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Research on the Influence of Typical Soil Parameters on Critical Breakdown Field Strength and Residual Resistivity Based on Discharge Topography[†]

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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). Abstract: Partial discharge of soil occurs when a lightning current enters the ground, and the strength of partial discharge is closely related to the magnitude of its critical breakdown field strength. Therefore, how to accurately obtain the variation law of the typical soil critical breakdown field strength and residual resistivity is the key to realizing the safe operation of the grounding devices and cables in the ground. This paper first selects a variety of typical soils to study the influence of various factors on the morphology of the discharge channel, and then studies the calculation methods of the soil critical breakdown field strength and residual resistivity under the introduction of different discharge channel morphologies and structures, and further discusses the reason why typical soil media factors have a small impact on the critical breakdown field. The experimental results show that under the same conditions, the critical breakdown field strengths of different soils from small to large are sand soil, loam soil and Yellow cinnamon soil. The largest ratio of residual resistivity to initial resistivity of the three soils is sand soil.

Keywords: discharge channel morphology characteristics; critical breakdown field strength; residual resistivity; X-ray imaging technology

1. Introduction

At present, people have carried out a lot of research on dielectric breakdown, lightning protection and grounding [1–12]. In the process of studying the mechanism of soil impact breakdown, determining the critical breakdown field strength *Ec* and residual resistivity ρ_{res} of the soil is a very important goal of the research work. This is because in any transient calculation model of grounding devices that considers soil discharge, the electrical parameters of soil discharge characteristics (critical breakdown field strength *Ec* and residual resistivity ρ_{res}) are important and critical parameters. Summarizing the current status of *Ec* research, the numerical values calculated by different scholars vary widely, ranging from 29 kV/m to 1850 kV/m [1,3,6,13–17]. The large difference in the calculation results is mainly due to the differences in the soil discharge models used when calculating the critical soil breakdown field strength. The reason is mainly due to the lack of a unified understanding of the real discharge area structure of the soil, so the soil discharge model used in the calculation is also different, resulting in such a big difference in the calculation

results. There are relatively few studies on the residual resistivity. In some studies, it is found that the resistivity of the soil discharge area has dropped significantly [4,11,16].

However, there are abundant soil types in the world, and various types of power facilities are distributed in different regions. Due to the different soil types, the impact discharge conditions of the soil around these facilities are also different. Therefore, it is not possible to simply use the impulse discharge characteristics of a certain type of soil to describe all impulse discharge characteristics. At present, most experiments on the research of soil impulse discharge use fine sand as simulated soil. However, there are differences between fine sand and actual soil, and the experimental results need to be improved. Some institutions have studied the comparison of impact characteristics of fine sand and red clay, which has certain reference significance, but the selected soil type is not sufficient [18]. At present, a large number of documents have studied the impact characteristics of grounding devices, and equivalently replaced them with some circuit models to obtain the value of impact grounding resistance or other parameters [19–25]. However, the number of articles on impulse discharge research on different soil types is relatively small, so it is necessary to study the impulse discharge characteristics of different typical soils.

The impact of soil discharge is related to many factors, the most important of which is the water content, salt content and density of the soil. When the values of the three parameters are different, the critical breakdown field strength and residual resistivity of the soil are different. Obtaining the minimum critical breakdown field strength of the soil has certain practical significance. Obtaining the influence of the three factors on the critical breakdown field strength and residual resistivity can better study the change law of them. At present, there are relatively few studies on the influence of these factors on the critical breakdown field strength and residual resistivity, so it is necessary to carry out relevant research.

In this paper, through the impulse current generator and the X-ray transmission imaging platform, relying on the three-dimensional reconstruction and inversion calculation methods, the influence of different typical soil media factors on the critical breakdown field strength and residual resistivity is studied, and the influence rules are analyzed. The soil breakdown mechanism is analyzed based on the experimental results.

