determined by measuring the perpendicular distance between the two edges along the skeleton line. The crack ratio was defined as the ratio of crack area to the total analysis area.

To verify the accuracy of the digital processing results, this study also used traditional measurement methods for comparison. A vernier caliper with 0.02 mm accuracy was used to physically measure the width and length of typical cracks on the soil column surface. Correlation analysis and statistical comparison between the traditional measurements and PCAS-extracted parameters ensured the reliability of the crack quantification data. This

combined method of digital image processing and physical measurement maintained data collection efficiency while improving parameter extraction accuracy. It provided a solid data foundation for subsequent research on crack evolution patterns.

### 2.5. Resistivity Parameter Inversion Method

The specific resistivity parameter extraction process is shown in Figure 5. High-density resistivity tomography was used for non-destructive monitoring and quantitative characterization of internal structural changes in the three-dimensional soil column. During the data inversion stage, a circular grid with a radius of 12 cm was established for each layer based on the finite element method. The least squares inversion algorithm performed iterative calculations on the collected apparent resistivity data. According to electromagnetic field theory, the resistivity of a medium closely relates to its composition. Inversion results showed: soil areas fully saturated with water exhibited significantly low resistivity due to the conductivity of ions in pore water, appearing as cool colors on the resistivity inversion map (shown in the red box in Figure 5). In contrast, crack development areas with air intrusion showed clearly high resistivity anomalies, displayed as warm colors on the color map (shown in the light blue box in Figure 5).

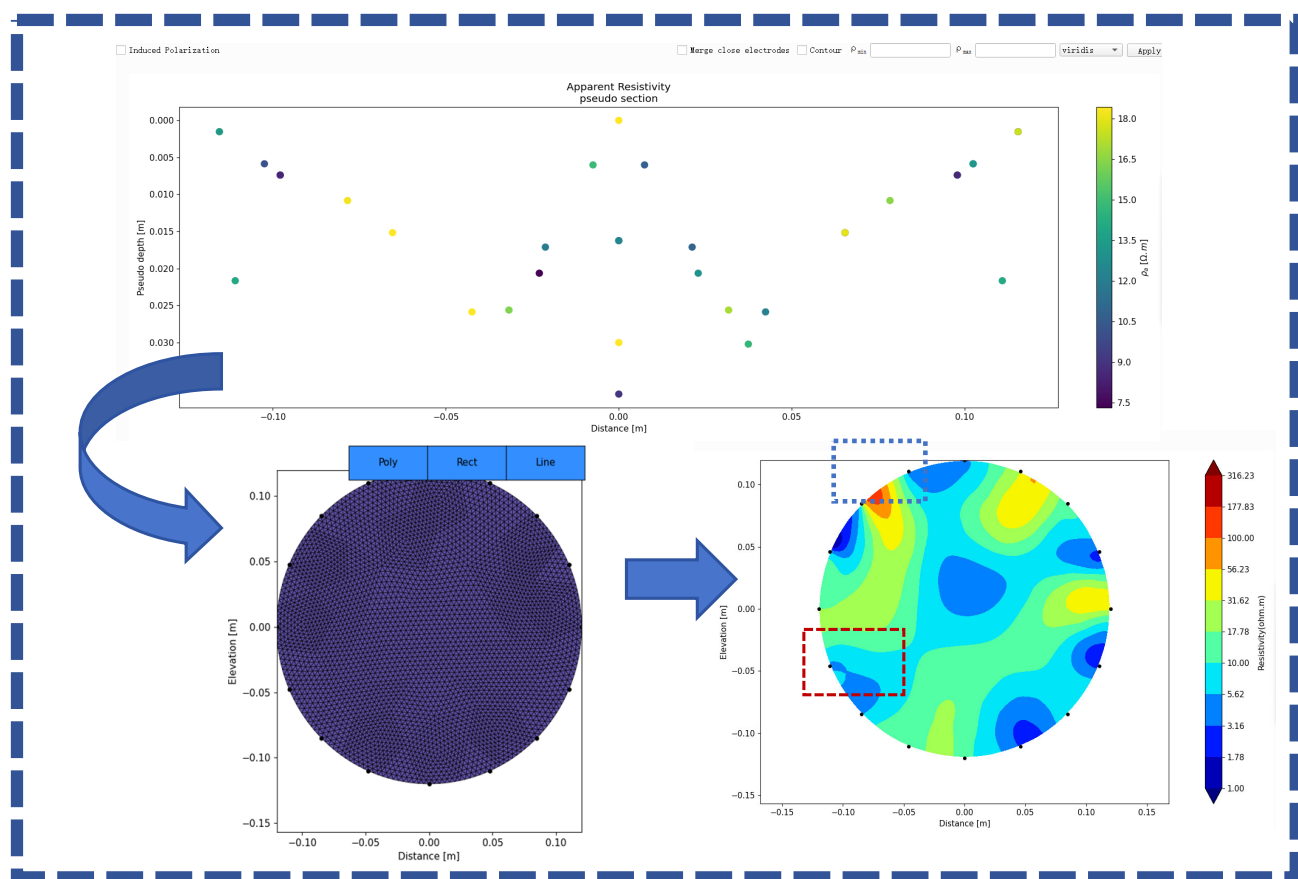


**Figure 5.** Resistivity parameter extraction diagram. (Color notes: The area enclosed by the blue dotted line represents high resistance, and the area enclosed by the red dotted line represents low resistance).

### 2.6. Theoretical Formula

#### (1) The box-counting dimension

The box-counting dimension [41,42] is defined by Equation (1).

$$D = A - \frac{\ln N_i}{\ln \varepsilon_i} \quad (1)$$

where  $A$  is a constant;  $D$  represents the fractal dimension of the cracks;  $N_i$  and  $\varepsilon_i$  denote the  $i$ -th level size and the corresponding number of similar blocks, respectively. If a linear relationship exists between  $\ln N_i$  and  $\ln \varepsilon_i$ , the slope between them approximates the fractal dimension  $D$  of the cracks.

## (2) Wenner array configuration

The apparent resistivity ( $\rho_\alpha$ ) under the Wenner array [43] configuration is defined by Equation (2).

$$\rho_\alpha = k \frac{\Delta V}{I} \quad (2)$$

where  $k$  denotes the geometric factor, a function of the electrode arrangement;  $\Delta V$  represents the measured potential difference; and  $I$  signifies the injected current.

## (3) The least squares method

Apparent resistivity cannot reflect true subsurface conditions due to various external influences. Therefore, inversion is necessary for the calculated apparent resistivity. This study uses the least squares method [44] for inversion. The principles are described below.

Equations (3) and (4) present the forward formula and the inversion formula, respectively. Equation (5) defines the objective function  $\phi$ , constructed from the forward model data and the field measured data. An iterative algorithm continuously updates the model  $m$  until the objective function converges to a minimum value. The resulting  $m$  then becomes the final inversion image.

$$d = F(m) \quad (3)$$

$$m = F^{-1}(d_{obs}) \quad (4)$$

$$\phi = \|W_d(d_{obs} - F(m))\|^2 + \lambda \|W_m(m - m_0)\|^2 \quad (5)$$

$d$ : observation point locations on the surface;  $F$ : forward modeling operator.  $D_{obs}$ : field-measured apparent resistivity data.  $W_d$ : data weight matrix, typically the inverse of the observed data standard deviation.  $W_m$ : model constraint matrix, usually applying first or second-order smoothness constraints to ensure gradual resistivity changes between adjacent grids.  $m_0$ : prior model reference.  $\lambda$ : regularization factor, balancing data fitting and model smoothness.

## (4) Calculation formula of rainfall infiltration coefficient

In this study, the rainfall infiltration [42,45] experiment under the condition of a crack is known, and the amount of rainfall and seepage to recharge the underground is known, and the evaporation of the experimental device and the measuring device is measured. Therefore, the water balance formula of formula (6) is selected to calculate the rainfall infiltration coefficient.

$$\lambda = \frac{P - R - E}{P} \times 100\% = \frac{I}{P} \times 100\% \quad (6)$$

where

$\lambda$ : rainfall infiltration coefficient (%);  $P$ : total rainfall (mm);  $R$ : total infiltration (mm);  $E$ : evaporation of the instrument (mm); and  $I$ : total infiltration (mm)  $I = P - E - R$ .

# 3. Result

## 3.1. Crack Rate Evolution

Table 3 and Figure 6 show the variation in crack width measured by manual measurement and PCAS software under 5 h/d light conditions. According to the chart data, the change trend of the crack width obtained by the two methods is basically the same, and the

error of each measuring point is less than 8%. Therefore, it is effective to use PCAS digital image processing software to measure the crack width.

**Table 3.** The crack width comparison table between manual measurement and PCAS recognition was used for four cycles (5 h/d).

|   | $\omega$ /% | Width/mm | $\omega$ /% | Width/mm | $\omega$ /% | Width/mm | $\omega$ /% | Width/mm |
|---|-------------|----------|-------------|----------|-------------|----------|-------------|----------|
| P | 22.5        | 2.34     | 23.54       | 2.49     | 22.12       | 4.24     | 20.34       | 4.46     |
|   | 18.56       | 3.10     | 19.22       | 3.30     | 18.78       | 5.64     | 19.09       | 5.83     |
|   | 17.5        | 3.42     | 18.56       | 3.74     | 18.28       | 6.56     | 18.02       | 6.79     |
|   | 17.18       | 3.76     | 17.77       | 4.22     | 16.88       | 7.50     | 17.65       | 7.71     |
|   | 16.65       | 3.89     | 16.78       | 4.42     | 16.61       | 7.82     | 16.59       | 8.12     |
|   | 15.06       | 3.98     | 15.24       | 4.67     | 15.64       | 8.04     | 15.87       | 8.35     |
|   | 14.76       | 4.07     | 14.65       | 4.85     | 15.12       | 8.26     | 15.48       | 8.61     |
|   | 14.34       | 4.16     | 13.95       | 4.90     | 14.24       | 8.39     | 14.23       | 8.77     |
|   | 13.03       | 4.19     | 13.06       | 4.91     | 13.45       | 8.43     | 13.60       | 8.82     |
| M | 20.4        | 2.3      | 23.7        | 2.3      | 23.8        | 4.2      | 22.7        | 3.2      |
|   | 19.5        | 2.5      | 20.2        | 2.5      | 21.3        | 4.9      | 21.8        | 3.2      |
|   | 18.4        | 2.5      | 19.6        | 3.1      | 19.6        | 5.1      | 20.6        | 5.2      |
|   | 17.5        | 2.8      | 17.4        | 3.4      | 18.2        | 5.2      | 18.8        | 5.6      |
|   | 16.4        | 3.1      | 16.2        | 3.8      | 17.1        | 6.2      | 17.6        | 6.3      |
|   | 15.7        | 3.2      | 15.7        | 3.8      | 16.2        | 5.8      | 17.2        | 5.9      |
|   | 14.5        | 3.8      | 14.8        | 3.8      | 15.8        | 6        | 16.6        | 6.4      |
|   | 13.8        | 3.8      | 13.7        | 3.8      | 14.9        | 6.7      | 15.5        | 7        |
|   | 13.3        | 3.7      | 13.4        | 3.7      | 13.4        | 6.7      | 14.4        | 6.4      |

