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Laboratory study on impulse current characteristics of clay

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Abstract

Lightning is recognised as one of the most detrimental natural disasters. While numerous research studies were carried out on the lightning impulse characteristics of the grounding system and the critical breakdown characteristics of soil, little attention was paid to the impulse current characteristics of soils when lightning strikes. In this study, the performance of typical soft soil in Shanghai under the action of lightning is analyzed. Different factors, including the impulse current waveforms, the front time and half peak time of impulse current, the quantity of electric charge and absorption of unit heat, have been studied by performing a series of laboratory tests. The test results show that the variation of impulse current due to lightning strike is time dependent. The higher the soil temperature, the larger the peak impulse current produced during lightning strike. The value of the front time decreases exponentially, while the value of the half peak time decreases linearly with the rise of soil temperature. Novel empirical relationships between the impulse current characteristics of soil and soil temperature are proposed, with the aim of providing useful practical references for the design of a grounding system for lightning strikes.

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Lightning is recognised as one of the most detrimental natural disasters. While numerous research studies were carried out on the lightning impulse characteristics of the grounding system and the critical breakdown characteristics of soil, little attention was paid to the impulse current characteristics of soils when lightning strikes. In this study, the performance of typical soft soil in Shanghai under the action of lightning is analyzed. Different factors, including the impulse current waveforms, the front time and half peak time of impulse current, the quantity of electric charge and absorption of unit heat, have been studied by performing a series of laboratory tests. The test results show that the variation of impulse current due to lightning strike is time dependent. The higher the soil temperature, the larger the peak impulse current produced during lightning strike. The value of the front time decreases exponentially, while the value of the half peak time decreases linearly with the rise of soil temperature. Novel empirical relationships between the impulse current characteristics of soil and soil temperature are proposed, with the aim of providing useful practical references for the design of a grounding system for lightning strikes.

Notation

e	void ratio
E_c	critical breakdown electric field strength
G_s	soil specific gravity
i	current
I	impulse current in the soil generated by the lightning strike
I_p	plasticity index
P	unit heat
Q	amount of electric charges
R^2	correlation coefficient
t	duration of impulse current in the soil
T	temperature
T_1	front time
T_2	half peak time
u_i^0	migration coefficient of ions in the water
v	voltage
W_L	liquid limit
W_P	plastic limit
$ z_i C_i$	number of ions charge
ρ	soil resistivity
$\tau(\omega)$	distortion rate of soil voids
ω	water content

Introduction

Lightning is a phenomenon of electrostatic discharge, which occurs when the electric field strength between the clouds and the earth

increases to a certain value. The electric currents generated by lightning are very large, ranging from 10 to 300 kA (Wakasa *et al.* 2012), and the heat generated by lightning strikes produces temperatures as high as 30 000°C (Nakano, 1996). As a result, many infrastructures, such as towers, chimneys and other buildings, often suffer lightning strikes when the currents involved in lightning are discharged, usually resulting in serious splitting and collapse (Wilson, 2003). Much lightning-related damage and several accidents have been reported in many countries during recent decades (Eriksson and Meal, 1984; Kithil, 2006; Pierce, 1971). For example, in the USA, about 30 000 unprotected buildings are burned or damaged annually, 18 000 of which are private homes (Frydenlund, 1986). According to statistics, the global annual direct economic loss caused by lightning is up to US\$1 billion (Scheuren *et al.*, 2007), and lightning disaster has been listed as one of the ten most serious natural disasters declared by the International Decade for Natural Disaster Reduction (Housner, 1989).

In order to reduce lightning disaster in infrastructures, in 1753 Franklin invented the lightning rod for the purpose of transmitting the lightning current into the earth. Since then, much research have been carried out on the characteristics of grounding systems subjected to lightning currents by using laboratory tests, field measurements and analytical models (Bellaschi *et al.*, 1942; Chien *et al.*, 2014; Geri *et al.*, 1992; Gonos and Stathopoulos, 2005; Loboda and Scuka, 1996). In contrast, limited studies have been reported that deal with the impulse performance of

the soil around the grounding system. However, the impulse characteristics of the grounding system are mainly governed by impulse current performance of the soil around the grounding system (He *et al.*, 2012; Zeng *et al.*, 2008).