2. Experimental Principle and Equipment

2.1. Impulse Current Generator

The schematic diagram of the soil impulse discharge observation platform based on X-ray digital imaging technology built in this paper is shown in Figure 1. The main equipment of the observation platform includes an impulse current generator (ICG) and an X-ray imaging system (XIS), which are connected by a time delay control unit (TDCU). The shortest exposure time of the X-ray machine is 1ms, and the impulse current wavelength is tens of microseconds, so TDCU is required to delay the triggering of the impulse current generator. When XIS is triggered, the TDCU unit gives ICG a delay signal to trigger the ICG to generate an impulse current. The delay accuracy of TDCU can reach the microsecond level, so the synchronous triggering of ICG and XIS can be guaranteed. The components of the ICG in Figure 1 are: voltage regulator T2, with a voltage regulation ratio of 380/45 kV; silicon stack rectifier D, with a maximum current of 1 A; capacitor bank C, with a capacitance value of $30 \,\mu\text{F}$; the values of wave modulating resistance R and inductance L are 6 Ω and 32.97 μ H, respectively; the current sensor CT has a maximum current capacity of 20 kA; VD is a voltage divider with a voltage division ratio of K = 691; a digital oscilloscope DSO with a sampling rate of 1.0 G samples/s and a bandwidth of 100 MHz; S is the ground electrode; ST is the sandbox. XRG is an X-ray generator; the model is MILLENNIUM (SEDECAL, Madrid, Spain); the shortest exposure time is 1 ms; the maximum output voltage is 150 kV; the output current is 500 mA; and the maximum output power is 80 kW. The digital flat-panel detector (FPD) uses Canon CXDI-50G (Canon Co., Ltd., Tokyo, Japan); the number of gray scales is 14-bit gray scale; the pixel size is

 160μ m; and the pixel size is 5.9 million. The image processing system PC is used to adjust the output parameters of the X-ray generator and display the imaging results.



Figure 1. Impulse discharge and X-ray imaging test wiring diagram.

2.2. X-ray Imaging System

The X-ray imaging system (X-ray image system, XIS) is mainly composed of X-ray source, imaging board, a control system and an image processing system. The function of the X-ray source is to provide X-rays with suitable and stable radiation quality and transmit X-rays to soil samples.

Based on the principle of X-ray digital imaging, when X-rays are uniformly incident, the X-ray absorption capacity of the electrode, the simulated soil sample and the discharge area are different, resulting in different doses of rays passing through different areas. The flat-panel detector receives different doses of X-rays, thereby presenting images with different gray values, as shown in Figure 2.



Figure 2. Schematic diagram of X-ray imaging of the soil discharge area.

Electrodes, discharge areas and simulated soil samples can be distinguished by different gray-scale images, which means that images of their discharge areas can be obtained by X-ray transmission imaging. The penetration thickness of X-rays depends on the nature of the penetrated medium and the power of the X-ray machine, according to Beer's law [26]

$$\frac{I}{I_0} = e^{-\mu_m \rho y} \tag{1}$$

where *I* is the amount of radiation after penetrating the substance, I_0 is the initial radiation amount of the X-ray machine, which depends on the power parameters of the X-ray machine itself, and μ_m is the attenuation coefficient of the soil. *y* is the thickness of the soil that can be penetrated, and the power of the X-ray machine is positively related to the thickness of the soil that can be penetrated.

The X-ray imaging board is also called a digital flat-panel detector. Its main function is to detect, collect and convert the digital signal of the X-ray irradiated on the detector. When the X-ray generated by the X-ray source is absorbed and attenuated by the soil sample, the remaining rays penetrate the soil and irradiate the digital flat-panel detector. The imaging board will convert the detected X-ray dose into a digital signal and transmit it to the image processing system, generating the corresponding gray-scale image after numerical operation. Based on the gray value information of different regions in the gray image, the condition of the discharge channel in the soil is obtained.

2.3. Preparation of Soil Samples

The type of experiment conducted in this manuscript is a small-scale simulation experiment carried out in the laboratory, so the soil samples need to be prepared using standardized methods during the experiment.

This article involves the preparation of three kinds of soils. The specific preparation steps of the three kinds of soils are as follows:

- 1. Separately screen and filter three kinds of soil with sufficient amounts to control the upper limit of the particle size of the three soils.
- 2. Add a sufficient amount of distilled water to the three types of soils, stir thoroughly until the salt in the soil is fully dissolved and when the natural precipitation is complete, pour out the water and measure the salt content with a refractometer. After repeating the same steps 6–9 times, when the salt content of the filtered soil exudate is less than 0.05%, it can be considered that the soil does not contain soluble salt.
- 3. Put the three kinds of soil into the drying box to dry. Each drying time is 5 h. After drying, take it out to measure its quality and make a record, until the difference between the two quality measurements is less than 0.5%, it is considered that the soil has been dried.
- 4. Configure the soil with different parameters according to the needs of the experiment.

3. Introduction to the Calculation Method of Discharge Channel Morphology and Characteristic Parameters

According to the principle of X-ray imaging, the electrode, as a solid metal, has the largest attenuation coefficient to X-rays, so it can absorb the most X-rays, and the place corresponding to the electrode has the highest gray value, showing a white image. The soil attenuation ability is inferior to the electrode and stronger than the discharge area, and its gray value will be somewhere in between. The discharge area has the weakest X-ray absorbing ability. The more X-rays pass through, the lower the gray value of the corresponding place and the black image is. The three views of the discharge channel are shown in Figure 3.