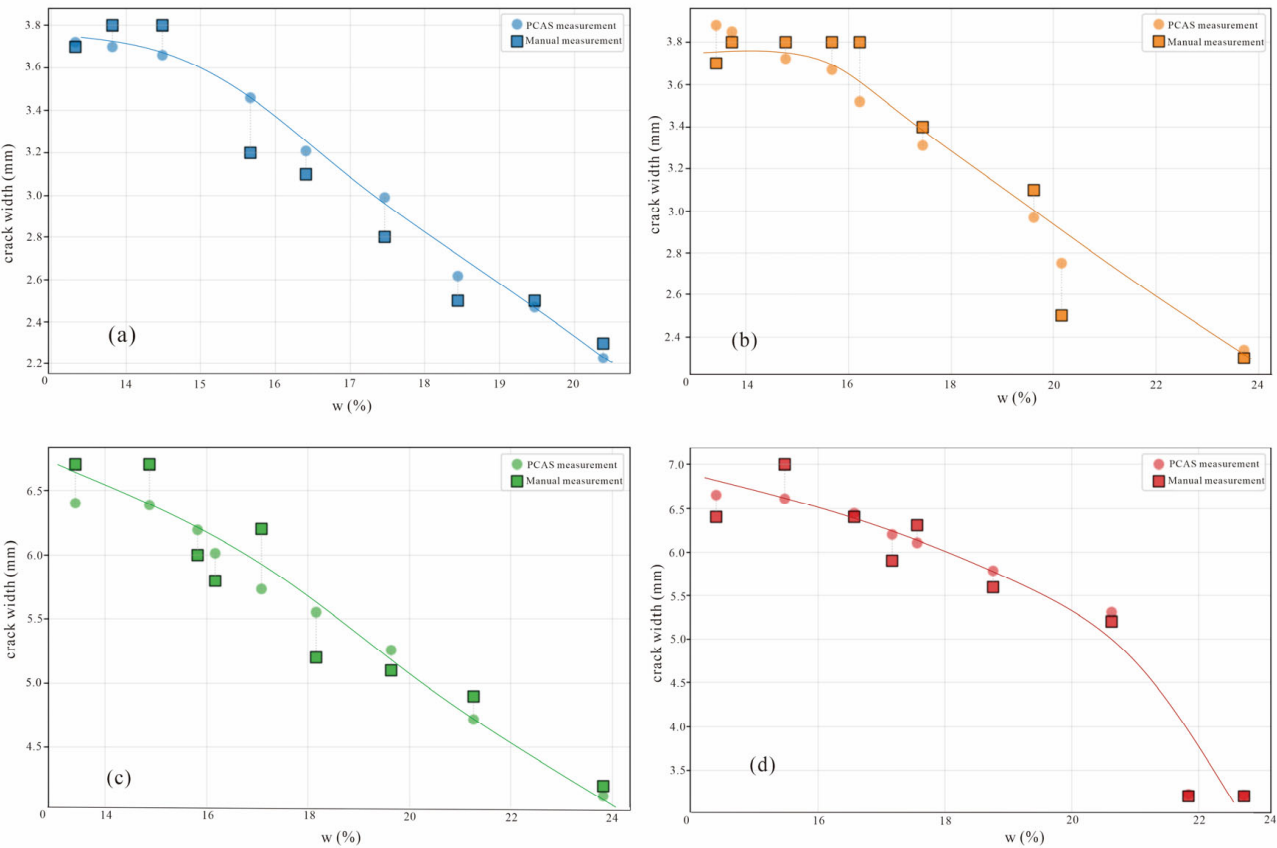


**Figure 6.** Comparison between PCAS and manual measurement of crack parameters ((a–d) represent the comparison of crack parameters from the first cycle to the fourth cycle at 5 h/d).

Figure 7 presents a partial comparison between the surface horizontal crack distribution and the electrical resistivity inversion results at a depth of 3 cm below the surface. Based on the crack inversion results and the actual crack orientations, it is evident that areas with a high density of cracks correspond to high resistivity, whereas areas with sparse cracks correspond to low resistivity. This demonstrates that the electrical resistivity tomography (ERT) method effectively characterizes the evolution of cracks by mapping the variations in resistivity.

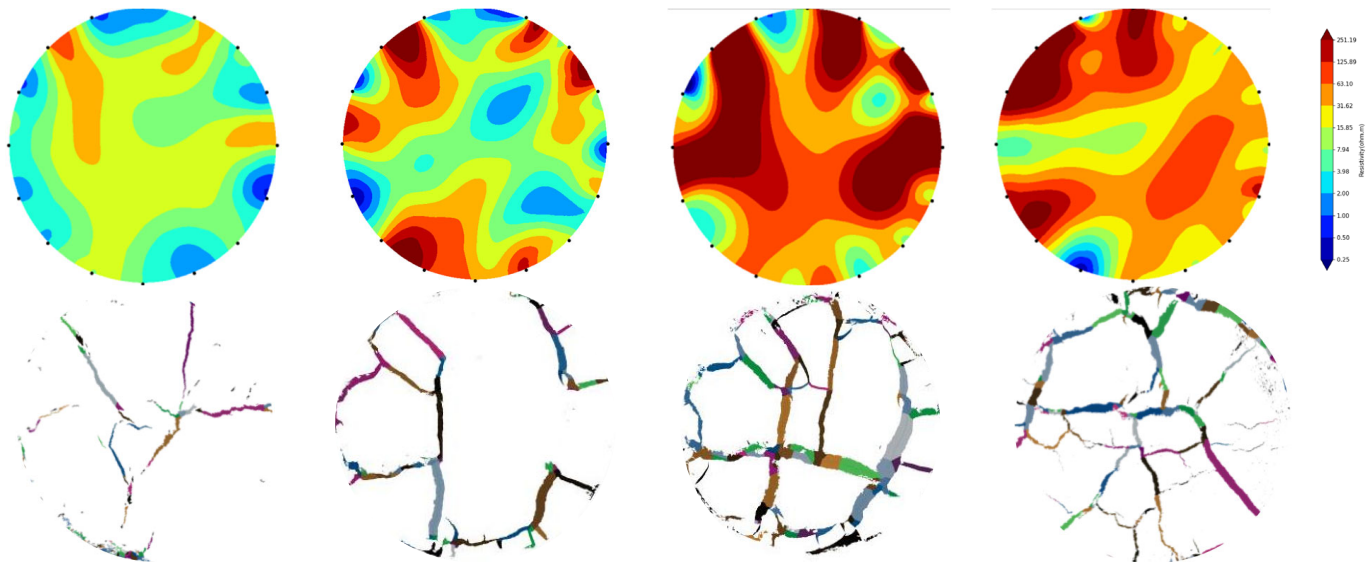


**Figure 7.** The resistivity inversion change at 3 cm below the surface is compared with the real surface crack. (Color note: different colors are used in PCAS software to distinguish various small crack angles).

Figures 8 and 9 show the evolution of crack width and crack ratio over time during drying–wetting cycles under different lighting conditions. Table 4 shows the variation of crack aperture with water content under different dry–wet cycling conditions under two light exposure conditions. Figure 8a–d present the crack width changes across four drying–wetting cycles. Among them, d1 represents a lighting condition of 10 h, and d2 represents 5 h. Overall, drying–wetting cycles significantly intensified crack development in the loess at the same moisture content. During the first cycle, as the moisture content decreased from 22.5% to 13.03%, the surface crack width increased from 2.34 mm to 4.19 mm, with a relatively gentle change curve. As the number of cycles increased, the initial crack width in subsequent cycles widened progressively. As shown in Figure 8b, the initial crack width had already reached 2.49 mm ( $\omega = 23.54\%$ ) and exceeded the width corresponding to a lower moisture content in the first cycle. By the third and fourth cycles, the initial crack widths further increased to 4.24 mm and 4.46 mm, respectively. The 5 h lighting group exhibited a relatively milder growth trend. Within a similar moisture content variation range (20.4% ~ 13.3%), the crack width increased from 2.23 mm to 3.72 mm. This indicates that after wetting, the cracks did not completely close, and the soil structure underwent permanent changes. As a result, in subsequent cycles, even with higher initial moisture content, the cracks reopened to a width greater than the minimum opening before the cycle.

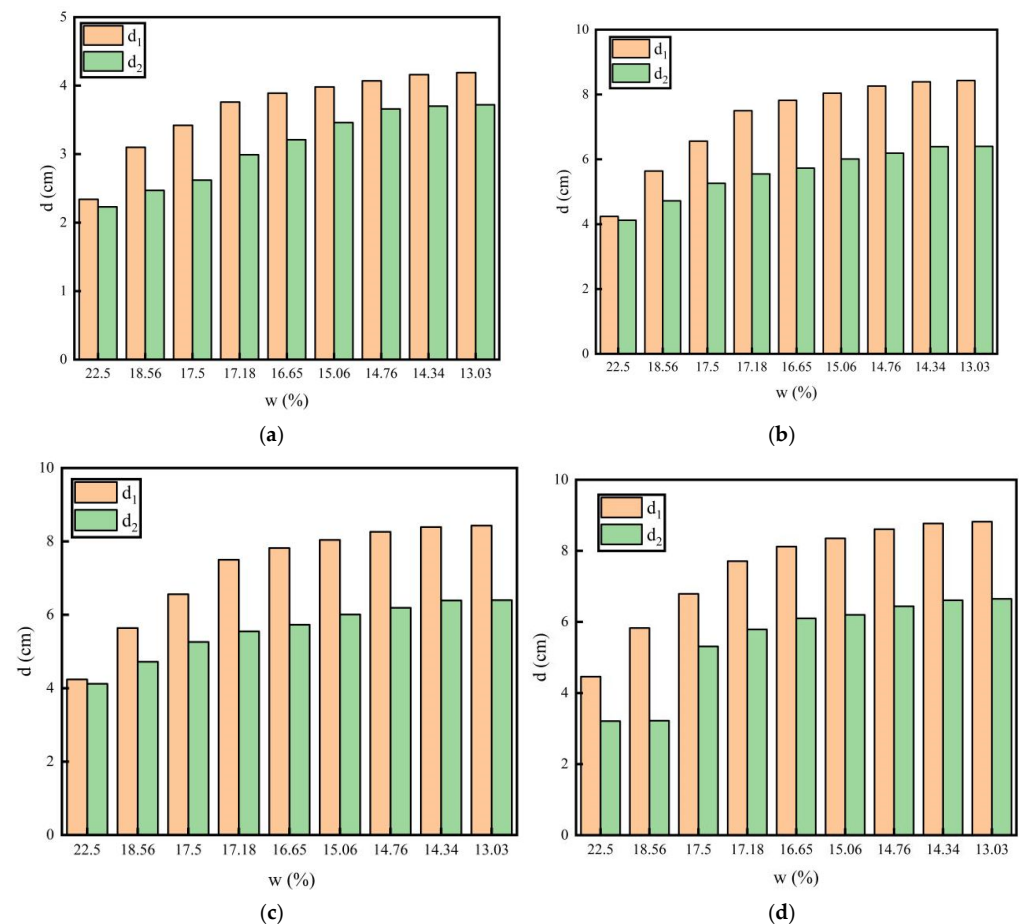


**Figure 8.** Crack width and water content change diagram under dry–wet cycle conditions ( $d_1$  and  $d_2$  are the crack width changes of illumination times of 10 h and 5 h, respectively). (a) Diagram of crack width variation with moisture content under two different light intensities after experiencing a dry–wet cycle condition; (b) The graph of crack width varying with moisture content under two different light intensities after experiencing two wetting–drying cycles; (c) The variation of crack width with moisture content under two different light intensities after experiencing three wetting–drying cycles; (d) Diagram of crack width variation with moisture content under two different light intensities after experiencing four wetting–drying cycles).

