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基于四端法和时域反射法的土壤电导率测量研究

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摘要：为探究电流–电压四端法和时域反射法两种接触式测量方法在不同质地土壤和不同含盐量、含水率土壤的适用性，设计基于“电流–电压”四端法的土壤电导率测量仪，对其标定并与时域反射法进行对比试验。标定结果表明，当电导率在0～14 mS/cm范围内时，该仪器具有较高准确度。不同含水率的对比试验结果表明，四端法和时域反射法在一定含盐量范围内都具有较好的线性度；而当砂质壤土含水率为20%、含盐量大于0.6%时，四端法电导率测量仪测得的电导率基本保持不变；当粉质黏土含水率较低和较高时，电导率均变化不大，因此在使用时应尽量避免在土壤含水率较低和较高时进行测量。不同质地土壤的对比试验表明，四端法和时域反射法均在含盐量较低时受土壤质地影响较小，在含盐量较高时受土壤质地影响较大。

关键词：土壤电导率；四端法；时域反射法；测量

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Soil Electrical Conductivity Measurement Based on Four-terminal Method and Time Domain Reflectometry Method

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Abstract: Obtaining farmland information quickly and efficiently is the basis of precision agriculture. “Current-voltage” four-terminal method and time domain reflectrometry (TDR) are two main methods for contact measurement of soil conductivity. A soil conductivity instrument based on the principle of “current-voltage” four-terminal method was designed, which was calibrated and compared with TDR to explore the applicability of the two methods. The calibration results showed that when the electrical conductivity was in the range of 0 and 14 mS/cm, the determination coefficient R^2 reached 0.960, and the instrument had high accuracy in this range. The results of soil contrast test showed that the four-terminal method and TDR had good linearity under the condition of low salt content and water content, but when the salt content of sandy loam was more than 0.6%, the change of conductivity measured by four-terminal method tended to be smooth. When the moisture content of silty clay was 20% and 25%, the measurement data of the two instruments were basically the same, so it was needed to try best to avoid measuring when the soil moisture content was high. The comparative experiments under different texture soils showed that the four-terminal method and TDR were greatly affected by the soil type, and the higher the clay content of the soil was, the smaller the conductivity of the soil was. During the test, the four-terminal conductivity meter can measure in real time, but the time of each TDR measurement was about 20 s, which was not conducive to real-time measurement.

Key words: soil electrical conductivity; four-terminal method; time domain reflectometry; measurement

0　引言

土壤电导率是反映土壤理化特性的重要指标之一[1]。研究表明，土壤电导率受土壤含水率、含盐量、土壤类型及其他因素的影响[2-4]，准确获取土壤电导率对指导农业生产具有重要的意义。

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目前,时域反射法(Time domain reflectrometry,TDR)[5]和电流-电压四端法是土壤电导率接触式测量的两种主要方法[6-7]。TDR通过测定时域反射波的起始和终止时间及反射波幅度,推算介质的介电常数和电导率。研究表明,TDR具有可同时测量电导率与含水率的优点[8],但TDR每次测量的时间约20 s,不利于实时测量。且商品化的TDR仪器价格昂贵,不能满足国内大田应用的需要[9-11]。“电流-电压”四端法通过检测2个电压端的电位差计算土壤电导率,此方法可连续输出测量结果,但需要将检测电极插入土壤中并保持与土壤良好的接触[12-13]。研究表明[14],在非盐渍条件下,土壤质地和土壤含水率是影响电导率的两个主要因素。

本文基于“电流-电压”四端法设计土壤电导率测量仪,并在不同质地土壤、不同含水率和含盐量土壤条件下,进行四端法与TDR法的对比试验,探讨两种方法的适用性,为准确测量土壤电导率提供数据支持。

1 测量原理

1.1 四端法测量原理

为了提高系统的测量精度,对“电流-电压”四端法进行了改进,如图1所示,包括2个电流端(A和B)和4个电压端(C、D、E和F),恒流源作为测量的激励信号,通过2个电流端传入土壤,并利用电压端采集土壤的反馈电压信号,即通过检测两个电压端之间的电位差计算土壤电导率[15]。