A transient electric field in the soil around the grounding system is generated as the impulse current. In the circumstance that the electric field is higher than the critical breakdown electric field strength, the surrounding soil is penetrated and the spark discharge occurs. In past decades, many studies focused on the mechanism of soil breakdown induced by the impulse current (Flanagan *et al.*, 1981, 1982; Nor and Ramli, 2007; Nor *et al.*, 2006a, 2006b). Moreover, much attention has been paid to identify the critical breakdown electric field strength E_c (Erlor and Snowden, 1983; Mousa, 1994; Nor *et al.*, 2005), ranging from tens to thousands of kilovolts per metre. Mousa (1994) indicated that E_c is generally determined at the instant when the $v-i$ characteristic starts to become non-linear. Oettle (1988) proposed a relationship between the critical breakdown electric field strength E_c and the soil resistivity.

While most of these studies focused on the characteristics of critical breakdown electric field strength of soils, studies on the impulse current response characteristics of soil are scarce. These studies are not only useful for understanding the impulse breakdown mechanism of soil but also important for accurately simulating the transient characteristics of grounding systems in different soils. Due to the complexity of soil, there are various factors, including soil temperature, moisture, salt content, soil density and the type of soil, that can affect the response characteristics of the soil under the action of lightning impulse currents. Nor *et al.* (2006a, 2006b) discovered that soil temperature significantly influences soil resistivity, which greatly dominates the lightning impulse current response characteristics of soil. However, compared with the studies on the critical breakdown electric field strength of soils, research on the effects of temperature on soil resistivity is limited (Abu-Hassanein *et al.*, 1996; Arps, 1953; Sen and Goode, 1992; Shah and Singh, 2005).

Over the past decade, urbanisation has increased dramatically in both developed and developing cities and countries, such as Shanghai, China (Chen *et al.*, 2011; Gao *et al.*, 2012; Liu *et al.*, 2015; Shi *et al.*, 2015). The rise in temperature is caused by air-conditioning systems, road and rail transportation and so on. Global warming has also become increasingly evident. As a result, the urban heat island effect is becoming of more serious concern. Therefore, the effects of the variation of temperatures on soil resistivity should be of great concern for comprehensive understanding of the impulse current characteristics of soil.

In this paper, the impulse current characteristics of soils under various temperatures are investigated by performing a series of laboratory tests using the impulse current generator and the self-designed test devices in Shanghai Jiao Tong University. Soft clay, a typical soil deposit in the Shanghai region, is selected for the tests.

Mineralogical investigations are also carried out on the soil sample before tests by using X-ray diffraction. The characteristics of soft clay are presented. In order to investigate the effects of temperature on soil impulse characteristics, the variation of the impulse current waveforms, front time and half peak time of lightning impulse current, quantity of electric charge, absorption of unit heat and so on are carefully analysed for different temperatures. Based on the laboratory observations, empirical equations expressing the value of soil resistivity, the front time, the half peak time, the quantity of electric charge and the unit heat in terms of temperature are also proposed, with the aim of providing useful practical references for the design of a grounding system for lightning.

Test arrangements and test methods

Test arrangements

Figure 1 shows the impulse current generator device, which includes an impulse capacitor, a current sensor, capacitor banks, wave-adjusting resistance, wave-adjusting inductance and copper sphere electrodes. Figure 2 shows the test control operation