Figure 9a,b show the changes in the crack rate of the soil column under different illumination conditions with the same number of dry–wet cycles. The crack development process in all loess columns consistently exhibited three stages: rapid growth, stable development, and slowdown until stabilization. Taking Figure 8a as an example, starting from the onset of visible crack development, the initial crack ratio was 4%. After the first cycle, it stabilized around 15%. With an increasing number of drying–wetting cycles, the crack rate rose significantly. As the number of cycles changed, the duration of each crack development stage varied. Within the same period, higher cycle numbers resulted in longer rapid growth and stable accelerated development phases. However, the total time required for complete crack development remained largely unchanged. The crack rate increased by 10% from the first to the fourth cycle. Yet, due to the moisture content increase in each cycle, some recovery of soil cracks occurred within limits, resulting in a final crack parameter lower than that at the end of the previous cycle.

In the 10 h group (Figure 9a), the crack ratio stabilized at 15.52% after the first cycle, increased to 21.36% in the second cycle, and further rose above 25% in the third and fourth cycles. The 5 h group showed a steady increase from 12.24% in the first cycle to 15.26% in the fourth cycle. These results confirm that each drying–shrinkage and wetting–swelling

cycle is not a reversible process. Instead, each cycle acts as a fatigue load on the cementation structure between soil particles, irreversibly weakening the soil integrity and continuously reducing its tensile strength.

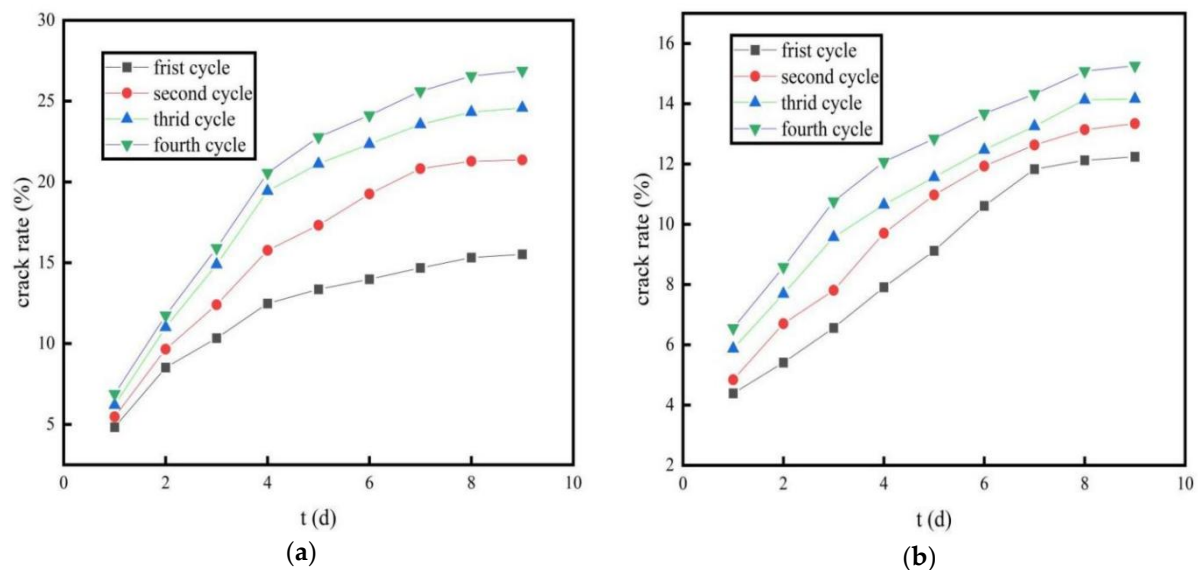


**Figure 9.** Crack rate variation with time during four dry-wet cycles under different light conditions ((a) and (b) are the crack rate changes of light for 10 h and 5 h, respectively).

**Table 4.** Crack width and water content change table under dry-wet cycle conditions ( $d_1$  and  $d_2$  are the crack width changes of illumination times of 10 h and 5 h, respectively).

|       | $\omega/\%$ | Width/mm | $\omega/\%$ | Width/mm | $\omega/\%$ | Width/mm | $\omega/\%$ | Width/mm |
|-------|-------------|----------|-------------|----------|-------------|----------|-------------|----------|
| $d_1$ | 22.5        | 2.34     | 23.54       | 2.49     | 22.12       | 4.24     | 20.34       | 4.46     |
|       | 18.56       | 3.10     | 19.22       | 3.30     | 18.78       | 5.64     | 19.09       | 5.83     |
|       | 17.5        | 3.42     | 18.56       | 3.74     | 18.28       | 6.56     | 18.02       | 6.79     |
|       | 17.18       | 3.76     | 17.77       | 4.22     | 16.88       | 7.50     | 17.65       | 7.71     |
|       | 16.65       | 3.89     | 16.78       | 4.42     | 16.61       | 7.82     | 16.59       | 8.12     |
|       | 15.06       | 3.98     | 15.24       | 4.67     | 15.64       | 8.04     | 15.87       | 8.35     |
|       | 14.76       | 4.07     | 14.65       | 4.85     | 15.12       | 8.26     | 15.48       | 8.61     |
|       | 14.34       | 4.16     | 13.95       | 4.90     | 14.24       | 8.39     | 14.23       | 8.77     |
|       | 13.03       | 4.19     | 13.06       | 4.91     | 13.45       | 8.43     | 13.60       | 8.82     |
| $d_2$ | 20.39       | 2.23     | 23.72       | 2.34     | 23.82       | 4.12     | 22.72       | 3.21     |
|       | 19.47       | 2.47     | 20.16       | 2.75     | 21.27       | 4.72     | 21.84       | 3.22     |
|       | 18.44       | 2.62     | 19.61       | 2.97     | 19.63       | 5.26     | 20.63       | 5.31     |
|       | 17.46       | 2.99     | 17.45       | 3.31     | 18.16       | 5.55     | 18.76       | 5.79     |
|       | 16.41       | 3.21     | 16.22       | 3.52     | 17.08       | 5.73     | 17.56       | 6.10     |
|       | 15.67       | 3.46     | 15.68       | 3.67     | 16.17       | 6.01     | 17.17       | 6.20     |
|       | 14.49       | 3.66     | 14.77       | 3.72     | 15.83       | 6.19     | 16.58       | 6.44     |
|       | 13.82       | 3.70     | 13.73       | 3.85     | 14.88       | 6.39     | 15.48       | 6.61     |
|       | 13.32       | 3.72     | 13.43       | 3.88     | 13.41       | 6.40     | 14.41       | 6.65     |

### 3.2. Fractal Dimension

The fractal dimension of cracks is a parameter describing the complexity of the crack network. For two-dimensional crack images, the fractal dimension  $D$  ranges between 1 and 2.

Figure 10 shows the variation in fractal dimension with moisture content under different drying-wetting cycle conditions. Among them, Figure 10(a1–a4) depict the changes in fractal dimension under 10 h lighting, while Figure 10(b1–b4) show the changes

under 5 h lighting. The images indicate that, regardless of lighting conditions, each new drying–wetting cycle causes the fractal dimension–moisture content curve to shift upward and leftward. The upward shift means that at the same moisture content, the fractal dimension of the cracks increases with more drying–wetting cycles. This shows that after experiencing drying–wetting cycles, the soil exhibits an irreversible increase in the complexity of its crack network under the same wet state. The leftward shift means that to reach the same fractal dimension, less drying is required in subsequent cycles. As shown in Figure 10(a1), during the first cycle, the moisture content needed to drop below 16% to achieve a fractal dimension above 1.75. By the next cycle, a similar fractal dimension could be reached with the moisture content only below 18%. This indicates that the damaged soil can develop a crack network as complex as that under previously high drying levels, but now under weaker drying conditions.

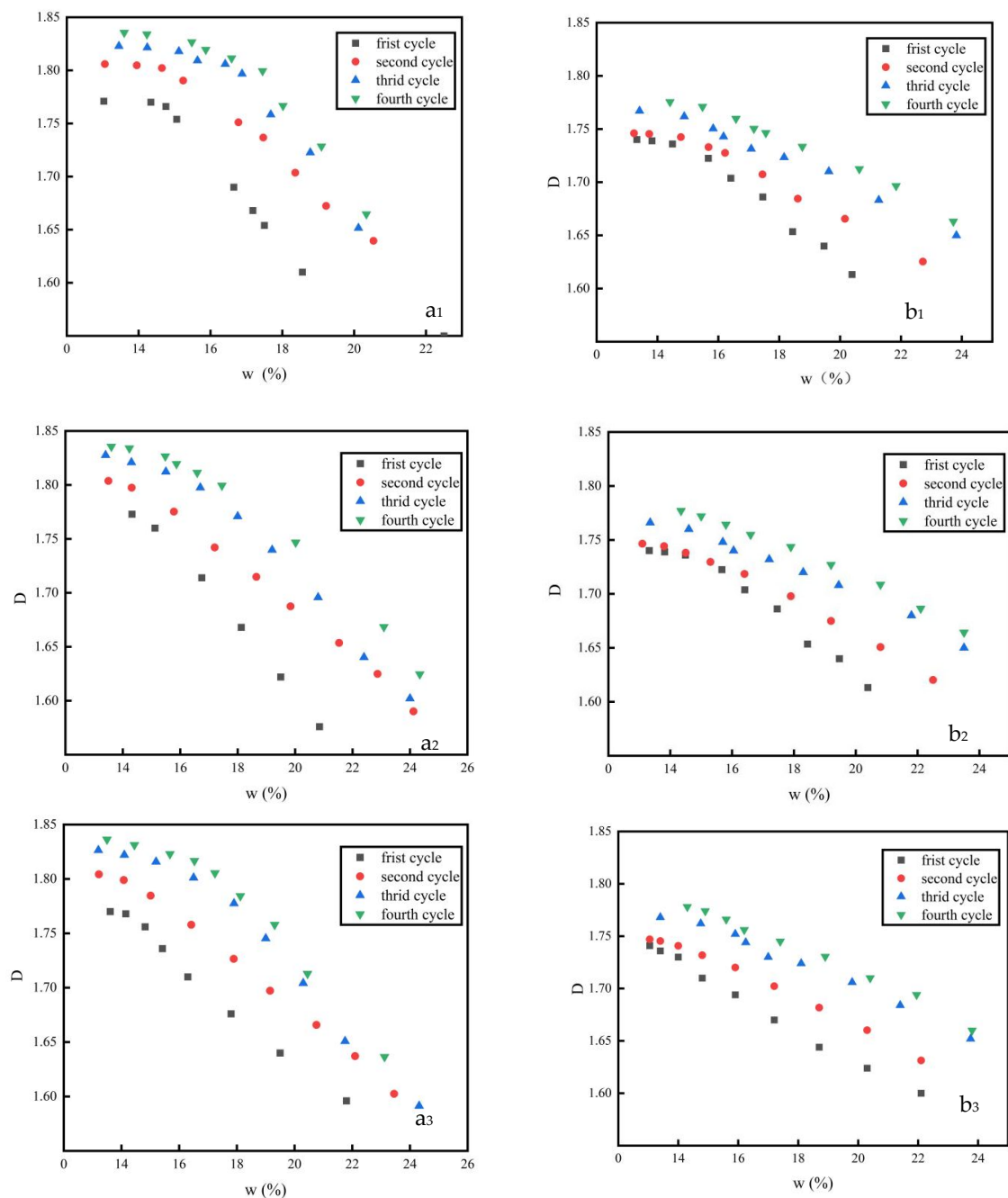


Figure 10. Cont.