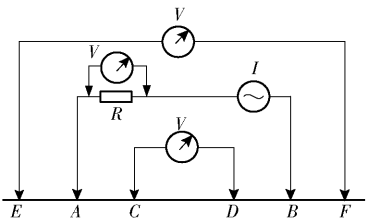

图1 四端法原理图

Fig. 1 Schematic of four-terminal method

为了减弱电子器件和外部环境对恒流的影响,将精密电阻连接到产生交流恒流电路的输出回路。土壤电导率计算公式为[16-17]

$$\sigma = kG \tag{1}$$

其中

$$k = \frac{\frac{1}{d_{AC}} - \frac{1}{d_{AD}} - \left(\frac{1}{d_{BC}} - \frac{1}{d_{BD}}\right)}{2\pi} \tag{2}$$

$$G = \frac{I}{V_{CD}} \tag{3}$$

$$I = \frac{V_R}{R} \tag{4}$$

式中 σ——土壤电导率,S/m

d_{AC}、d_{AD}、d_{BC}、d_{BD}——AC、AD、BC、BD之间的距离,m

I——恒流源提供的电流,A

k——距离函数

R——精密电阻,Ω

V_R——精密电阻上的压降,V

V_{CD}——C和D之间的电压差,V

G——土壤电导,S

1.2 TDR测量原理

TDR是基于电介质理论的电导率测量方法。其通过测量波导中电磁波传递的时间测量被测介质的介电常数[18]。TDR系统由脉冲产生电路、采样器、同轴电缆及探针构成。采样器比较探针顶端与探针底端两次反射回波波形确定其时间差进而计算被测介质的相对介电常数。TDR测量原理如图2所示。

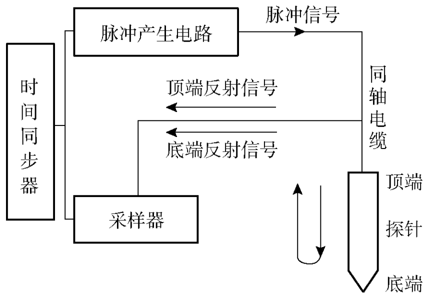

图2 TDR测量原理示意图

Fig. 2 Schematic of TDR measurement principle

土壤电导率σ计算式为[19]

$$\sigma = \frac{\sqrt{\varepsilon_r}}{120\pi}\ln\frac{V_1}{V_2 - V_1} \tag{5}$$

式中 ε_r——土壤的相对介电常数

V_1——脉冲在探针上的传播幅度

V_2——一次反射回波幅度

2 材料与方法

2.1 土壤样本和试验仪器

选用两种质地土壤进行试验,土壤样本质地如表1所示。

表1 土壤质地

Tab. 1 Soil texture %

样品	颗粒质量分数		
	砂粒	粉粒	粘粒
砂质壤土	88.2	7.0	4.8
粉质黏土	42.2	36.0	21.8

选用波兰ET-FOM/mts型TDR测量仪和设计的基于四端法的土壤电导率测量仪进行电导率的对比试验,选用美国OMEGA公司的CDH222型号电

导率测量仪测量标准电导率。

如图 3 所示，设计的基于四端法的土壤电导率测量仪可向电流端施加 160 Hz[20] 交流恒流源，同时采集精密电阻和电压端的反馈电压。将反馈电压经过信号调理电路转换后，发送给单片机(MSP 430)进行 AD 转换。并通过蓝牙将电导率数据发送到计算机。计算机具有数据显示、数据处理和分析功能。仪器电极部分有 6 个不锈钢实心探针，长度 10 cm，直径 3 mm，间距 3 cm。