Figure 3. Three views of discharge channel.

According to Figure 3, on the basis of the known three views of the soil discharge channel, a three-dimensional reconstruction of the soil discharge channel is carried out, and the reconstructed model is exported to finite element simulation software. There is a more detailed description of this type of model by Luo et al. [27]. Figure 4 shows the model after three-dimensional reconstruction.



Figure 4. Three-dimensional reconstruction model.

The software used for simulation calculation is COMSOL Multiphysics 3.5a (COMSOL Inc., Stockholm, Sweden).

In this paper, the injected impulse current amplitude is 2.0 kA under the simulated test conditions, and the impulse voltage test measurement value is 23.5 kV. Using the method proposed in this section to combine the three-dimensional morphology of the discharge area with the finite element method, set the soil residual resistivity is 7% ρ_0 in the discharge area. The voltage value of the electrode injection point can be calculated by using the finite element method. After a certain step length iteration, the voltage calculated value and the actual measured value can be within the allowable 1% error range, then the value at this time is the convergence value.

When the soil residual resistivity is iterated to 000362% ρ_0 , the impulse voltage simulation calculation value is 23.4 kV, and the error is 0.5%, which meets the allowable error requirements. At this time, take the average value of the field strength in the discharge area as the critical breakdown field strength value of 216.21 kV/m as the soil critical breakdown field strength value under the set of test conditions.

4. The Influence of Medium Factors on the Critical Breakdown Field Strength

Studies have shown that the soil water content, salt content and soil density have an impact on the value of soil critical breakdown field strength. In addition, different soils have different properties and their influence laws are also different. Therefore, in this section, we study the variation of the critical breakdown field strength of different typical soils under the conditions of different water content, salt content and Soil density.

4.1. The Influence Law of Water Content on Ec

In order to study the influence of the water content of sandy soil, loam soil and Yellow cinnamon soil on the electrical parameters of soil discharge characteristics in the laboratory, this paper, according to the actual situation, maintains the soil salt content at 0.5% and the soil density at 1.250 g/cm³, and the water content is 3%, 5%, 7%, 9%, 11%, 13% and 15% of simulated soil samples, which were subjected to an impulse current with an amplitude of 2.0 kA. Soil moisture content refers to the ratio of the quality of water in the soil to the quality of dry soil [28,29]. The electrode used in the simulation experiment is a vertical electrode with a diameter of 3 mm and a length of 10 cm, and the following experimental electrodes maintain this parameter. Through an inversion calculation, we can obtain the law of three kinds of soil critical breakdown field strength with water content, as shown in Figure 5.



Figure 5. The influence of water content on the critical field strength of soil breakdown.

It can be seen from Figure 5 that under the condition of 3–15% water content, the three types of soil critical breakdown field strengths all show a trend of first decreasing and then increasing and finally becoming saturated with the increase in soil water content. The critical breakdown field strength of sandy soil varies between 161 kV/m~251 kV/m, the critical breakdown field strength of loam between 175 kV/m~268 kV/m and the critical breakdown field strength of Yellow cinnamon soil varies between 195 kV/m~278 kV/m. Additionally, under the same soil medium conditions, the relationship between the critical breakdown field strengths of the three soils is: *Ec* of sandy soil < *Ec* of loam soil < *Ec* of Yellow cinnamon soil.

The law of the critical breakdown field strength of sandy soil, loam soil and Yellow cinnamon soil with water content is as follows:

- 1. When the soil water content is between 3% and 7%, due to the increase in the water content, the salt in the soil is dissolved into conductive ions, which enhances the conductivity of the soil, and the critical breakdown field strength decreases with the increase in the water content.
- 2. When the water content is between 7% and 11%, as the soil water content further increases, the salt has been fully dissolved. At this time, as the water content increases, the soil ion concentration decreases, the soil conductivity becomes weak and the critical breakdown field strength increases.
- 3. When the water content exceeds 11%, *Ec* gradually becomes saturated, and the critical breakdown field strength tends to be stable with the change in water content.

4.2. The Influence Law of Salt Content on Ec

In order to study the influence of salt content on *Ec*, on the basis of maintaining soil water content of 5% and soil density of 1.250 g/cm^3 , the salt contents were 0.1%, 0.3%, 0.5%, 0.7% and 1.0%, respectively. The impulse current with an amplitude of 2.0 kA was applied to the three soil samples. Through inversion calculations, we can acquire three kinds of soil critical breakdown field strengths with salt content, as shown in Figure 6.