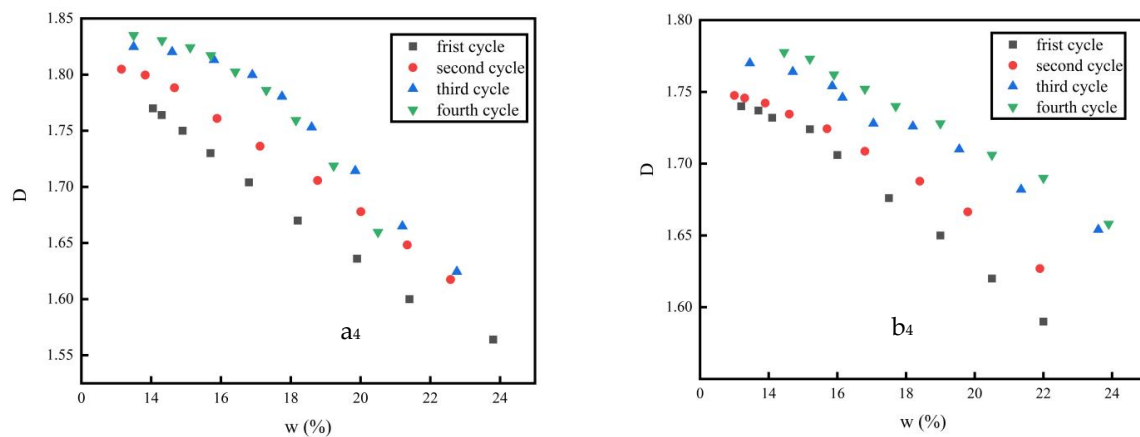


**Figure 10.** The relationship between fractal dimension and water content ((a1–a4) and (b1–b4) are the relationships between fractal dimension and water content under 10 h of illumination and 5 h of illumination, respectively).

Wetting–drying cycles do not cause intact soil to crack anew. In fact, each wetting process leaves behind residual cracks that cannot fully close. These residual cracks provide preset weak surfaces for crack development in the next cycle. As a result, new cracks not only propagate along existing ones but also generate more secondary branches as cycles proceed, causing the complexity of the crack network to accumulate across cycles. Light intensity has a significant yet limited promoting effect on crack development in loess: compared with low-intensity light (5 h/d), the fractal dimension under 10 h/d light increased on average by only about 1.5%. The effect of light is primarily reflected in the timing characteristics of crack development rather than the final degree of development—high-intensity light advances the cracking process, resulting in faster early growth.

### 3.3. Resistivity Changes

Resistivity serves as a comprehensive parameter reflecting the internal structure, moisture status, and pore-crack composition of soil. Under the influence of wet–dry cycles, variations in the resistivity of loess can effectively indicate changes in its structural integrity and internal moisture content. Figure 11 illustrates the evolution of shallow-layer resistivity in a loess column during crack development across different numbers of wet–dry cycles. Figures 12 and 13 represent the resistivity inversion profiles from shallow to deep layers of the soil column under the first to fourth wet–dry cycles, respectively.

Initially, the soil column was fully saturated, exhibiting uniformly low resistivity values below  $2 \Omega \cdot \text{m}$ . As drying began, the overall decrease in moisture content led to a gradual increase in resistivity. When shrinkage-induced tensile stress exceeded the soil's tensile strength, cracks began to form. Given that air-filled cracks have significantly higher resistivity than water-saturated soil, they appear as distinct high-resistivity anomalies in the electrical resistivity tomography inversion models.

As wet–dry cycles progressed, the vertical cracks continued to develop and gradually propagated through the soil column. The persistence and intensification of these cycles further promoted the extension and interconnection of cracks, resulting in an increasingly complex crack network. This microstructural evolution was consistently captured by the ERT monitoring, demonstrating its sensitivity to both moisture dynamics and structural changes in loess under cyclic hydraulic loading.

Figures 12 and 13 present the resistivity inversion images of the soil column in vertical and horizontal sections, respectively. As shown in Figure 12, vertical cracks developed primarily in the shallow to middle layers after the first wet–dry cycle. With increasing cycle numbers, these cracks gradually extended downward and eventually penetrated the

entire soil column. Following the initial wet–dry cycle, the soil column exhibited a distinct dry upper layer and wet lower layer profile, accompanied by localized high-resistivity anomalies. After one cycle, the soil column could be divided into three distinct layers: a dry surface layer, a dense intermediate layer, and a moist basal layer.

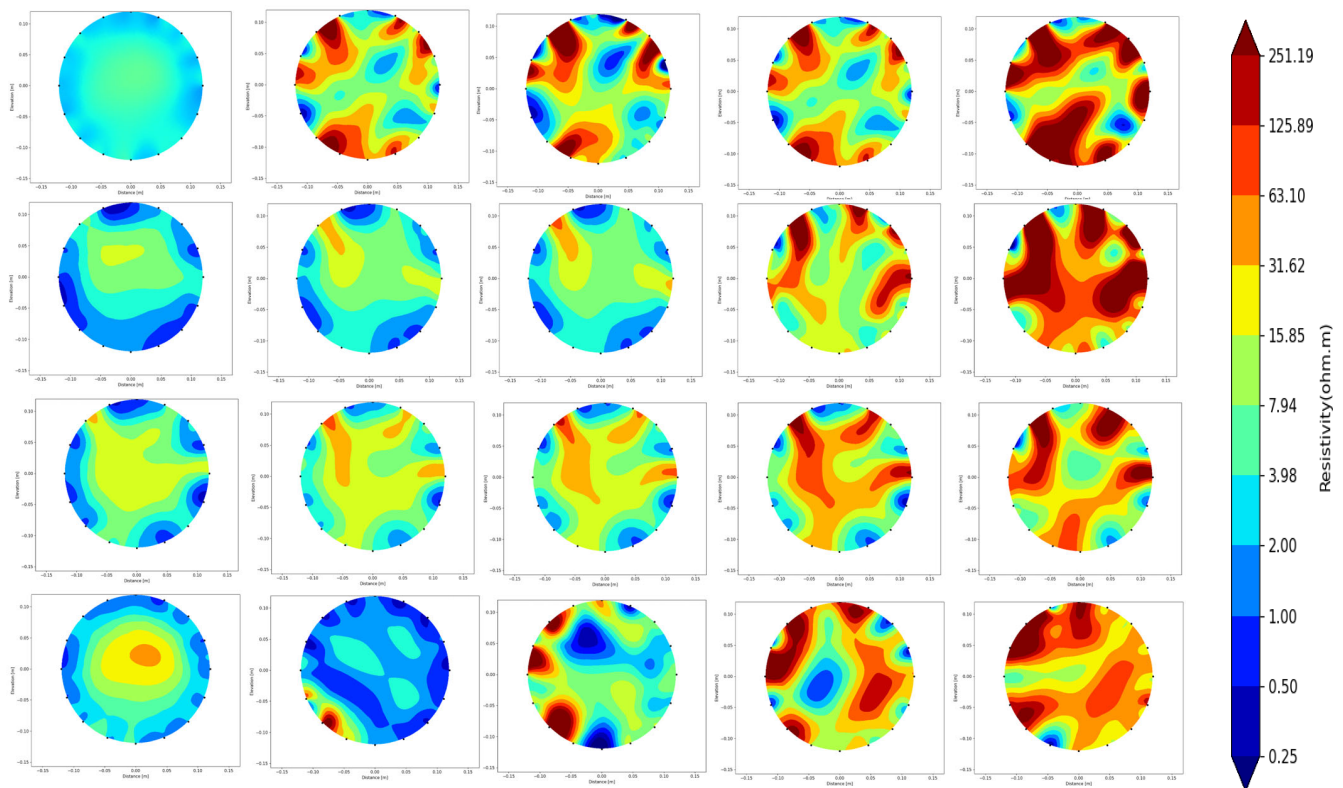


**Figure 11.** Crack inversion diagram of the 3 cm horizontal plane in the process of the dry–wet cycle. (Each small image in the picture has a virtual coordinate system with both horizontal and vertical axes corresponding to a length slightly larger than the diameter of a circular slice (15 cm). The corresponding color changes reflect the changes in resistivity, as shown in the color legend on the right side of the figure. Color note: The black dots in the picture indicate the positions where the electrodes are located in the horizontal layer).

Figure 13 is an inversion diagram of resistivity for crack development in soil columns (horizontal section) under different dry–wet cycle conditions. Based on the inversion diagram of horizontal fractures in the four soil layers shown in Figure 13, combined with Figures 11 and 12, the dry–wet cycle has a regular effect on the distribution of the loess resistivity field. With the increase of in the number of cycles, the high resistivity anomaly (resistivity  $> 150 \Omega \cdot \text{m}$ ) shows an obvious trend of deep expansion. In the first cycle, the high resistance anomaly is mainly concentrated in the shallow surface layer (0–10 cm) of the sample, with an average area ratio of 8.3% and a discrete distribution. During the second cycle, the anomalous area extends to the depth of 10–25 cm, the area of shallow anomalies increases to 15.7%, 5.2% of the anomalous areas appear in the middle and shallow layers, and some anomalous bodies show preliminary signs of connectivity. In the third cycle, the anomalous body further extends to the depth of 25–40 cm, forming a rudimentary vertical connected network. During the fourth cycle, the abnormal body completely penetrated into the deep layer of 40–55 cm, and the abnormal area of each layer increased significantly, forming a continuous high resistance channel through the sample.