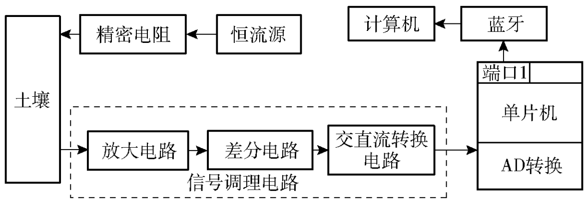

图 3　系统设计示意图

Fig. 3　Schematic of system designing

2.2　试验方法

试验于 2019 年 4 月在中国农业大学实验室进行。试验土壤首先自然风干后经过 2 mm 筛后待用。试验时将土壤放入 105℃干燥箱中干燥 24 h[21]，取出后晾至常温，将其配制成不同含水率和不同含盐量土壤样本，共设计 9 个土壤含盐量和 5 个含水率，含盐量分别为 0.1%、0.2%、0.3%、0.4%、0.5%、0.6%、0.7%、0.8%、0.9%，含水率分别为 5%、10%、15%、20%、25%并依次装盆。将其用保鲜膜密封后静置 24 h，待其均匀，用两种土壤电导率测定仪器依次测量每盆土壤电导率。测量温度为 25℃左右，反复测量 8 次，求平均值。

3　结果与分析

3.1　四端法电导率测量仪的标定试验

在电导率为 0～14 mS/cm 范围内制备了 6 个 NaCl 溶液样品，用本文设计的电导率测量仪对样品的电导率进行测量，同时用电导率仪(美国 OMEGA 公司 CDH222 型号电导率传感器)记录样品的电导率。标定结果如图 4 所示，由图可知，四端法电导率测量仪输出的电导与标准电导率呈线性关系，决定系数 R^2 为 0.960，表明本文设计的四端法电导率测量仪具有较高准确度。

3.2　四端法与 TDR 法测量盐溶液的对比试验

在含盐量为 0.1%～0.9%范围内制备了 9 个 NaCl 溶液样品。用 TDR 测量仪和本文设计的电导率测量仪对样品的电导率进行测量，结果如图 5 所示。

由图 5 可知，当含盐量小于 0.6%，含盐量与四端法电导率测量仪测得的电导率呈线性关系，当含

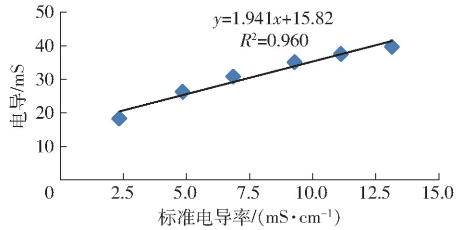

图 4　基于四端法的电导率测量仪的标定

Fig. 4　Calibration of conductivity meter based on four-terminal method

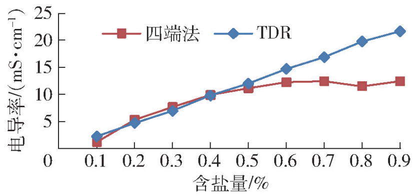

图 5　TDR 和四端法电导率测量仪测得的电导率对比

Fig. 5　Electrical conductivity measured by TDR and four-terminal conductivity meter

盐量大于 0.6%，四端法电导率测量仪测得的电导率基本保持不变。而在整个测量范围内 TDR 测量仪测得的电导率与含盐量呈线性关系，结果表明 TDR 法的测量范围大于四端法的测量范围，可达 23.25 mS/cm。

3.3　四端法和 TDR 法测量土壤的对比试验

按照 2.2 节中试验方法配置土壤样本，利用 TDR 测量仪和四端法电导率测量仪置于同等深度测量电导率，测量温度为 25℃。

图 6 为四端法测量仪和 TDR 测量仪在砂质壤土中的测量结果，在相同土壤含水率时，土壤含盐量越高，土壤电导率越大。从图 6d 可以看出，当砂质壤土的含水率为 20%，含盐量大于 0.6%时，即砂质壤土电导率大于 10 mS/cm 时，四端法电导率测量仪测量的电导率基本保持不变，而 TDR 测量仪测得的电导率与含盐量仍具有良好的线性关系。与 3.2 节盐溶液下对比试验结果相符合，表明 TDR 法的测量范围更广。