Figure 1. The impulse current generator device

Figure 2. The test control platform

platform, in which a digital storage oscilloscope was used to capture current signals and analyse data with a response time of 20 ns. The impulse current generator can produce a standard lightning response of 4/10 μ s (the discharge time to the maximum current value is 4 μ s and the discharge times to half the maximum current value are 10, 8/20, 18/40 and 30/80 μ s waveform). Using this circuit, it can generate high-current impulses up to 50 kA. In order to obtain the insulation effect, the test box was made by using the material organic glass, with a size of 130 $\times$ 60 $\times$ 60 cm, as shown in Figure 3. Two copper flat electrodes were arranged on the two sides of the box, and both ends of the electrodes were

Figure 3. Sketch of soil test box

connected to an external circuit with bolts. The procedures for impulse current tests meet the requirements of the IEC standard 60060-1-1989 (IEC, 1989). The circuit diagram is shown in Figure 4. The impulse current can be generated by a group of high-voltage large-capacity capacitors arranged in parallel through direct-current high-voltage charge. The impulse current can be changed by adjusting the capacitor storage capacity. When the capacitor fills the copper ball by touching momentarily, the sample capacitor discharges, resulting in a sample flowing through the impulse current; waveforms finally change when a large current flows through the sample through an oscilloscope.

Soil samples and experiment settings

Compared with sand or rock, soft clay has low resistivity, which is favourable for grounding systems. Soil samples were taken from the Bund of Shanghai, and the parameters of physical and mechanical properties of the soil are described in Table 1. The soil samples were dried, crushed, sieved and prepared to a moisture content of 20%. Then they were placed in an organic glass box with a size of 130 $\times$ 60 $\times$ 60 cm. The soil samples were prepared with temperatures of 35, 40, 45, 50, 55, 60 and 65°C.

Figure 5 shows the scanning electron microscopy (SEM) images of soil samples at a magnification of $\times 10\,000$. As shown, the soil mineral particles form a flat plate or sheet, and the typical structure is a decentralised structure. In addition, the X-ray diffraction test shows that the main clay mineral composition of soil samples is illite, which accounts for more than 60%, followed by the chlorite, kaolinite and montmorillonite.

Figure 4. Circuit diagram

Source	e	w: %	G_s	W_L : %	W_p : %	I_p	Gradation composition: %		
							<0.002 mm	0.002–0.005 mm	0.005–0.25 mm
The Bund	1.3	45.8	2.73	44.5	23.5	21.0	23.6	12.1	64.3

Table 1. Physical and mechanical properties of soft clay in Shanghai

Figure 5. SEM images of test samples (magnified $\times 10\,000$)

Results and analysis

The effects of temperature on various parameters such as soil resistivity, impulse current waveform, front time and half peak time, quantity of electric charge and unit heat are illustrated hereafter.

Soil resistivity

Soil resistivity varies not only with the temperature but also with moisture, salt content, soil density and the type of soil (Erzin *et al.*, 2010; Long *et al.*, 2012). It is reported that soil resistivity is one of the most important factors affecting the lightning impulse characteristics of soil, ranging from a few ohm

Figure 6. Variation of soil resistivity against a given range of temperatures

metres for clay to several kilohm metres for igneous rocks (Flanagan *et al.*, 1982; Gonos and Stathopoulos, 2004; Nor *et al.*, 2006a, 2006b).

Figure 6 shows that the soil resistivities for soft clay are 7.41, 6.45, 5.88, 5.26, 4.54, 4.26 and 3.77 Ωm . The corresponding soil temperatures are 35, 40, 45, 50, 55, 60 and 65°C, respectively. That is, the values of soil resistivity decrease with the increase in the values of temperature.

In order to get the relationship between temperature and soil resistivity, empirical equations can be obtained by regression in terms of experimental data as follows

$$1. \quad \rho = -0.1189T + 11.31 \quad R^2 = 0.981$$

where ρ is the value of soil resistivity (Ωm), T is the temperature of soil (°C) and R^2 is the correlation coefficient.

The reduction in soil resistivity with the increase in temperature is adequately represented by a linear relationship with a good correlation. This is due to the following aspects.