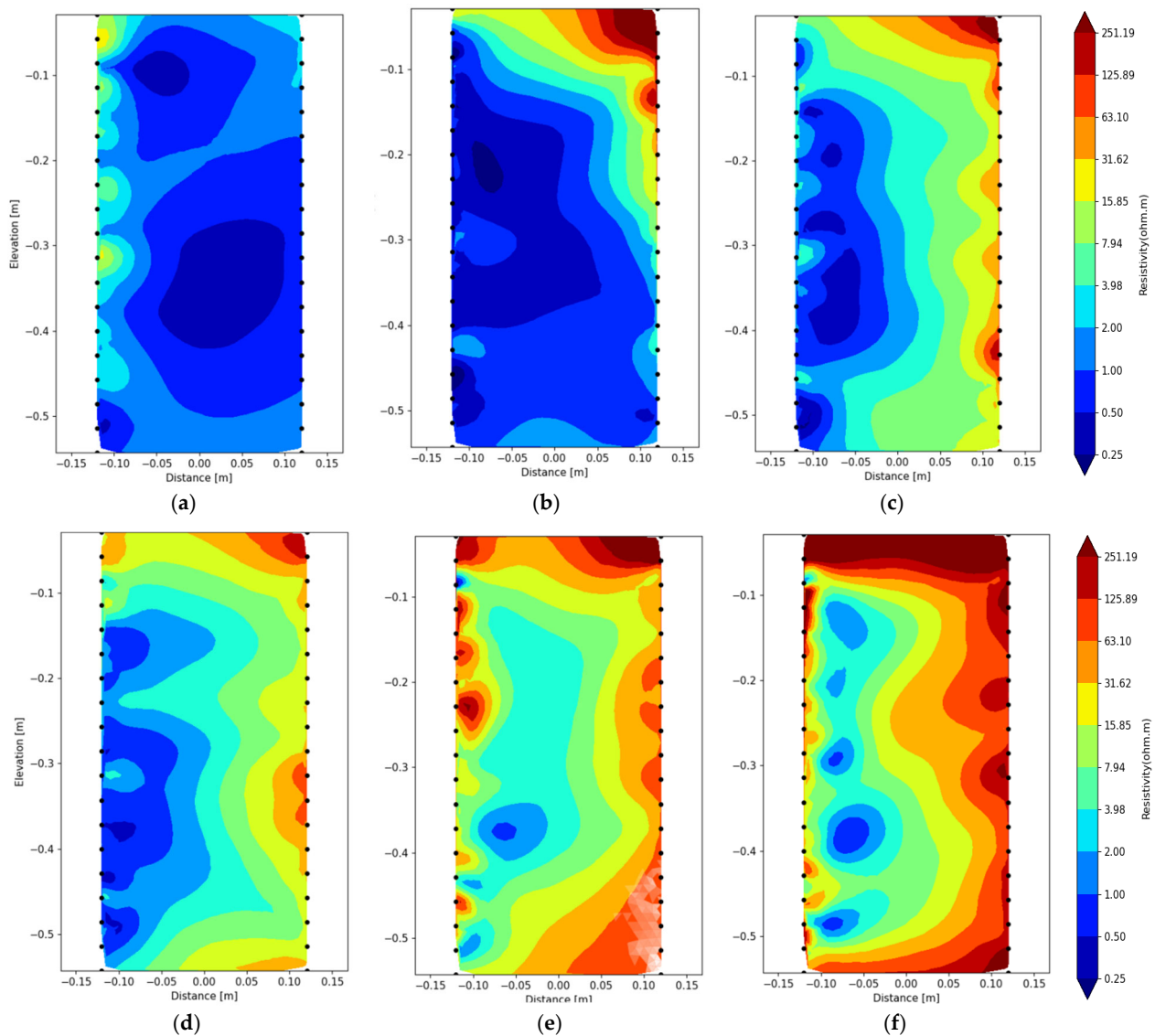


**Figure 12.** Vertical resistivity inversion diagram ((a) is the initial saturation state; (b) is the end of the first cycle; (c) is the end of the second cycle; (d) is the end of the third cycle; and (e,f) is the fourth cycle. Color note: The black dots in the picture indicate the positions where the electrodes are located in the vertical layer).

Figure 14 is a graph showing the changes in resistivity, crack width, and water content. As can be seen from Figure 14, the electrical resistivity of loess exhibits a significant multifactorial coupling relationship with moisture content, crack width, and light intensity. Moisture content is the dominant direct factor controlling resistivity, showing a negative power–function correlation ( $\rho = \rho = 1/w^{1.86} \times 1/(1 + 0.032 \text{ width})$ ). For every 10% increase in moisture content, resistivity decreases by 60–80%, with the most sensitive changes occurring in the low moisture content range ( $w < 15\%$ ). Crack width significantly enhances soil conductivity by providing additional pathways for electrical conduction, exhibiting a nonlinear influence. For every 2 mm increase in crack width, resistivity decreases by 20–40%, with the most pronounced effects observed in the moderate crack width range (4–6 mm). Light intensity indirectly affects resistivity by regulating the evaporation rate: strong light exposure (10 h/d) accelerates soil drying and crack development. Compared with moderate light exposure (5 h/d), it increases crack width by 9.0%, reduces resistivity by 17.4%, and accelerates damage progression during wetting–drying cycles.

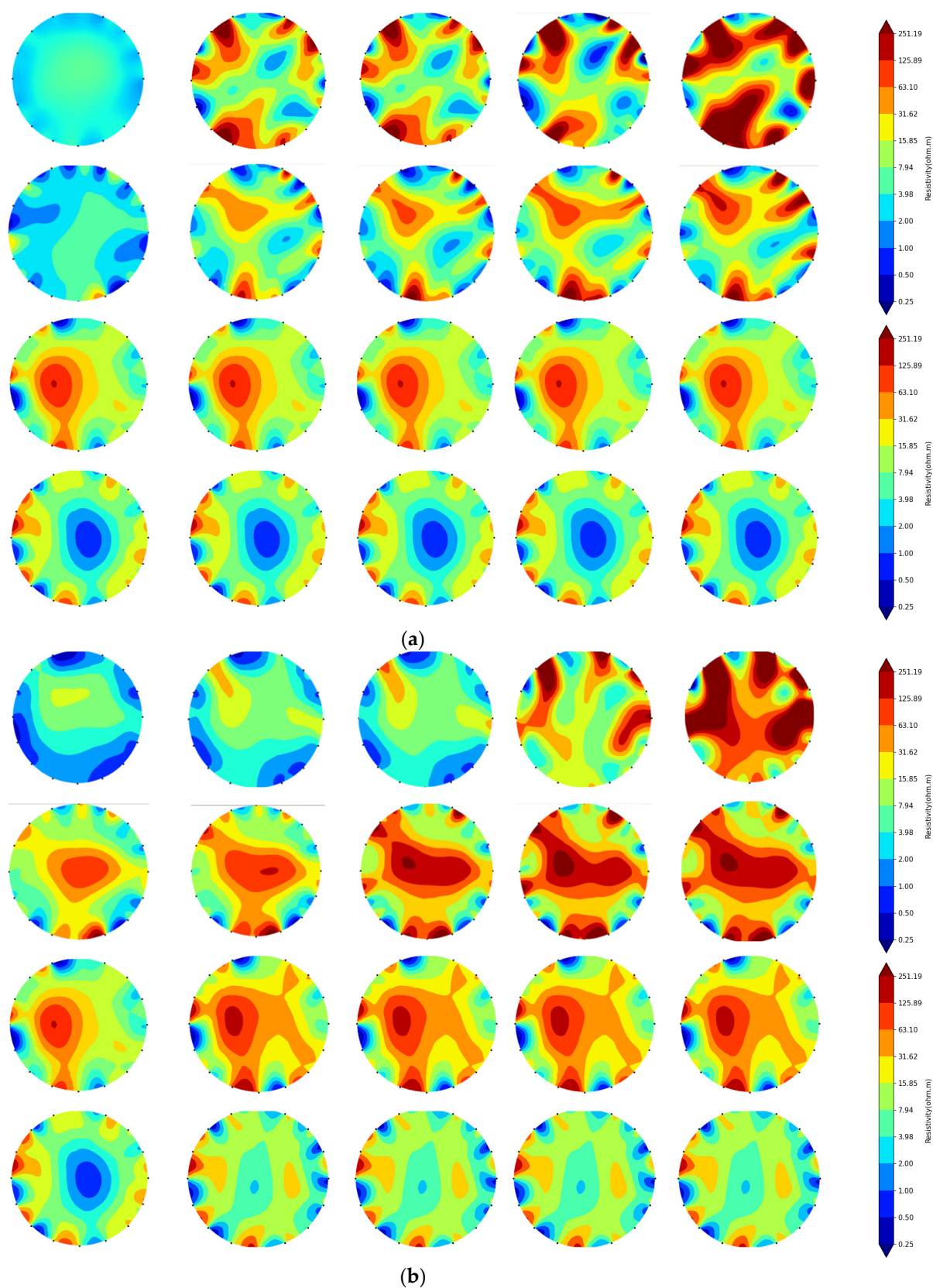


Figure 13. Cont.

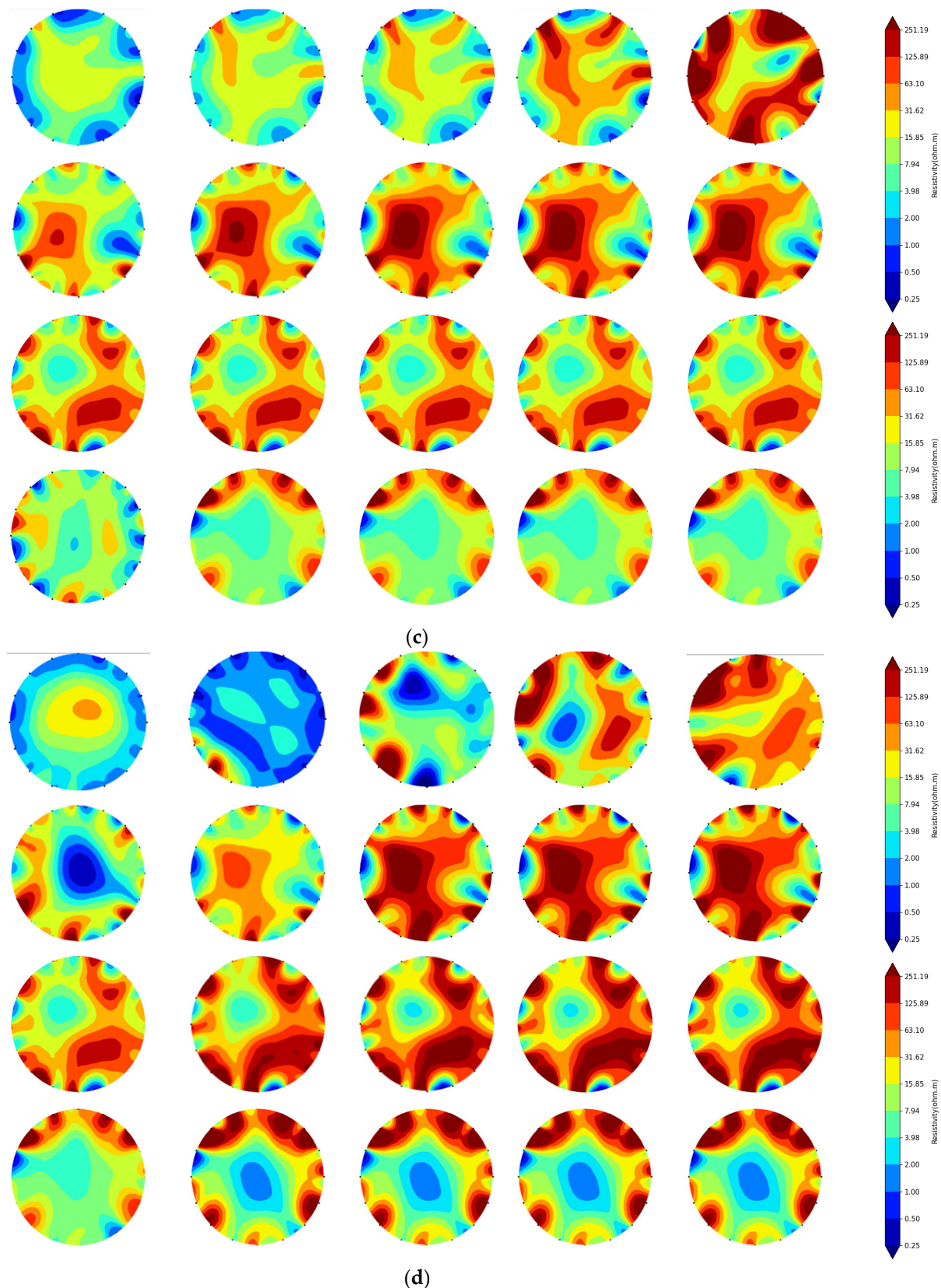


**Figure 13.** The resistivity inversion map of crack development of the soil column (horizontal section) under different dry–wet cycle conditions. ((a–d) are the first to fourth dry–wet cycles, respectively. Every four rows from top to bottom are the shallow to deep soil columns. Color note: The black dots in the picture indicate the positions where the electrodes are located in the horizontal layer).

