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Improved near surface soil characterizations using a multilayer soil resistivity model

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ABSTRACT

This paper presents a method for determining near surface soil characteristics using multi-layer soil resistivity model. Usual soil resistivity model has its limitations in obtaining accurate soil characteristics because of the interrelationships between soil apparent electrical resistivity (ρ) and other soil physical or chemical properties. For most soils with varying layers, multi-layer resistivity profile is therefore more suitable to obtain near surface soil characteristics. The nobility of the research is to obtain soil characterizations using multi-layer resistivity model in near surface soil profile. In this multi-layer soil model, soil resistivity and resistivity ratio in soil medium at various depths are considered for soil field investigations. The results of multi-layer model are compared with the data from standard penetration test (SPT) and the profile from Multi-channel Analysis of Surface Wave (MASW) method to show the feasibility and reliability of using this model in soil profile. This method is also far simpler to perform compared to SPT and other methods.

1. Introduction

Near surface soil characterizations and soil strength determinations are prerequisite in highway and road engineering, geotechnical engineering, and other divisions of civil engineering. Soil electrical resistivity has been widely applied to many geotechnical and other engineering investigations to obtain near surface soil profile (Chaplot et al., 2010; Zhu et al., 2007). In particular, direct current (DC) resistivity monitoring has been widely used by correlating the changes of subsurface resistivity with the soil properties (Samouelian et al., 2005; Son et al., 2010). Soil electrical resistivity is a very important parameter which can be used to determine the specific soil characteristics of a soil profile in the near surface such as soil type, dry density of soil compaction, salinity and porosity of soil (Yoon and Park, 2001).

The soil resistivity measurements are commonly used with a four-point probe method such as Wenner's method. The basic principle of the soil resistivity, ρ measurement system is that when a constant voltage is applied across two probes placed in the soil, the current that flows between the probes is inversely proportional to the resistance of the soil (Herman, 2001).

As shown in Fig. 1, current, I is passed through two conducting probes, at the surface of the earth. The potential difference, v between two points at the surface of the earth is then taken as shown in Fig. 1. The electrical resistance, R is then obtained by dividing v by I according to the Ohm's law.

The passing of electric current using a four-point probe method creates electric field in near surface soil profile (Lu et al., 2002). The equation of the electric filed is a function of the gradient of scalar potential (Dutta, 1997; Herman, 2001).

$$E = -grad\,\psi \tag{1}$$

Another basic equation is related to current density, **J** is that

$$div\,\mathbf{J} = 0. \tag{2}$$

The conductivity, $\sigma(z)$ varies according to the depth, z. Hence, the partial differential equation of electrical potentiality can be expressed as,

$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}+\frac{\partial^2\psi}{\partial z^2}+\frac{1}{\sigma}\left[\frac{\partial\psi}{\partial x}\frac{\partial\sigma}{\partial x}+\frac{\partial\psi}{\partial y}\frac{\partial\sigma}{\partial y}+\frac{\partial\psi}{\partial z}\frac{\partial\sigma}{\partial z}\right]=0. \tag{3}$$

Using cylindrical coordinates (r,z), we obtain

$$\frac{\partial^2\psi}{\partial r^2}+\frac{1}{r}\frac{\partial\psi}{\partial r}+\frac{\partial^2\psi}{\partial z^2}+\frac{\partial\psi}{\partial z}\frac{1}{\sigma}\frac{\partial\sigma}{\partial z}=0 \tag{4}$$

where $r=\sqrt{x^2+y^2}$.

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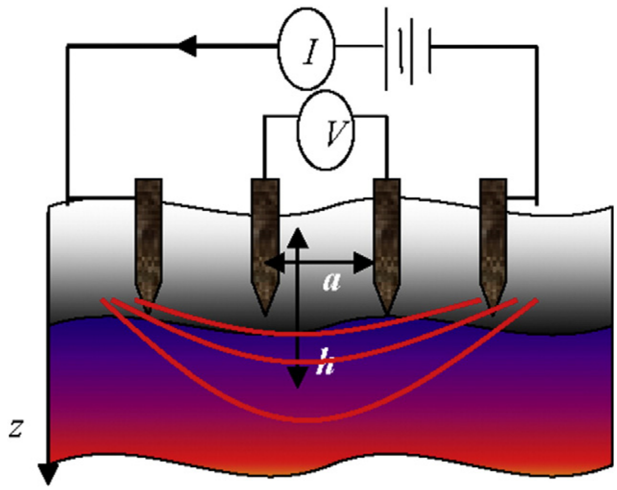

Fig. 1. Soil resistivity measurements using a four-point probe method.