Figure 6. The influence of salt content on the critical breakdown field strength of soil.

In the case of 0.1~1% salt content, it can be seen from Figure 6 that the critical breakdown field strengths of sand, loam and Yellow cinnamon soil are between 207 kV/m~254 kV/m, 215 kV/m~264 kV/m and 225 kV/m~274 kV/m. As the salt content increases, the *Ec* of the three soils all show a change situation that first decreases and then tends to saturation. Additionally, under the same soil medium conditions, the relationship between the critical breakdown field strengths of the three soils is: *Ec* of sandy soil < *Ec* of loam soil < *Ec* of Yellow cinnamon soil.

The critical breakdown field strength of sandy soil, loam soil and Yellow cinnamon soil changes in the same way with the salt content, and the details are as follows:

- 1. When the salt content is between 0.1% and 0.5%, due to the unsaturation of salt dissolution, as the salt content increases, the dissolved ions in the solution increase, the soil conductivity increases and the soil critical breakdown field strength decreases.
- 2. When the salt content continues to increase, because the dissolution has reached saturation, as the salt content increases, the conductivity of the solution does not change. Therefore, in this interval, as the salt content increases, the critical breakdown field strength no longer has significant changes.

4.3. The Influence Law of Soil Density on Ec

In order to study the influence of soil density on the electrical parameters of soil discharge characteristics, according to actual conditions, on the basis of maintaining a soil water content of 5% and a salt content of 0.5%, the soil density samples are 1.042 g/cm^3 , 1.145 g/cm^3 , 1.250 g/cm^3 , 1.354 g/cm^3 and 1.458 g/cm^3 , respectively. Since the volume of the experimental sandbox selected in the experiment is fixed, the density of the soil can be changed by changing the quality of the soil filled in the sandbox of a fixed volume. After the above-mentioned soil density is normalized, the soil density can be expressed as: 1.0, 1.1, 1.2, 1.3 and 1.4. Applying an impulse current with an amplitude of 2.0 kA, through the inversion calculation, the variation law of the soil critical breakdown field strength with the salt content can be obtained, as shown in Figure 7.



Figure 7. The influence of soil density on the critical breakdown field strength.

It can be seen from Figure 7 that when the soil density is 1~1.4, the critical breakdown field strengths of sandy soil, loam soil and Yellow cinnamon soil are 122 kV/m~240 kV/m, 128 kV/m~252 kV/m and 146 kV/m~268 kV/m, respectively. The soil density has a significant effect on the critical breakdown field strength. As the soil density increases, the *Ec* of the three soils gradually increases. Additionally, under the same soil medium conditions, the relationship between the critical breakdown field strengths of the three soils is: *Ec* of Yellow cinnamon soil < *Ec* of loam soil < *Ec* of sandy soil.

The variation law of the critical breakdown field strength of sandy soil, loam soil and Yellow cinnamon soil with soil density is as follows:

- 1. When the soil density is between 1 and 1.2, as the soil density increases, the soil becomes denser, and the gap between the particles in the soil is smaller, so that it is less likely to break down. Therefore, in this area, the soil is critically broken down The field strength increases as the tightness increases.
- 2. With the further increase in soil density, although the critical breakdown field strength continues to increase, its influence weakens, and the increasing trend of the critical breakdown field strength slows down.

It can be seen from Figures 5–7 that under the same soil parameter conditions, the magnitude relationship of the critical breakdown field strength value is: Ec of Yellow cinnamon soil < Ec of loam soil < Ec of sand soil.

4.4. Analysis of the Influence of Three Factors on the Critical Breakdown Field Strength

Soil is a complex mixture composed of three-phase media of gas, liquid and solid. The particle size of different soils is different. This factor will affect the content of water and air in the gaps between soil particles. The internal structure of the three soils is different. There are many clay particles in the loam soil and Yellow cinnamon soil, which can bond the surrounding soil particles to form larger particles [18]. The breakdown voltage between water, air and solid is: air < water < solid. Therefore, in the process of soil breakdown, water and solids can be regarded as insulators relative to air, and air can be regarded as conductors. However, in an unbreakable soil medium, the conductivity of water is greater than that of air. Therefore, whether it is broken down or not, soil particles are regarded as dielectrics, and air and water are regarded as conductors according to breakdown and non-breakdown, respectively.

When the impulse current flows into the soil, due to the conductivity of the water, a certain amount of leakage current flows through the water, so that the internal temperature of the soil rises rapidly. The temperature rise causes the air molecules in the soil to thermally

dissociate, and electron jumps are formed under the action of the external electric field, which causes the soil to break down.