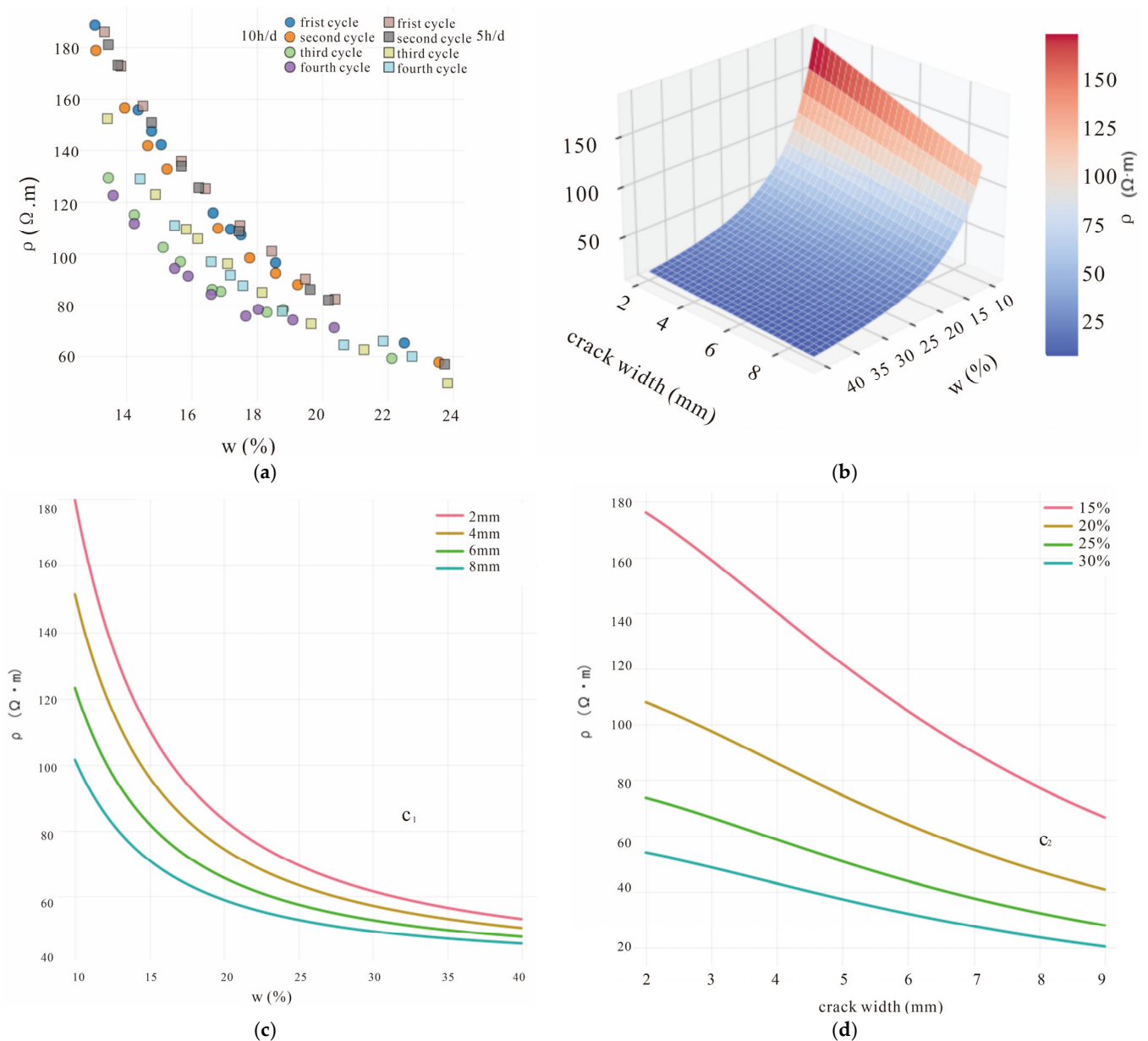


**Figure 14.** Resistivity and crack width, and water content change diagram ((a) Graph showing the variation of resistivity with water content under two light intensities under different dry-wet cycling conditions, (b) resistivity and crack width, and water content of the three-dimensional surface diagram, (c) variation in resistivity and water content under different crack width conditions, and (d) variation in resistivity and crack width under different water content conditions).

### 3.4. Rainfall Infiltration Recharge Changes

Figure 15 shows the variation in rainfall infiltration recharge coefficient and infiltration recharge depth with the number of dry-wet cycles under 10 h/d and 5 h/d light conditions. Under the condition of constant total rainfall (100 mm), the infiltration depth and infiltration coefficient of different cycles are different. The wetting-drying cycle significantly changed the infiltration characteristics of soil samples, and the degree of influence was positively correlated with the number of cycles. In the initial state (no wetting-drying cycle), the rainfall infiltration coefficient of the sample was only 0.44%, and the permeability was extremely low. This behavior is consistent with the dense structure of the undisturbed loess, and the water movement mainly depends on the slow matrix suction through the pore space.

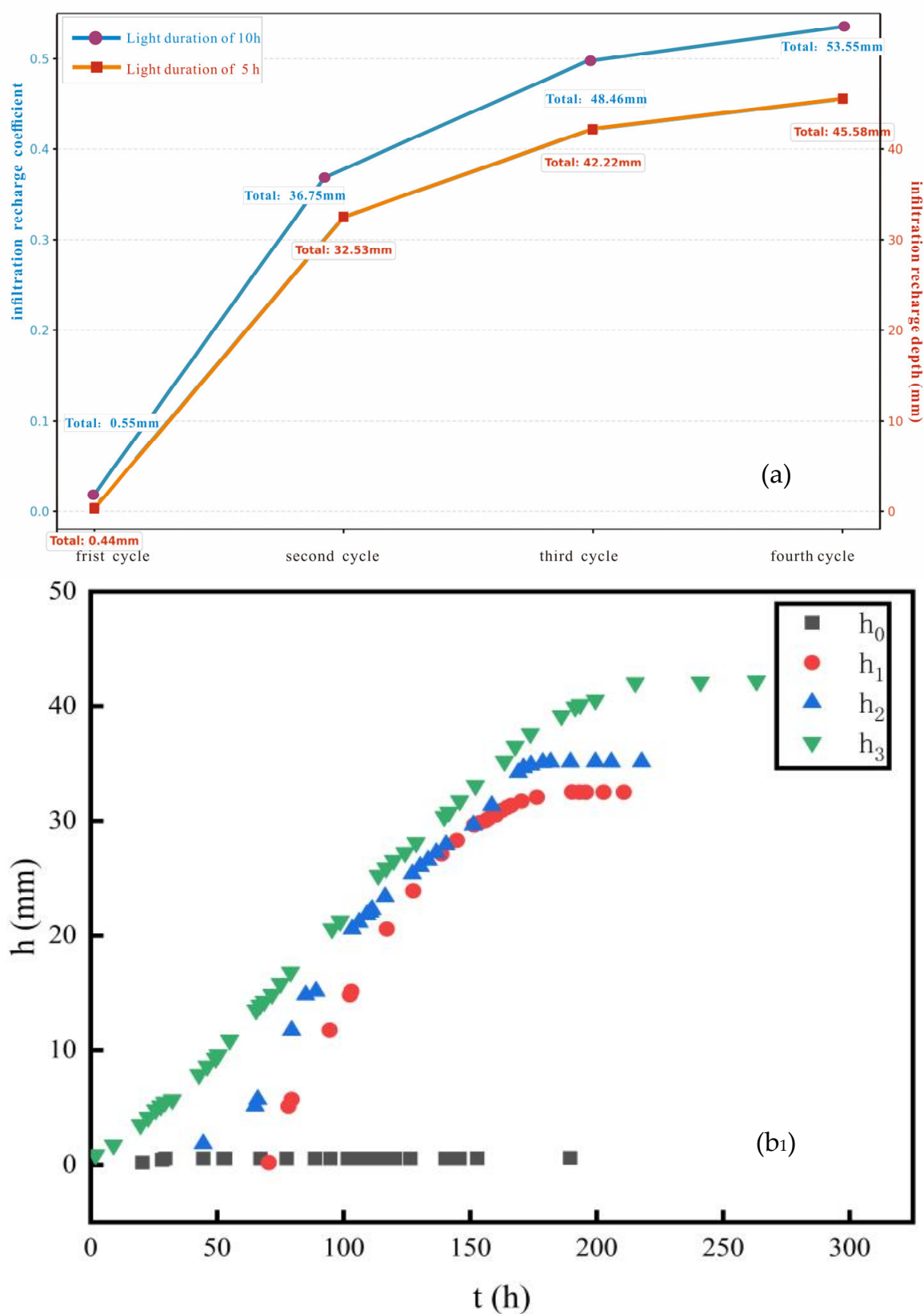


Figure 15. Cont.