Due to the azimuthal symmetry, we can separate Eq. (4) into two equations as

$$\frac{d^2\hat{\mathbf{R}}}{dr^2}+\frac{1}{r}\frac{d\hat{\mathbf{R}}}{dr}+\lambda^2\hat{\mathbf{R}}=0 \tag{5}$$

where $\hat{\mathbf{R}}$ is the vector of cylindrical coordinates, and

$$\frac{d^2Z}{dz^2}+\frac{1}{\sigma}\frac{d\sigma}{dz}\frac{dZ}{dz}-\lambda^2Z=0 \tag{6}$$

where λ is the separation constant.

Thus, a general solution for electric potential can be written as Eq. (7).

$$\psi=\int_0^\infty F(\lambda)\hat{\mathbf{R}}(\lambda,r)Z(\lambda,z)d\lambda \tag{7}$$

In addition, because the electric potential varies according to depth, it is also a function of z. For two-layer resistivity model, the potentiality is given by Seedher and Arora (1992).

$$\psi_1=\frac{I\rho_1}{2\pi}\int_0^\infty\left[A(\lambda)e^{-\lambda z}+B(\lambda)e^{\lambda z}\right]J_0(\lambda r)d\lambda \tag{8}$$

Lower layer is considered as half space in two-layer model where $z\to\infty$ is seen. So, the factor $e^{\lambda z}$ cannot appear. Now,

$$\psi_2=\frac{I\rho_1}{2\pi}\int_0^\infty C(\lambda)e^{-\lambda z}J_0(\lambda r)d\lambda. \tag{9}$$

The apparent resistivity is obtained through this model which is converted to true resistivity to get near surface profile. There is the lack of accuracy for empirical relationship between soil apparent electrical resistivity and several soil physical or chemical properties (Herman, 2001; Samouelian et al., 2005). Therefore, some researchers concentrate for optimization in inversion analysis to get soil true resistivity corresponding to depth (Kleefeld and Reibel, 2011).

Some researchers also include multi-layer soil structure to optimize soil apparent resistivity profile (Takahashi and Kawase, 1990). There is another theoretical approach of using multi-layer structure from kernel function to get optimization of soil apparent resistivity profile (Kang et al., 2010; Zhang et al., 2006). The apparent resistivity curves in multi-layer soil structure, different parameters are calculated again and again to fit the measurement data (Zhang et al., 2005, 2006). It is also difficult to obtain the derivatives of the optimized expression. Two stage algorithms are presented to invert the parameter of horizontal multi-layer soil (Zou et al., 2004). There is inclusion of error factor at conversion of apparent resistivity to true resistivity in straight forward inversion (SIS) algorithm (Gupta et al., 1997). Kang et al. (2010) show another algorithm for optimization of apparent resistivity data based on kernel function through multi-layer earth structure. This optimization also includes complex on nonlinear multivariable equation for matching of apparent resistivity data.

Moreover, electric resistivity tomography (ERT) is obtained based on soil apparent resistivity data by Loke (2007). This ERT is used in hydrological applications (Cousin et al., 2009) and agricultural applications (Michot et al., 2003). For ERT, soil apparent resistivity is converted to true resistivity through inversion analysis for soil characterizations (Sudha et al., 2009).

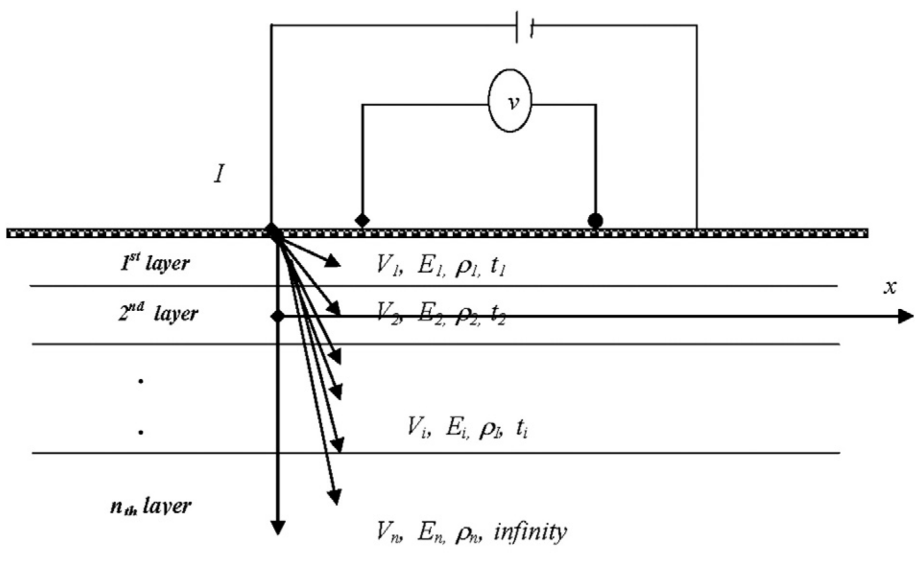

Fig. 2. Multi-layer resistivity profile in soil characterizations.