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Principle Analysis of Soil Electrical Conductivity Test Based on Pulsed Eddy Current

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Abstract: Nowadays, soil salinization is one of the major environmental geological disasters in the world. The rapid survey of soil conductivity through pulsed eddy current detection helps reflect the salinization degree, which can save cost and improve efficiency. In this paper, the basic principle of pulsed eddy current for soil conductivity detection is expounded, the detection depth of pulsed eddy current is theoretically analyzed, and the principle of soil conductivity detection based on pulsed eddy current is studied as well as analyzed.

1. Introduction

Soil is the material basis for agricultural production and human survival, therefore, rapid and accurate detection of soil conductivity to reflect the basic conditions of the soil is of great significance for agricultural production[1-3], which helps promote the development of agricultural activities. In 1971, Rhoades group measured soil conductivity by “four-electrode method”; in 1998, Boike group proposed to measure soil conductivity via time domain reflectometry (TDR); in 1999, Kitchen group put forward the measurement of soil conductivity by using electromagnetic induction (EM)[4-9]. At present, the potential detection method in EM is pulsed eddy current, which has the following strengths compared with other detection technologies[10-15]:

(1) The received signal is directly correlated to the magnetic field signal generated by the tested soil and the conductive properties of the tested soil;

(2) The received signal is mainly influenced by external sources of interference (natural electromagnetic fields and artificial interference sources), but the signal-to-noise ratio and detection sensitivity can be improved by increasing the exciting power or enlarging the emission magnetic moment;

(3) The appropriate excitation frequency and exciting power are selected for different soil characteristics and detection depths, which makes the detected signal having higher processing significance.

2. Materials and Methods

2.1Pulsed Eddy Current (PEC) Detection Technology

Compared with traditional eddy current testing technology, the pulsed eddy current detection adopts the pulsed square signal with certain duty cycle as the excitation and loads square signal is on both ends of the excitation coil. In this way, when the square signals at both ends of the excitation coil are instantaneously cut off, the excitation coil will induce a rapidly decaying pulsed magnetic field, which in turn induces a pulsed eddy current in the conductor test piece. Finally, the pulsed eddy current will induce a decaying secondary magnetic field, which in turn induces a transient induced voltage on the detection coil. If there is a conductivity difference in the tested soil, it will affect the distribution of the pulsed eddy current in the soil. Meanwhile, the change of eddy current will influence the variation of induced magnetic field, which eventually leads to a change in the induced voltage on the detection coil. Therefore, the conductivity information in the soil can be obtained by analyzing the induced voltage on the detection coil.

Formula:

$$EC_a = 4(H_s / H_p) / \omega\mu_0 S^2 \tag{1}$$

EC_a is soil conductivity, mS /m; H_s, H_p respectively are secondary magnetic field and primary magnetic field; respectively; $\omega=2\pi f$, f is the transmission frequency, Hz; S is the distance between the transmitting terminal and the receiving terminal, m; μ_0 is the conduction coefficient of spatial magnetic field.

2.2Penetration Depth of Pulsed Eddy Current

In conventional eddy current testing, the distance that the eddy current penetrates into the conductor is called the penetration depth. In the conductor, the eddy current density is generally in exponential decay as the increase of distance from the conductor surface. When the eddy current density inside conductor is decayed to 1/e (37%) of conductor surface current value, the intermediate distance from the conductor surface to conductor internal eddy current density at 37% is called the standard penetration depth, which is also named as skin depth; the penetration depth of eddy current is generally expressed by δ. The greater δ indicates deeper penetration depth of eddy current and larger defect depth of the corresponding eddy current detection. On the contrary, the smaller the penetration depth δ is, the smaller the detection depth will be.