图 7 为四端法测量仪和 TDR 测量仪在粉质黏土中的测量结果，相同土壤含水率时，土壤含盐量越高，土壤电导率越大。从图 7d 可看出，当粉质黏土含水率为 20%，含盐量大于 0.6%时，即粉质黏土电导率大于 8 mS/cm 时，四端法电导率测量仪测得的电导率基本保持不变。由图 7a 可知，当粉质黏土含水率为 5%时，土壤电导率变化不大，含水率较低时，粉质黏土电导率主要受含盐量的影响，且由图 7d、7e 可得，四端法电导率测量仪和 TDR 测量仪测得的土壤电导率在含水率为 20%和 25%时相差不大，因为土壤含水率已接近饱和限度的缘故，与孙宇瑞[6]的研究结果基本符合。

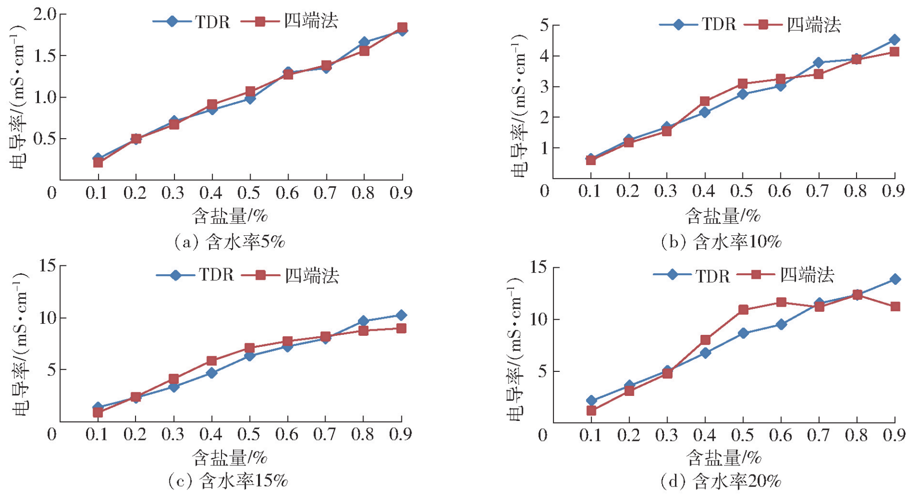

图 6 四端法和 TDR 测量仪在砂质壤土中的测量结果

Fig. 6 Measurement results of four-terminal method and TDR measuring instrument in sandy loam

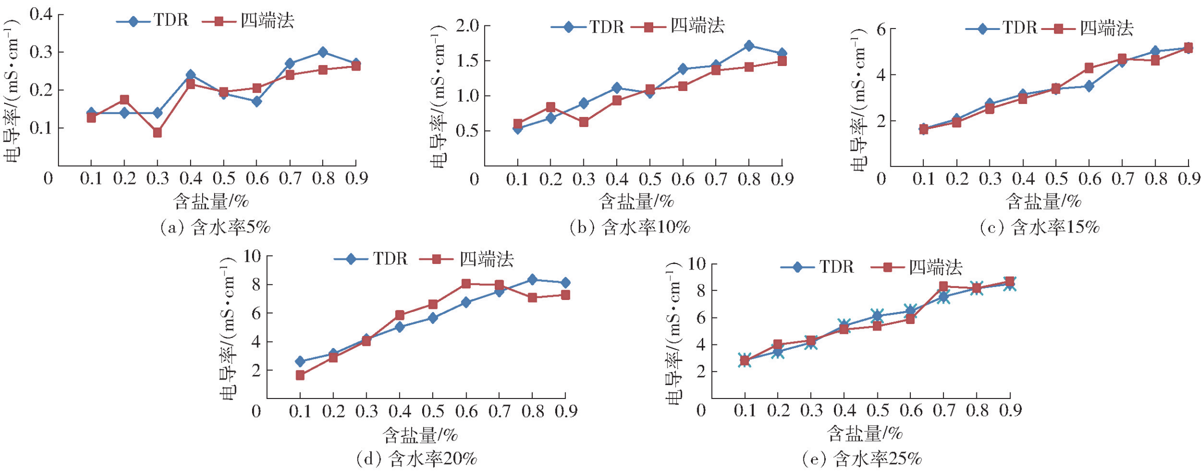

图 7 四端法和 TDR 测量仪在粉质黏土中的测量结果

Fig. 7 Measurement results of four-terminal method and TDR measuring instrument in silty clay