When the salt content and soil density are constant, at the beginning, the water content and the leakage current are small, so less heat is generated. At this time, a larger voltage is required to make the soil break down. In the process of increasing water, the leakage current in the soil increases, and the temperature rises rapidly, which promotes the thermal dissociation of the air and forms electron jumps to break down the soil. Therefore, the critical breakdown field strength decreases with the increase in water content. When the water content continues to increase, as the water content in the soil voids gradually increases, under the same voltage, the leakage current increases, and the current is more likely to be discharged in the form of a diffuse current rather than spark discharge. Therefore, with the increase in the water content at this time, the critical breakdown field strength of the soil gradually increases.

When the water content and soil density are constant, as the salt content increases, the ion concentration and the leakage current increase, so that the heat generated in the soil is higher, which promotes the thermal dissociation of air gap molecules, thereby promoting the formation of the electronic bounce. However, after the salt content increases to a certain level, the ion concentration no longer increases, and the critical breakdown field strength no longer drops significantly.

When the water content and salt content remain unchanged, the increase in soil density will reduce the water and air content per unit volume, thereby greatly reducing the content of conductive substances per unit volume, so the soil critical breakdown field strength increases.

It can be seen from Figures 5–7 that, compared with water content and soil density, salt content has the lowest impact on the critical breakdown field strength, because its impact is only the single factor of soil ion concentration. Compared with the water content, the maximum and minimum difference of the critical breakdown field strength caused by soil density is about 125 kV/m in this experiment, and under the water content factor, the maximum and minimum difference of the critical breakdown field strength is only 95 kV/m, so the soil density has the greatest impact on the critical breakdown field strength.

5. The Influence of Medium Factors on Residual Resistivity (ρ_{res})

For the residual resistivity of the soil discharge area, the general concern is its relationship with the initial resistivity of the soil, and the initial resistivity of the soil is affected by the soil water content, salt content, soil density and soil types. Therefore, this chapter starts from the perspective of soil initial resistivity changes, and comprehensively considers the influence of water content, salt content, and soil density on the relationship between ρ_{res} and initial resistivity ρ_0 under different soil conditions.

5.1. The Influence of Water Content on ρ_{res}

In order to study the influence of water content of sandy soil, loam soil and Yellow cinnamon soil on soil ρ_{res} , this paper, according to the actual situation, maintains a soil salt content of 0.5% and soil density of 1.250 g/cm³, and the water content is 3%, 5%, 7%, 9%, 11%, 13% and 15%, respectively. Simulated soil samples were subjected to an impulse current with an amplitude of 2.0 kA. The electrode used in the simulation experiment is a vertical electrode with a diameter of 3 mm and a length of 10cm, and the following experimental electrodes maintain this parameter. Through inversion calculations, we can obtain three kinds of soil residual resistivity changes with water content, as shown in Figure 8.



Figure 8. The influence of water content on ρ_{res} under different soil types.

As shown in Figure 8, the ρ_{res}/ρ of the three soils all increase with the increase in soil water content, and the relationship between the maximum values of the ρ_{res}/ρ of the three soils is Yellow cinnamon soil ρ_{res} < loam soil ρ_{res} < sandy soil ρ_{res} .

5.2. The Influence of Salt Content on ρ_{res}

In order to study the influence of salt content on ρ_{res} , on the basis of maintaining a soil water content of 7% and soil density of 1.250 g/cm³, the salt content was 0.1%, 0.3%, 0.5%, 0.7% and 1.0%, respectively. Impulse currents with amplitude of 2.0 kA are applied to the three soil samples. Through inversion calculations, the change rule of the residual resistivity of the three soils with the salt content can be obtained, as shown in Figure 9.



Figure 9. The influence of salt content on ρ_{res} under different soil types.

As shown in Figure 9, the ρ_{res}/ρ of the three soils all increase with the increase in soil salt content, and the relationship between the maximum values of ρ_{res}/ρ of the three soils is Yellow cinnamon soil ρ_{res} < loam soil ρ_{res} < sandy soil ρ_{res} .

5.3. The Influence of Soil Density on ρ_{res}

In order to study the influence of soil density on soil ρ_{res} , according to actual conditions, on the basis of maintaining a soil water content of 7% and salt content of 0.5%, the simulated

soil density is 1.042 g/cm³, 1.145 g/cm³, 1.250 g/cm³, 1.354 g/cm³ and 1.458 g/cm³, and the normalized soil density can be expressed as: 1.0, 1.1, 1.2, 1.3 and 1.4. Since the volume of the experimental sandbox selected in the experiment is fixed, the density of the soil can be changed by changing the quality of the soil filled in the sandbox of a fixed volume. Applying an impulse current with an amplitude of 2.0 kA, through inversion calculations, the residual resistivity of the soil can be obtained with the change in the soil density, as shown in Figure 10.