- With the increase in temperature, the solubility of electrolyte salts in the soil and the degree of ionisation increase. Also, the ions' activity increases, which encourages the relative increase of conductive ions and results in lower resistivity.
- When the ions diffuse in the soil solution, the diffusion velocity is affected by the resistance of water molecules. With the increase in temperature, the viscosity of water decreases. Its rate of diffusion then increases, leading to reduction in the resistance of water molecules. In addition, ions are affected by the electrostatic resistance of the soil. With the rise in temperature, the average kinetic energy of ions increases, so the capability of ions to overcome the soil electrostatic resistance also increases and the diffusion velocity speeds up, resulting in the decrease in resistivity.

The above analysis is in close agreement with the empirical relationship based on the test data by Cao *et al.* (2007), which can be expressed as

$$2. \quad \rho = \frac{1}{\sum_i |z_i| C_i \mu_i^0 w \tau(w)}$$

where $|z_i| C_i$ is the number of ions charged, μ_i^0 is the migration coefficient of ions in the water, w is the water content and $\tau(w)$ is the distortion rate of soil voids. With the increase in the soil temperature, the values of w and $\tau(w)$ will not change, but the solubility of electrolyte salt and the degree of the ions' ionisation increase, respectively. In other words, when the value of $|z_i| C_i$ increases, the viscosity of pore water decreases – that is, the μ_i^0 increases, which results in the decrease in soil resistivity.

Figure 7. Electric double layer of clayed particle

- Based on the classical theory of electrical double layer for clay, soil particles consist of a negative charge as potential ions, which are the inner layer of the electrical double layer, and the outer layer is compensated for by the adsorption of cations. These soil particles are composed of fixed layer (namely strongly associated water) and diffusion layer (weakly associated water), as shown in Figure 7, in which the strongly associated water cannot move freely due to the great intensity of the electrostatic field, even under experimental temperatures, while the weakly associated water molecules are more active and weakly orientated, and the sensitivity to

temperature variation of the weakly associated water is more evident than that of the strongly associated water. As a result, with the increase in temperature, some parts of the weakly associated water molecules dissociate from the diffusion layer and switch to ordinary liquid water, leading to the decrease in resistivity.

Impulse current waveform

The impulse current waveform is one of the most important parameters related to impulse current, which is closely associated with lightning-induced damage. Based on the characteristics of

Figure 8. Time-dependent variation of impulse current waveforms at different temperatures

the waveform, the peak value of the waveform, the maximum current rise rate and the peak time, the front time (T_1) and the half peak time (T_2) of waveforms can be obtained. It is reported from the observed data that lightning often produced a negative impulse current wave in the soil (Chen *et al.*, 2009; Shu *et al.*, 2010). In this study, in order to investigate the effects of temperature on impulse current waveform, a negative current wave is employed in the tests.

Figure 8 indicates the lightning impulse current waveforms corresponding to different temperatures (i.e. 35, 45, 55 and 65°C) under the influence of a voltage of 11.1 kV. It is found that the variation of impulse current in the soil induced by the lightning strike time dependent. The impulse current in the soil reaches the maximum value immediately after the lightning strike and then decreases relatively slowly, and the discharge time lasts around 10 ms. Moreover, Figure 8 also shows that, corresponding to the different soil temperatures of 35, 45, 55 and 65°C, the peak currents induced by lightning strike are -38.8, -47.2, -59.6 and -72.0 A, respectively. In other words, the higher the temperature of the soil, the larger the impulse current peak induced by the lightning strike. This phenomenon can be explained by the fact that the resistivity decreases with the rise of temperature of the soil, resulting in a lower voltage drop, and then the impulse current peak induced by lightning strike increases correspondingly. In addition, combined with the source experimental data, Figure 8 also shows that the peak times of impulse current waveform corresponding to the soil temperatures of 35, 45, 55 and 65°C are 0.02, 0.008, 0.005 and 0.003 ms, respectively, which exemplified that with the increase in temperature, the peak time increases and diffusion decreases. This may be due to the fact that, with the increase in temperature, the activity of ions increases and the amount of free water in the soil grows correspondingly, and then the soil electrical conductivity

becomes higher; thus, the current can flow through the soil more easily.