将含水率为10%和15%的砂质壤土和粉质黏土样本进行对比,如图8、9所示,四端法和TDR法在电导率的测量上均具有较高的精度,且在含盐量较低时受土壤质地影响较小,在含盐量较高时受土壤质地影响较大。粉质黏土的电导率低于砂质壤土

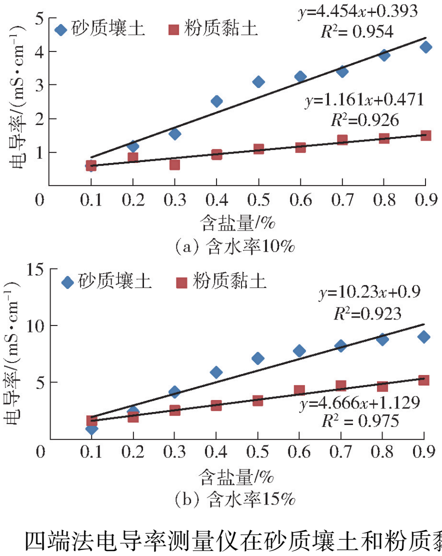

图 8 四端法电导率测量仪在砂质壤土和粉质黏土中的测量结果

Fig. 8 Measurement results of four-terminal method measuring instrument in sandy loam and silty clay

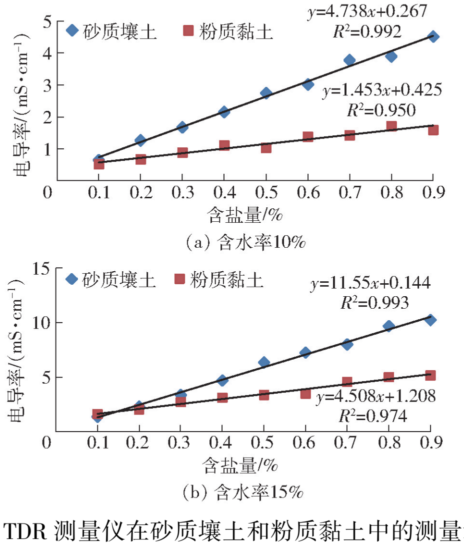

图 9 TDR 测量仪在砂质壤土和粉质黏土中的测量结果

Fig. 9 Measurement results of TDR measuring instrument in sandy loam and silty clay

的电导率,土壤粘粒含量越高,土壤电导率越小。在相同含水率情况下,介电常数随粘粒含量的增加而减小[22],且介电常数越大,电导率越大,粉质黏土的粘粒含量高于砂质壤土粘粒含量(表1),所以粉质黏土的电导率更低。

4 结论

(1)设计了基于四端法的土壤电导率测量仪并对其进行了标定试验,结果表明,当电导率在0 ~ 14 mS/cm范围内,决定系数 R^2 达0.960,在此范围内具有较高准确度。

(2)四端法与TDR法测量盐溶液对比试验表明,TDR法测量范围大于四端法,可达23.25 mS/cm。

(3)相同质地、不同含水率土壤条件下四端法和TDR法的对比试验表明,四端法和TDR法在一定范围含盐量和含水率条件下近似呈线性关系;而当砂质壤土的含水率为20%、含盐量大于0.6%时,四端法电导率测量仪测得的电导率基本保持不变;当粉质黏土的含水率为5%时,土壤电导率变化不大,且当粉质黏土的含水率为20%和25%时,两种仪器的测量数据都基本相同。相同含水率、不同质地土壤条件下四端法和TDR法的对比试验表明,四端法和TDR法在含盐量较低时受土壤质地影响较小,在含盐量较高时受土壤质地影响较大,且土壤粘粒含量越高,土壤的电导率越小。

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