Figure 10. The influence of soil density on ρ_{res} under different soil types.

As shown in Figure 10, the ρ_{res}/ρ of the three soils all increase with the increase in soil density, and the relationship between the maximum values of ρ_{res}/ρ of the three soils is Yellow cinnamon soil ρ_{res} < loam soil ρ_{res} < sandy soil ρ_{res} .

5.4. Analysis of the Influence of Three Factors on Residual Resistivity

The graphical results of the analysis show that within the experimental conditions of this paper, with the increase in water content, the ρ_{res}/ρ of the three soils gradually increases. The range of ρ_{res}/ρ for sandy soil is between 0.007 and 0.120, for loamy soil it is between 0.001 and 0.129, and for Yellow cinnamon soil it is between 0.015 and 0.099. Analyzing the reason, as the water content increases, on the one hand, water increases the conductivity of the soil, and on the other hand, the increase in water content enables the salt in the soil to be fully dissolved. Therefore, the resistivity of the soil gradually decreases, and ρ_{res}/ρ gradually increases.

Similarly, when the salt content of sandy soil, loam soil and Yellow cinnamon soil changes, the range of ρ_{res}/ρ is 0.021~0.0735, 0.012~0.066 and 0.018~0.064. The increase in salt content increases the amount of dissolved salt in the soil, which makes the initial resistivity of the soil decrease, and ρ_{res}/ρ gradually increases.

With the increase in soil density, the range of ρ_{res}/ρ of sandy soil, loam soil and Yellow cinnamon soil was 0.047~0.085, 0.033~0.08, 0.04~0.0695. The increase in soil density means that the contact between soil particles is closer, the gap between soil particles will decrease, and the soil resistivity will increase. Therefore, it will be more difficult to generate discharge channels in the soil, so ρ_{res}/ρ will gradually decrease.

6. Analysis of Soil Impact Breakdown Mechanism

Based on the existing research results, it can be analogous to the air breakdown mechanism to explain the impact breakdown mechanism of the soil as follows:

- 6.1. "Electron Avalanche-Streamer Discharge-Pilot Discharge" Process
- 1. Electron avalanche stage: When using rod-plate electrodes, the electric field distribution between the electrodes is uneven. The maximum field strength of this uneven electric field appears near the vertical electrode with a small radius of curvature. Under the same conditions without the radius of curvature, the smaller the electrode curvature radius, the greater the maximum field strength, and the more uneven the electric field distribution. The free electrons existing in the soil near the vertical electrode are continuously accelerated along the direction of the electric field under the action of the electric field and they accumulate kinetic energy. When the voltage applied across the electrode reaches a certain value, the electric field near the vertical electrode provides free electron kinetic energy equal to or greater than the free energy of air molecules in the soil particle gap, and even the free energy of soil particle molecules, resulting in air molecules or the soil particle molecules split into electrons (or negative ions) and positive ions. The new electrons generated at this time, like the original free electrons, obtain kinetic energy from the electric field, and continue to move toward the positive electrode of the electric field to cause more collisions and dissociation, forming an initial electron avalanche.
- 2. Streamer discharge: With the continuous development of electronic avalanche, the number of electrons, negative ions and positive ions in the avalanche increases sharply with the distance of the development of the electronic avalanche. Due to the smaller mass of electrons, the acceleration obtained from the electric field is much greater than that of positive ions. Therefore, when electrons move quickly to the positive electrode, the positive ions slowly move to the negative electrode, and the positive ions can be considered to be static relative to the electrons. When the electron avalanche continues to develop toward the positive electrode, the positive ions remaining in the negative electrode act as positive space charges to distort and strengthen the electric field around the negative electrode, thereby emitting a large number of photons to the surroundings. These photons in turn cause the nearby molecules to undergo a process of light dissociation, generating secondary electrons. These secondary electrons form a new secondary electron avalanche under the action of the positive space charge distortion and the enhanced electric field. The electrons in the secondary electron avalanche move to the positive space charge region of the initial electron avalanche, and merge with it to form a mixed channel full of positive and negative charged particles, forming a streamer discharge channel.
- 3. Pilot discharge: Due to the long distance between the positive and negative electrodes, when the streamer discharge channel is not enough to penetrate the entire gap, the electrons move along the streamer channel due to the collision between the electrons and the molecules to make the temperature of the channel constantly increasing, up to thousands of degrees or higher, so that molecules produce thermal dissociation. This discharge process with the thermal dissociation process is called pilot discharge. Since the pilot discharge has a stronger process than the streamer discharge, it can promote the streamer to continue to grow until it penetrates the entire gap between the electrodes.