The formula of penetration depth is as follows:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{2}$$

In formula (2), δ is the penetration depth with unit of m; π is the pi; f is the excitation frequency with unit of HZ; μ is the conductor permeability with unit of H/m; σ is the conductor conductivity with unit of S/m. In pulsed eddy current detection, the eddy current penetration formula (2) is also applicable to pulsed eddy current detection. For instance, in pulse eddy current detection, a pulse square exciting signal g(t) is given, where T is the cycle of pulse square exciting signal, Δ is the width of pulse square, and V is the amplitude value of pulse square. According to Fourier transform principle, it can be known that the pulse square exciting signal *g(t)* can be developed into a sine or cosine combination of the fundamental wave component and multiple harmonic wave components, so the Fourier expansion formula in the pulsed square signal *g(t)* can be expressed as

$$g(t) = A_0 + \sum_{n=1}^{\infty} A_n \sin(n\omega_1 t + \phi) \tag{3}$$

In formula 3, A_n is the amplitude spectrum, ω_1 is the reference angular frequency, that is, the fundamental frequency, and φ is the phase spectrum, where the amplitude spectrum An can be expressed as

$$A_n = \frac{2V}{n\pi} \left| \sin(\frac{n\pi\Delta}{T}) \right| \tag{4}$$

The reference angular frequency ω_1 is generally expressed as

$$\omega_1 = 2\pi f_1 \tag{5}$$

When the cycle of pulse square exciting signal $T=2\Delta$, its reference angular frequency can be expressed as

$$\omega_1 = 2\pi f = 2\pi \frac{1}{T} = \frac{2\pi}{2\Delta} = \frac{\pi}{\Delta} \tag{6}$$

Then the frequency fundamental wave component and harmonic wave components ω in pulsed square signal can be expressed as

$$\omega = n\omega_1 = n\frac{\pi}{\Delta}, n = 1,3,5,7,\ldots,\infty \tag{7}$$

The frequency of single frequent exciting signal generally can be expressed as

$$f = \frac{1}{T} = \frac{\omega}{2\pi} \tag{8}$$

By putting formula (7) into formula (1), the formula of standard penetration depth can be converted into:

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu}} \tag{9}$$

By putting the ω in formula (6) into formula (8), the formula below can be obtained:

$$\delta = \sqrt{\frac{2\Delta}{n\pi\sigma\mu}}, n = 1,3,5,7,\ldots,\infty \tag{10}$$

When n=1, and taking fundamental wave component, the standard penetration depth of pulsed eddy current can be defined as

$$\delta_{PW} = \sqrt{\frac{2\Delta}{\pi\sigma\mu}} \tag{11}$$

It can be seen from formula (11) that when increasing the pulse width Δ while decreasing the excitation frequency f, the standard penetration depth δ_{PW} of pulsed eddy current can be increased. That means, the deeper conductivity can be detected in the pulsed eddy current with large pulse width and low frequency.

2.3Basic Principle of Soil Electrical Conductivity Test Based on Pulsed Eddy Current

The schematic diagram of detection of soil conductivity by pulsed eddy current is shown in Figure 1. The sensor coil is placed above the soil, which is composed of the excitation coil and receiving coil. The excitation coil excites through the bipolar pulse square current.