Figure 9 shows the impulse current attenuation rates corresponding to different temperatures. It can be found that the impulse current attenuation rate increases greatly with the increase in the temperature of the soil. However, the difference between the attenuation rates gradually diminishes with the increase in time.

Front time and half peak time

The front time (T_1) and the half peak time (T_2) are two important parameters for the evaluation of building lightning flashover rate. According to the IEC standard 60060-1-1989 (IEC, 1989), the value of T_1 equals 1.25 times the time interval between the impulse current generated by the lightning strike as it approaches 10% and 90% of the peak current. T_1 reflects the rise rate of the impulse current waveform from zero to the peak, and the rise rate of the impulse current waveform increases with decrease in the front time T_1 . Accordingly, the value of T_2 equals the interval between the time at peak impulse current and the time when the peak impulse current attenuates to 50% of the peak impulse current. The half peak time is one of the most important parameters determining the attenuation rate of the impulse current in the soil generated by a lightning strike. Thus, the attenuation performance of the impulse current can significantly affect the characteristics of the impulse current in the soil.

It can be seen from test results shown in Figure 10 that the values of T_1 corresponding to the soil temperatures of 35, 40, 45, 50, 55, 60 and 65°C are 0.030, 0.024, 0.012, 0.010, 0.008, 0.006 and 0.005 ms, respectively, which indicates that the value of T_1 gradually decreases with the increase in soil temperature. Here, it should be noted that the effect of soil temperature on T_1 is becoming slightly significant after the temperature is over 50°C.

Figure 9. The attenuation rate of impulse current at different temperatures

Figure 10. The dependence of front time of waveform on temperature of soil

In order to obtain the relationship between the temperature and the front times, empirical equations can be obtained by regression in terms of experimental data as follows

$$3. \quad T_1 = 1287.4T^{-2.9963} \quad R^2 = 0.977$$

where T_1 is the value of the front time (ms), T is the temperature of soil ($^{\circ}\text{C}$) and R^2 is the correlation coefficient.

It is also found from experimental data shown in Figure 11 that the values of T_2 corresponding to the soil temperatures of 35, 40, 45, 50, 55, 60 and 65°C are 1.78, 1.50, 1.46, 1.36, 1.17, 1.11 and 0.98 ms, respectively. That is, the value of T_2 decreases with the increase in temperature in the soil. The linear relationship between the soil temperature and T_2 can also be found, which is significantly different from the attenuation performance of T_1 as the temperature increases.

Based on the experimental data, regression analysis is carried out and empirical equations between the half peak current (T_2) and soil temperature (T) can be obtained as

$$4. \quad T_2 = -0.0276T + 2.7441 \quad R^2 = 0.991$$

where T_2 is the value of the half peak time (ms), T is the temperature of soil ($^{\circ}\text{C}$) and R^2 is the correlation coefficient.

Electric charge

When the impulse current occurs, several electric charges will dissipate into the soil. The amount of electric charge discharged into soils can be calculated by

$$Q = \int_0^t I dt$$

5.

Figure 11. The dependence of half peak time of waveform on temperature of soil

where Q is the amount of electric charges (unit: C), I is the impulse current in the soil generated by the lightning strike (unit: A) and t is the duration of impulse current in the soil (unit: ms).

In order to investigate the effects of soil temperature on the quantity of electric charge from the impulse current in the soil, the amounts of electric charges corresponding to soil temperatures of 35, 40, 45, 50, 55, 60 and 65°C are obtained in terms of Equation 5, which are 94.8, 98.6, 101.1, 104.6, 111.2, 117.3 and 123.6°C , respectively, as shown in Figure 12. Based on the experimental data, regression analysis is carried out and empirical equations between the quantity of electric charge (Q) and soil temperature (T) is obtained as

$$6. \quad Q = 0.9386T + 60.2143 \quad R^2 = 0.987$$

It is found from Equation 6 that the quantity of electric charges increases linearly with the rise in temperature of the soil, which will cause the increase in the soil conductivity due to the increasing amount of electric charge in the soil.