6.2. "Water Evaporation" Process

Compared with the breakdown process of air, in addition to the above-mentioned breakdown process of "electron avalanche-streamer discharge-leader discharge" in the breakdown of soil, there is also a process in which liquid water in the soil turns into gaseous water.

- 1. Under the effect of the collision of free electrons and new electrons generated by the collision, the distance between molecules becomes larger, and the water changes from liquid to gas.
- 2. Under the effect of the collision of electrons and molecules, the temperature of the discharge channel increases sharply, and a large amount of heat energy promotes

the evaporation of the surrounding water from a liquid to a gaseous state. The gas moisture produced by the process of "water evaporation" acts on the soil discharge channel, and together with the heated air, the discharge channel expands to the surroundings. It is precisely because of the distortion and strengthening of the electric field caused by the irregularity of the edge of the soil particles, and the existence of the "water" evaporation process, that the critical breakdown field strength of the soil is much smaller than the breakdown field strength of the equivalent air gap.

From the analysis of the "water evaporation" process, it can be inferred that the discharge channel is formed in the process of developing from the top to the bottom while also developing to the left and right. The soil impulse discharge mechanism analyzed in this paper is based on the image characteristics of the soil impulse discharge, and there is still a lack of direct verification results, such as the temperature change characteristics of the discharge channel. This problem still needs further research in the future.

7. Conclusions

The partial discharge of soil that occurs when the lightning current enters the ground through the grounding electrode poses a threat to the safety of personnel and equipment, but the difficulty of the formation of the soil discharge channel is closely related to the magnitude of the critical breakdown field strength, and the critical breakdown field strength of the soil residual resistivity are two key parameters of soil discharge. In this paper, a variety of typical soils were carried out to study the influence of soil water content, salt content, soil density and other factors on the morphological characteristics of the discharge channel, and then analyzed the critical breakdown field strength and the soil critical breakdown field strength with the introduction of different discharge channel morphologies and structures. The accurate measurement method of residual resistivity was carried out and we further discussed the minimum critical breakdown field strength of typical soil and its value conditions. The specific conclusions are as follows:

- The three types of soil critical breakdown field strengths first decrease, then increase, and then become stable with the increase in water content; with the increase in salt content, they first decrease and then become stable; with the increase in soil density, the increase shows the rule of first increasing and then tending to be stable;
- 2. The residual resistivity of the three soils increases with the increase in soil water content and salt content and decreases with the increase in soil density.
- 3. Under the conditions of the same water content, salt content and soil density, the critical breakdown field strength value relationship is: *Ec* of sandy soil < *Ec* of loam soil < *Ec* of Yellow cinnamon soil.