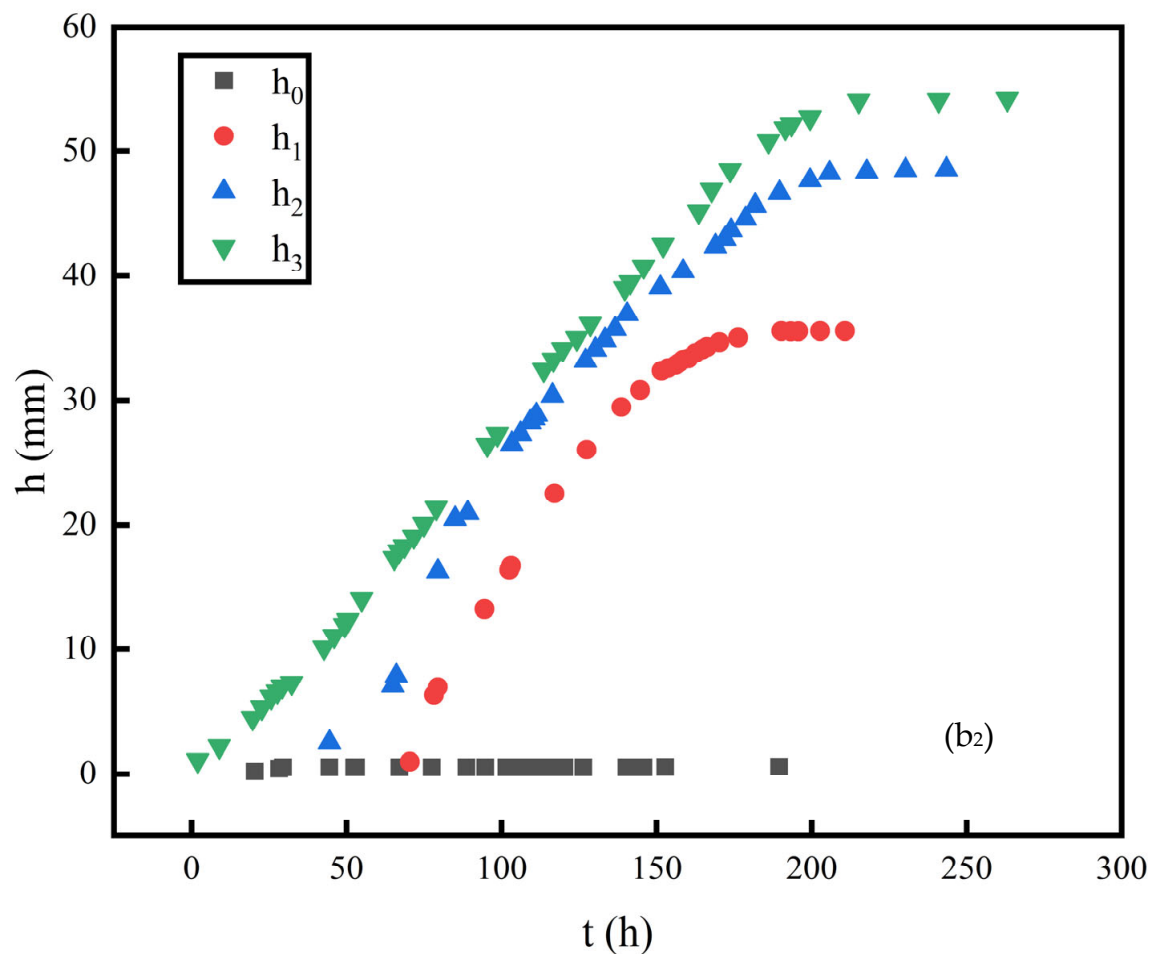


**Figure 15.** The variation in rainfall infiltration recharge coefficient and infiltration recharge depth with the number of dry–wet cycles under 10 h/d and 5 h/d light conditions. ((a) is the change in the rainfall infiltration recharge coefficient with the number of dry–wet cycles under 10 h and 5 h light duration, (b1) and (b2) are the changes in rainfall infiltration recharge depth with the number of dry–wet cycles under 5 h and 10 h light duration, respectively, and  $h_0$  to  $h_3$  are the rainfall infiltration recharge depths from the first cycle to the fourth cycle, respectively).

After the first drying–wetting cycle, micro-cracks began to form in the sample, leading to a preliminary increase in the infiltration coefficient. Following two cycles, a significant jump in infiltration performance occurred—the coefficient sharply rose from the initial 0.44% to 32.53%. In subsequent cycles (2nd to 4th), the infiltration coefficient continued to grow steadily: from 32.53% to 42.22%, and then to 45.58%. This gradual increase reflects continuous optimization of the crack network, involving both the expansion of existing cracks and the initiation of new ones, which together form a more complex water transport system. It is worth noting that starting from the third cycle, the growth rate of the infiltration coefficient slowed, indicating that the development of the crack network was gradually stabilizing.

Figure 15 is the outflow variation diagram under different dry–wet cycle conditions of two light intensities. As shown in Figure 15, outflow velocity calculated under the first cycle condition ranged from 0.0035 to 0.0147 mm/s, significantly lower than the 1 mm/s threshold commonly associated with rapid flow. This indicates that, under the experimental conditions, water movement in the soil occurred as low-velocity seepage rather than pipe flow. The transport mechanism is thus primarily governed by flow through soil matrix pores and the micro-crack network, consistent with the fundamental principles of Darcy’s law.

Figure 16 shows the changes in flow rate during four alternating dry-wet cycles under two different lighting conditions. As the number of cycles increased from one to four, the maximum pore flow velocity under the 5 h/d condition rose from 0.0035 mm/s to 0.3052 mm/s, an increase of nearly two orders of magnitude. This trend visually demonstrates the fundamental structural transformation of the loess induced by wetting–drying cycles: each cycle progressively accumulates damage, driving the development of the crack network from initiation through expansion and eventually resulting in a substantial enhancement of the soil’s equivalent permeability coefficient and hydraulic conductivity. Under the same number of wetting–drying cycles, increased illumination (10 h/d) systematically and significantly elevated the pore discharge rate. This light-amplification effect was consistently observed across the first to fourth cycles, with corresponding increases of 8.7%, 37.2%, and 28.4%.

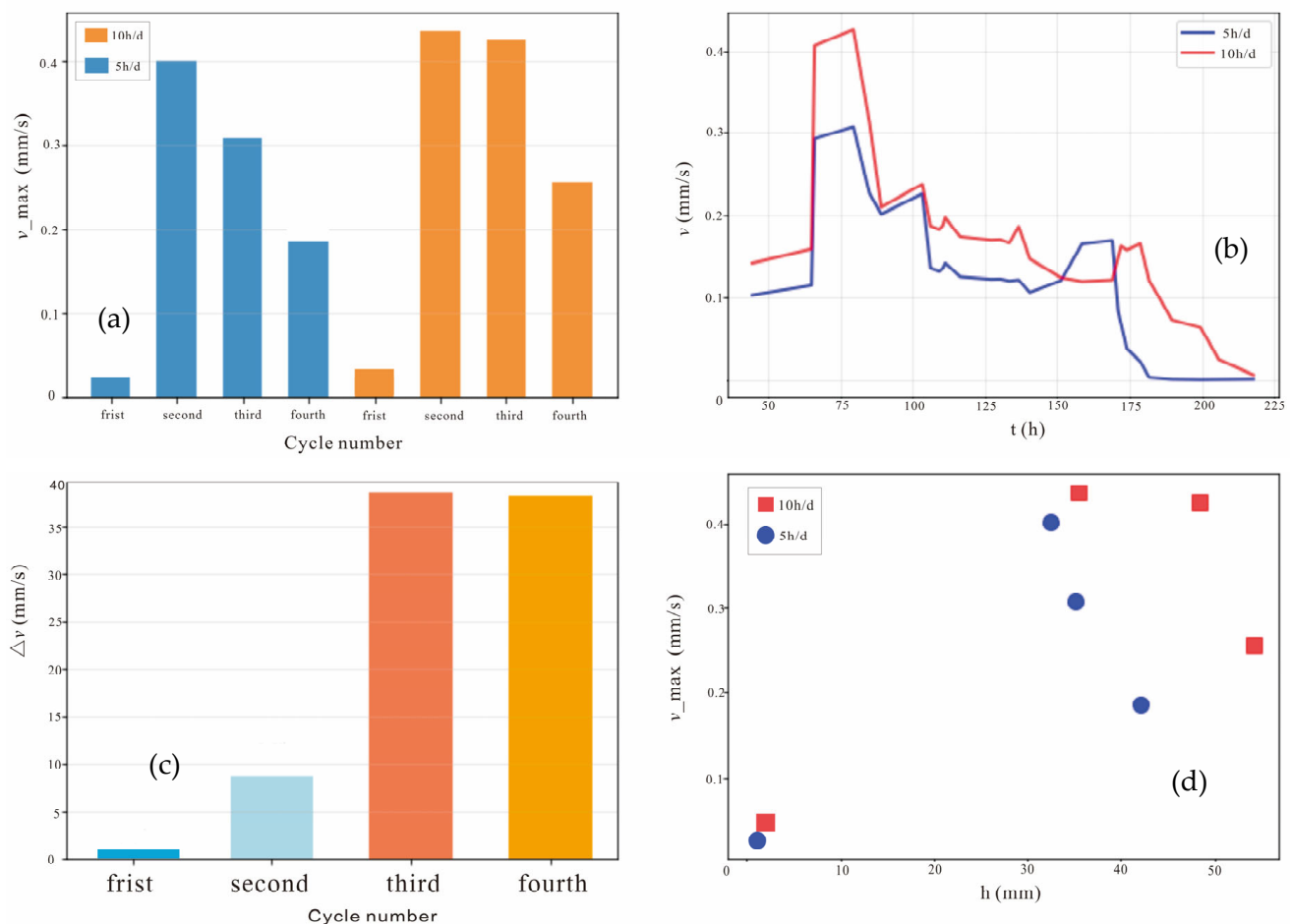


**Figure 16.** Outflow variation diagram under four wet–dry cycles under two different lighting conditions ((a) is a comparison chart of the maximum outflow velocity for four cycles; (b) illustrates the variation in outflow velocity with time during the third cycle under these two lighting conditions, (c) shows the rate of speed increase due to improved lighting conditions, and (d) depicts the relationship between outflow velocity and infiltration depth across the four cycles).

#### 4. Discussion

The selection of 10 h/d and 5 h/d light conditions was based on three main considerations. First, these conditions correspond, respectively, to typical high-intensity summer sunlight and moderate spring/autumn sunlight in real-world engineering contexts, providing clear environmental relevance. Second, the two-fold difference between them generates observable and significant experimental contrasts while avoiding excessive gradient com-

plexity. Third, this design effectively reveals how drying rate influences soil damage and resistivity evolution, thereby testing the core scientific hypothesis. Overall, this choice balances engineering representativeness, scientific rigor, and experimental feasibility.

As shown in Figure 8, the overall trend indicates that crack width continuously increases with decreasing moisture content under both 10 h and 5 h lighting conditions. In the 10 h group, as moisture content decreased from 22.5% to 13.03%, the crack width increased from 2.34 mm to 4.19 mm. During the high moisture content stage (e.g.,  $\omega > 18\%$ ), the crack width increased particularly sharply with decreasing moisture content. This suggests that intense evaporation drives rapid shrinkage strain, causing cracks to widen quickly in the early drying stage. The two datasets reveal different critical moisture content phenomena. Critical moisture content refers to the moisture level at which crack growth tends to stagnate and crack development stabilizes. In the 10 h group, crack width gradually stabilized within the moisture content range of approximately 14.5% to 13.0% (with width variation within 0.1 mm), indicating that soil shrinkage was nearly complete at this moisture level. In the 5 h/d group, this stabilization occurred earlier, roughly when moisture content dropped to about 14.5%, with no significant further increase in crack width. A possible mechanism for this difference is that intense lighting (10 h/d) creates a steeper moisture gradient inside the soil. The surface layer dries and hardens rapidly, forming a crust that partially inhibits further evaporation from deeper layers and limits full shrinkage expression. In contrast, weaker lighting (5 h/d) allows more uniform drying throughout the soil, enabling a more complete shrinkage process. Thus, the shrinkage limit is reached at a relatively higher overall moisture content.