Unit heat

The current thermal effect has gained a great deal of attention from many researchers in the past (Nakano, 1996; Wakasa *et al.*, 2012; Wilson, 2003). Due to lightning strike, a high impulse current is generated and then flows into the surrounding soil. Heat is created in the soil after conversion of electric energy during the dissipation process of the impulse current into the soil, which leads to the rise in soil temperature and increase in soil conductivity as well. Therefore, the heat generated by the impulse current should be of great concern for further studies on the impulse current performance of the soil around grounding systems.

Figure 12. The variation of quantity of electric charges corresponding to different temperatures

Figure 13. The unit heat induced by lightning strike for different temperatures

Unit heat can be determined by

$$P = \int_0^t I^2 dt$$

7.

where P is unit heat converted from electric energy in the soil induced by the lightning strike (unit: J).

In order to study the effects of temperature on the unit heat absorbed into soils, based on the source experimental data shown in Figure 7, the unit heat for soil temperatures of 35, 40, 45, 50, 55, 60 and 65°C are calculated from Equation 7, which are 1.98, 2.36, 2.39, 2.63, 3.05, 3.13 and 3.67 J, respectively, as shown in Figure 13. As the same time, regression analysis is carried out and an empirical equation between the unit heat (P) and temperature (T) can be achieved as

$$8. \quad P = 0.0519T + 0.1479 \quad R^2 = 0.958$$

Equation 8 indicates that the unit heat absorption into the soil increases significantly and linearly with the rise in soil temperature. In other words, for soil with higher temperature, it is easier to absorb the heat converted from electric energy generated by impulse current in the soil under lightning strike, which will further increase the temperature in the soil.

Conclusions

The urban heat island effect has become increasingly predominant in the past decades, and the soil temperature in the city has become significantly higher than that in the adjacent suburban regions. Temperature is thus an important parameter affecting the characteristics of impulse current responses in the soil. In this study, a series of laboratory tests were carried out using the impulse

current generator and the self-designed test devices in Shanghai Jiao Tong University. These tests were aimed at investigating the effects of temperature on the lightning impulse current characteristics of soil. The variations of soil resistivity, impulse current waveforms, front time and half peak time of lightning impulse current, quantity of electric charge and absorption of unit heat in the soil at different soil temperatures were carefully analysed. Appropriate empirical relationships showing good correlation with test data are proposed, which can provide useful practical references for the design of a grounding system for lightning. The following conclusions are drawn from the current study.

- The values of soil resistivity decrease linearly with the rise in temperature of the soil.
- The variation of impulse current in the soil induced by lightning strike is time dependent; the impulse current reaches the maximum value immediately after lightning strike and then decreases relatively slowly. The higher the temperature of the soil, the larger the peak impulse current produced by the lightning strike.
- The front time and the half peak time are two important parameters for evaluation of building lightning flashover rate. The value of the front time decreases exponentially with the increase in temperature in the soil, while the value of the half peak time decreases linearly with the rise in soil temperature.
- The quantity of electric charges produced by the impulse current in the soil generated by lightning strike increases linearly with the rise in soil temperature, which in turn causes the increase in the soil conductivity.
- Heat is created in the soil after conversion of electric energy during the dissipation process of the impulse current into soils, which leads to the rise in soil temperature as well as increase in soil conductivity. The unit heat absorption in the soil increases linearly with the rise in soil temperature. In other words, for soil with higher temperature, it is easier to absorb the heat converted from electric energy generated by the impulse current in the soil under lightning strike, which will further increase the temperature of the soil.
- Empirical relationships between the parameters of the impulse current characteristics of soil and soil temperature are proposed, which show strong correlation. This proposed empirical relationship can provide useful practical references for the design of a grounding system for lightning strike.

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