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References

- 1. Liew, A.C.; Darveniza, M. Dynamic model of impulse characteristics of concentrated earths. *Electr. Eng. Proc. Inst.* **1974**, 121, 123–135. [CrossRef]
- 2. Mazzetti, C.; Veca, G.M. Impulse Behavior of Ground Electrodes. *IEEE Trans. Power Appar. Syst.* 1983, 9, 3148–3156. [CrossRef]
- 3. Mousa, A.M. The soil ionization gradient associated with discharge of high currents into concentrated electrodes. *IEEE Trans. Power Deliv.* **1994**, *9*, 1669–1677. [CrossRef]
- 4. Bellaschi, P.L.; Armington, R.E.; Snowden, A.E. Impulse and 60-cycle characteristics of driven grounds—II. *Electr. Eng.* **1942**, *61*, 349–363. [CrossRef]
- 5. Bellaschi, P.L.; Armington, R.E. Impulse and 60-Cycle Characteristics of Driven Grounds–III Effect of Lead in Ground Installation. *Am. Inst. Electr. Eng. Trans.* **1943**, *62*, 334–345. [CrossRef]
- 6. Towne, H.M. Impulse characteristics of driven grounds. Gen. Electr. Rev. 1929, 31, 605–609.
- Geri, A. Behaviour of grounding systems excited by high impulse currents: The model and its validation. *IEEE Trans. Power Deliv.* 1999, 14, 1008–1017. [CrossRef]
- 8. Nekhoul, B.; Labie, P.; Zgainski, F.X.; Meunier, G.; Morillon, F.; Bourg, S. Calculating the impedance of a grounding system. *IEEE Trans. Magn.* **1996**, *32*, 1509–1512. [CrossRef]
- 9. Otani, K.; Baba, Y.; Nagaoka, N.; Ametani, A.; Itamoto, N. FDTD surge analysis of grounding electrodes considering soil ionization. *Electr. Power Syst. Res.* 2014, 113, 171–179. [CrossRef]
- 10. Viola, F.; Romano, P.; Miceli, R. Finite-Difference Time-Domain Simulation of Towers Cascade under Lightning Surge Conditions. *IEEE Trans. Ind. Appl.* **2015**, *51*, 4917–4923. [CrossRef]
- 11. Li, J.; Yuan, T.; Yang, Q.; Sima, W.; Sun, C.; Zahn, M. Numerical and Experimental Investigation of Grounding Electrode Impulse-Current Dispersal Regularity Considering the Transient Ionization Phenomenon. *IEEE Trans. Power Deliv.* **2011**, *26*, 2647–2658. [CrossRef]
- 12. Habjanic, A.; Trlep, M. The simulation of the soil ionization phenomenon around the grounding system by the finite element method. Magnetics. *IEEE Trans. Magn.* **2006**, *42*, 867–870. [CrossRef]
- 13. Chisholm, W.A.; Janischewskyj, W. Lightning surge response of ground electrodes. *IEEE Trans. Power Deliv.* **1989**, *4*, 1329–1337. [CrossRef]
- 14. Petropoulos, G.M. The high-voltage characteristics of earth resistances. *Electr. Eng. Proc. Inst.* 1948, 95, 59–70.
- 15. Korsuntcev, A.V. Application of the theory of similitude to the calculation of concentrated earth electrodes. *Elektrichestvo* **1958**, *5*, 31–35.
- 16. Oettle, E.E. A new general estimation curve for predicting the impulse impedance of concentrated earth electrodes. *IEEE Trans. Power Deliv.* **1988**, *3*, 2020–2029. [CrossRef]
- 17. Nor, N.M.; Haddad, A.; Griffiths, H. Determination of threshold electric field E_C of soil under high impulse currents. *IEEE Trans. Power Deliv.* **2005**, *20*, 2108–2113. [CrossRef]
- 18. Du, J. Research on Typical Soil Erosion Characteristics of Yunnan and Analysis of Spark Discharge Phenomena; Southwest Jiaotong University: Chengdu, China, 2017.
- 19. Guo, Y.; Wang, G.; Yang, M. Circuit method simulation analysis of impact characteristics of horizontal-vertical grounding body model. *Mod. Build. Electr.* **2010**, *1*, 56–59.
- 20. Li, J.; Jiang, J.; Li, L. Full-time domain electrical network model of grounding device transient characteristics considering soil spark discharge. *Chin. J. Electr. Eng.* 2017, *37*, 7058–7065.
- Li, H.; He, Z.; Chen, S.; Zhang, M.; Shu, Y.; Hu, C. Finite element calculation and analysis of impact dissipation characteristics of grounding device considering spark effect. *Electr. Porcelain Arrester* 2019, 6, 104–110.
- 22. Deng, C.; Zhou, W.; Wei, S. Analysis of the influence of inductance effect and spark effect on the lightning strike characteristics of grounding body and surrounding soil. *High Volt. Technol.* **2015**.
- 23. Feng, Z.; Tong, X.; Cai, H.; Li, J.; Liu, G.; Jia, L.; Lu, H. Simulation study on impact characteristics of tower grounding device considering nonlinear ionization of soil. *Hydropower Energy Sci.* **2016**, *34*, 173–177.
- 24. Zhu, C.; Xing, P.; Lu, H.; Lan, L.; Feng, Z. Calculation and analysis of impact characteristics of tower grounding body based on electromagnetic field. *China Electr. Power* **2014**, *47*, 83–87.
- 25. Xu, W.; Liu, X.; Huang, W. Calculation model of impact grounding resistance of tower grounding body based on ATP-EMTP. *Electr. Power Constr.* **2010**, *31*, 22–25.
- 26. Liu, Y. Principles of Medical Imaging Imaging; Jilin University Press: Changchun, China, 2012.
- 27. Luo, D.; Sima, W.; Yuan, T.; Sun, P.; Chen, W.; Wang, J. Influence-Factor Analysis and Parameter Calculation of Soil Discharge and Recovery Characteristics under Successive Impulse Currents. *IEEE Trans. Power Deliv.* **2019**, *34*, 514–523. [CrossRef]
- 28. Zhu, Z. Soil Science; Agricultural Press: Warsaw, Poland, 1983.
- 29. He, J.; Zeng, R. Power System Grounding Technology; Science Press: New York, NY, USA, 2007.