A comparison between Figure 10 indicates that lighting duration significantly influences both the development rate and ultimate magnitude of cracking. Under 10 h lighting conditions, both the growth rate and final stabilized crack rate in all cycles were consistently higher than those in the 5 h group. Taking the fourth cycle as an example, by day 1, the crack rate in the 10 h group had already reached 6.88%, while that in the 5 h group was only 6.55%. At  $t = 4$ , the 10 h group (20.56%) substantially exceeded the 5 h group (12.07%). Comparing the final stabilized crack rates across all four cycles, the values for the 10 h group (15.52%, 21.36%, 24.58%, and 26.88%) were all markedly higher than those of the 5 h group (12.24%, 13.34%, 14.16%, and 15.26%). The intense moisture evaporation induced by stronger lighting not only leads to greater overall volumetric shrinkage but also tends to generate pronounced anisotropic shrinkage and localized stress concentration. These factors collectively contribute to the formation of a more complex and dense crack network, resulting in a higher final surface crack rate.

The data demonstrate that increased lighting exposure, and thus stronger evaporation, accelerates crack opening and propagation due to a more intense drying-shrinkage strain rate. Under 10 h/d lighting, from the first to the fourth cycle, not only did the crack ratio values increase, but the shape of the time-dependent curves also became progressively steeper. This suggests that the soil's crack response became more sensitive and severe as damage accumulated. In contrast, under 5 h lighting, although the curves shifted toward higher values in later cycles, their relatively gentle shape compared to the 10 h group remained. This indicates that milder drying conditions suppressed the expression of damage in a more abrupt manner.

Comparison of the last column in each cycle with the first column of the next cycle in Figure 11 indicates that high-resistivity cracks form preferential flow paths during wetting. Precipitation first fills the open surface cracks, causing the high-resistivity anomalies to transform into low-resistivity water, which appears as distinct low-resistivity zones in the ERT inversion images. This transition from high to low resistivity serves as direct evidence for identifying cracks and confirming their role as preferential flow channels. However, as

shown in Figure 10, moisture distribution exhibits strong spatial heterogeneity. In areas with crack development, preferential flow leads to extensive low-resistivity zones, while the underlying soil matrix remains relatively high-resistivity, forming a sharp contrast. Thus, it can be concluded that with an increasing number of drying–wetting cycles, the high-resistivity crack network during the drying phase becomes more complex and distinct, while during the wetting phase, the response of low-resistivity preferential flow channels becomes faster and affects deeper regions.

According to the change curve of resistivity and the parameters in Figure 14 and Table 5, the light intensity indirectly affects the resistivity by regulating the evaporation rate: strong light (10 h/d) accelerates soil drying and crack development. Compared with medium light (5 h/d), it can increase the crack width by 9.0%, reduce the resistivity by 17.4%, and accelerate the dry–wet cycle damage process. There is a significant interaction between the three factors: the influence of cracks is amplified at low water content, and the illumination effect is weakened at high water content. The most sensitive area appears in the range of 15–20% water content and 4–6 mm crack width.

**Table 5.** The contrast change table of crack width and water content and resistivity under 10 h/d and 5 h/d illumination conditions.

|       | Cycle | Average Moisture Content | Standard Deviation of Water Content | Average Crack Width (mm) | Standard Deviation of Crack Width | Average Resistivity ( $\Omega \cdot m$ ) | Maximum Resistivity | Minimum Resistivity |
|-------|-------|--------------------------|-------------------------------------|--------------------------|-----------------------------------|------------------------------------------|---------------------|---------------------|
| $d_1$ | 1     | 16.62                    | 2.65                                | 3.66                     | 0.58                              | 111.52                                   | 183.6               | 45.2                |
|       | 2     | 16.97                    | 3.06                                | 4.17                     | 0.79                              | 114.93                                   | 197.2               | 37.8                |
|       | 3     | 16.79                    | 2.50                                | 7.21                     | 1.37                              | 91.86                                    | 159.8               | 40.1                |
|       | 4     | 16.76                    | 2.09                                | 7.50                     | 1.42                              | 102.87                                   | 178.6               | 52.4                |
| $d_2$ | 1     | 16.61                    | 2.37                                | 3.12                     | 0.54                              | 93.51                                    | 152.9               | 47.6                |
|       | 2     | 17.20                    | 3.21                                | 3.33                     | 0.51                              | 93.98                                    | 159.7               | 36.5                |
|       | 3     | 17.81                    | 3.10                                | 5.60                     | 0.74                              | 72.18                                    | 142.7               | 30.8                |
|       | 4     | 18.35                    | 2.70                                | 5.50                     | 1.28                              | 73.37                                    | 143.5               | 38.5                |

Based on Figure 15, the rainfall infiltration recharge coefficient of the soil column increased from less than 1% in the first cycle to 33.53% in the second drying–wetting cycle. This sharp rise indicates a qualitative leap in infiltration capacity between the first and second cycles. The initial drying–wetting cycle critically damaged the intact loess structure, activating the soil’s permeability and creating initial crack pathways. The final infiltration depth after the third cycle ( $h = 35.1$  mm) exceeded that of the second cycle ( $h = 32.5$  mm), reflecting continued damage accumulation and further development of the crack network. The fourth cycle reached a significantly greater final infiltration depth ( $h = 42.2$  mm) than the previous cycles. The initial effect of temperature gradually became apparent, resulting in a 9.2% greater final infiltration depth under the 10 h/d condition compared to that under the 5 h/d condition. During the third cycle, the effect intensified sharply and peaked. Here, the final infiltration depth under 10 h/d (48.35 mm) was 37.6% greater than that under 5 h/d (35.15 mm). Meanwhile, the maximum infiltration rate increased by 40.2%, and the time required to reach 50% saturation depth was reduced by 25.0%. These findings suggest that soil structure enters a “most sensitive window period” in response to thermal driving forces. Over the following four cycles, the effect remained significant but receded from its peak, showing a depth increase of 28.6%.

However, its initial infiltration rate and mid-term depth were lower than those in the second and third cycles. This suggests that with increasing cycle numbers, not only the number and width of cracks changed, but also the spatial structural characteristics such as tortuosity and connectivity evolved. Early cycles may have generated numerous poorly connected cracks, causing moisture to encounter flow bottlenecks during mid-

term infiltration. After the fourth cycle, one or a few highly efficient preferential flow paths likely formed, extending deeply and allowing water to break through previous bottlenecks more effectively, thus achieving greater final depth. The permeability coefficient depends not on the total number of cracks, but on a few dominant flow pathways that fully penetrate the sample and exhibit the highest hydraulic conductivity. The first drying cycle generates numerous random cracks, many of which are initially disconnected. Subsequent wetting–drying cycles then promote the extension and interconnection of select cracks. After three to four cycles, dominant seepage pathways have become established and stabilized. Further cycling may only fine-tune these paths—for example, by widening certain cracks or allowing partial clogging by particles—without fundamentally altering the overall topology or hydraulic conductivity of the network. Consequently, the permeability coefficient plateaus, indicating that the system has reached a steady hydraulic state.

The above conditions are based on the artificial addition of 100 mm rainfall, revealing the maximum infiltration potential of the soil: under the condition of continuous water supply, water can fully enter and activate all potential seepage channels, including the deep dominant cracks formed after the dry–wet cycle transformation. Therefore, the infiltration depth and outflow rate measured in this study characterize the maximum hydraulic conductivity of loess samples under optimal water supply conditions. This condition is closer to the scenario of surface waterlogging caused by short-term heavy rainstorm in natural state. Therefore, the conclusions of this study are particularly applicable to the assessment of extreme rainfall events in loess areas. The water accumulation conditions ensure that the crack network jointly shaped by light and dry–wet cycles can be fully utilized, so that we can clearly capture and quantify the decisive impact of this structural transformation (such as 37% increase) on hydrological functions. In intermittent rainfall, this effect may be masked by insufficient water supply.

In summary, this experiment was designed to investigate the response of loess when the hydraulic driving force reaches the upper limit of water conductivity. The findings provide key parameters for assessing the safety of loess under the most unfavorable hydrological conditions. Future studies could further explore the critical conditions for the shift in infiltration patterns from matrix-dominated to preferential-flow-dominated by controlling the water supply intensity to simulate different rainfall intensities.

To explore the water distribution pattern during the development of soil column shrinkage cracks, this study simultaneously monitored the surface soil moisture content and shallow resistivity. The resistivity signal is influenced by crack development, temperature changes, and the comprehensive distribution of water within a certain detection depth, and there are physical scale differences compared to a single surface moisture content measurement point. Therefore, this study focuses on analyzing the synergistic and divergent relationships between the two in terms of temporal dynamic trends, and combines visual observations of crack development to qualitatively explain the mechanism. Future work will utilize a three-dimensional monitoring network and resistivity imaging technology to more accurately quantify the three-dimensional coupling relationship between cracks, water, and resistivity.

## 5. Conclusions

This study conducted four drying–wetting cycles on identical loess samples under two evaporation intensities. By combining crack image extraction with high-density resistivity monitoring, parameters including crack width, crack rate, fractal dimension, and resistivity were collected and analyzed. The main conclusions are as follows:

- (1) Wetting–drying cycles cause irreversible damage to loess. Cracks develop in stages with more cycles. They grow from isolated to connected and complex. Fractal

dimension rises significantly. Crack parameters relate clearly to cycle numbers. This confirms the cumulative, permanent damage.

- (2) Light duration strongly controls crack growth. Under the same cycles, 10 h light gave a 26.88% crack ratio, much higher than 15.26% at 5 h. More light also makes crack networks more complex. Fractal dimension increased by about 18%. Energy estimates show more light raises soil temperature by 5–9 °C. Higher temperature speeds up drying and stresses soil more. This widens cracks and improves water pathways.
- (3) Cracks change how rain enters loess. Water flows mainly through cracks, not evenly through soil. After four cycles, the infiltration coefficient jumped from 0.44% to 45.58%. This is over 100 times higher. Water moves fast along cracks, creating a short-cut effect.
- (4) The resistivity ( $\rho$ ) is sensitive to the water content ( $w$ ), crack width (width) and light-driven wetting–drying process. The relationship is  $\rho \propto (\rho = 1/w^{1.86} \times 1/(1 + 0.032 \text{ width}))$ . The resistivity in the low water content area ( $w < 15\%$ ) is extremely sensitive to the change in water content, while the medium crack width (4–6 mm) has the most significant enhancement effect on the conductive network. Light promotes the evolution of soil to the dangerous state of low resistivity and high water conductivity by aggravating the alternation of dry and wet.
- (5) Wetting–drying cycles and light work together nonlinearly. Cycles set the stage for cracking. Light makes the process faster and stronger. Together they cause a 37% peak risk rise in the second cycle.

In summary, wetting–drying and light jointly damage loess structure. Cracks form, change water flow, and increase outflow. This study quantifies the risk increase. It supports better hazard warning in loess areas.

**Author Contributions:** Methodology, G.Z. and S.C.; Software, Z.W.; Formal analysis, H.L.; Data curation, D.L.; Writing—original draft, C.Z., D.L., G.Z., S.C., H.L., Z.W. and X.L.; Writing—review and editing, C.Z. and G.Z.; Supervision, J.W. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** Author Jinna Wang was employed by the company Mineral Resources Exploration Center of Henan Geological Bureau. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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