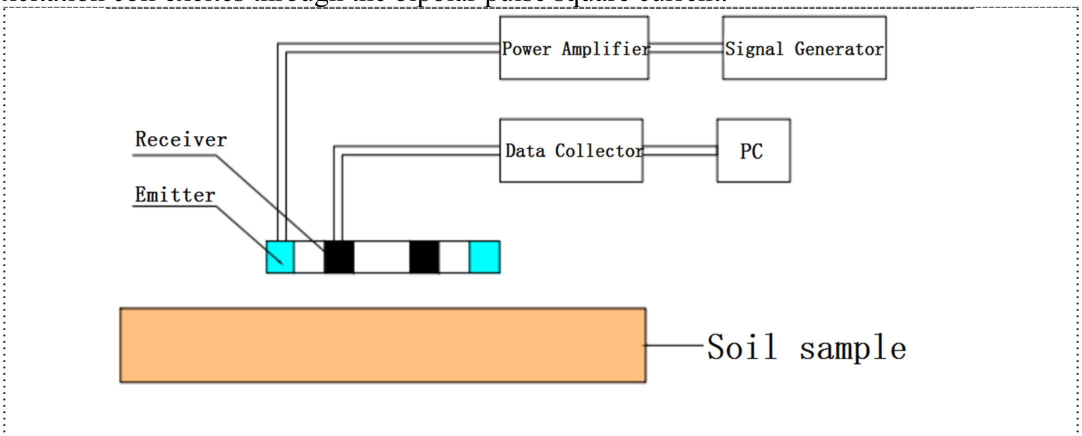

Figure 1. The schematic diagram of detection of soil conductivity by pulsed eddy current

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When the current in the excitation coil is momentarily cut off, a rapidly decaying pulsed magnetic field is generated in the excitation coil under the action of the instantly cutoff exciting current. At the same time, the changing pulsed magnetic field induces an instantaneous eddy current in the soil, which in turn induces a secondary magnetic field. The magnetic field is accepted by the receiving coil and it induces a transient induced voltage.

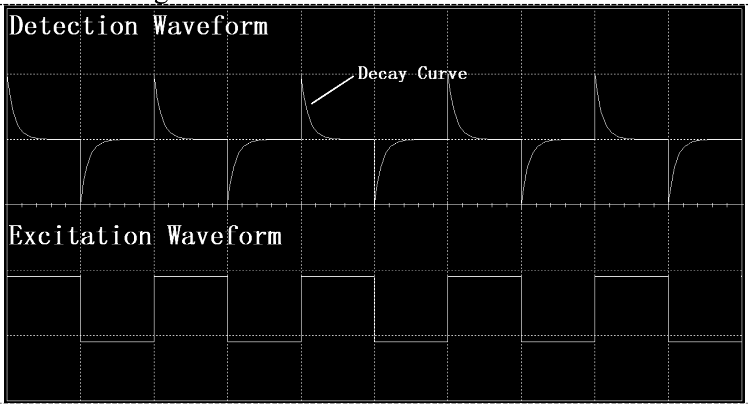

Figure 2. excitation waveform and its response detection waveform used by pulsed eddy current.

Figure.2 shows the excitation waveform and its response detection waveform used by pulsed eddy current for detecting salinized soil. According to the Figure,2, the induced voltage on the receiving coil basically satisfies the law of exponential decay after a period of time.

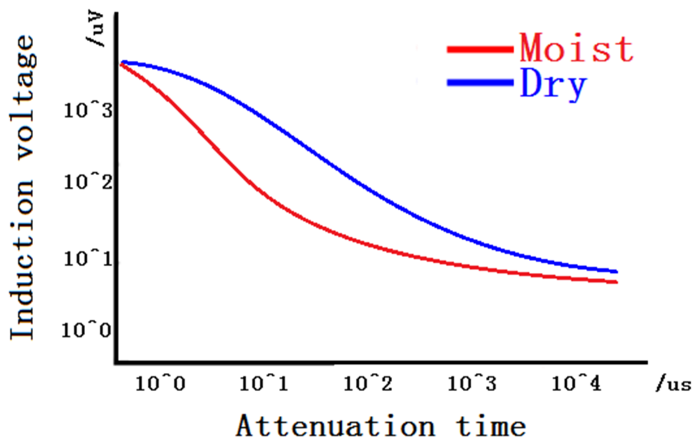

Figure 3. difference of the induced voltage response curve

Finally, by comparing the induced voltage decay curves at all the detection points, the decay difference of the induced voltage response curve at each detection point is analyzed, so that the change of the conductivity is obtained.

3. Conclusions:

In traditional soil conductivity detection, the soil samples need to be taken back to the laboratory for testing, which is time costing and will increase the detection expenses. The detection cost of radiation detection is very expensive since it requires perfect protection measures. The emerging electromagnetic eddy current test can directly measure soil conductivity, which is suitable for the rapid measurement of large area soil salinization. The research of this technology is of great significance to the occurrence mechanism, prediction and evaluation of regional soil salinization.

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