Soil Suction Dynamics in Vegetated Soil: From Deterministic to Probabilistic Analysis with Electrical Resistivity

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ABSTRACT

The importance of soil suction measurement in site characterization is very well recognized. In the field, soil suction is typically measured using tensiometers, which give point information. In vegetated soil, the change in soil suction is difficult to predict in a deterministic manner using point-based information due to spatial variability and heterogeneity. Large-scale field soil suction characterization is even more challenging. On the other hand, electrical resistivity is an important parameter in geophysical engineering, which is acquired by tomography surveys in the field. Therefore, probabilistically correlating soil suction with resistivity in the field might render a representative site characterization. The major objective of this paper was to correlate soil suction to electrical resistivity based on field investigation results using both deterministic and probabilistic methods. To pursue the objective, tensiometers were installed at multiple depths in multiple vegetated soils, and resistivity tests were conducted at the same location periodically. An analytical relationship between the field-measured suction and resistivity was derived, and the degree of strength of the correlation between suction and resistivity was measured using the non-parametric statistical measure: Spearman Rank Correlation Coefficient. The correlation was found to be highly dispersed at a resistivity value of more than 60 Ω-m. The higher resistivity values were congregated into small clusters. The Gaussian distribution theorem was then used to correlate the soil suction at higher resistivity values probabilistically. The results indicated that the probabilistic method better portrays the relationship between soil suction and resistivity in vegetated soil. Our findings provided the high potential of the electrical resistivity method in contributing to more effective monitoring and estimating soil suction in vegetated soil.

INTRODUCTION

The significance of soil suction is well-recognized in unsaturated soil mechanics. Given its importance in pavement engineering, foundations, earthen slopes, and waste containment system design, soil suction measurement is essential (Fredlund et al. 1994; Oberg 1995; Rahardjo et al. 1995; Durmusoglu 2006; Liang et al. 2008). The soil water characteristic curve (SWCC) is a graphical representation of the relationship between soil suction and water content. When modeling the behavior of unsaturated soil for geo-infrastructure, one of the most crucial considerations is the SWCC (Wilson et al. 1997). The SWCC is usually considered a static property of soil that does not change temporally and spatially for a given soil (Bordoni et al. 2017).

It is now widely accepted that one specific soil can have different SWCC curves for a variety of reasons, including the type of equipment used for the SWCC measurement, the equipment's capacity for measuring the SWCC, the initial density of the soil sample, the hysteresis phenomenon, temperature, and the chemical composition of the pore water, among other factors (Prakash et al. 2020). Due to fluctuating weather patterns, the wet-dry cycle, root development, fracture formation, and other factors, the uncertainties may even be quite high in the field conditions. Furthermore, because of fluctuations in climatic conditions and variabilities in soil properties, matric suction measurement to quantify in-situ SWCC of soil, especially vegetated land, maybe more unpredictable under natural field conditions (Allen et al. 1998; Garg et al. 2015). Therefore, it appears necessary to characterize the field-SWCC to improve the reliability of analysis and design for earth infrastructures (Fredlund et al. 2012).

The temporal and spatial variability in unsaturated soil properties is typically expressed by a probability distribution for risk analyses, reliability considerations, and other types of probabilistic assessments. A field study (Garg et al. 2015) demonstrated the variations in soil suction between vegetated and bare soil. It was concluded that because of environmental variability, the variance in suction caused in bare and vegetated soils is highly uncertain. Thus, to reduce uncertainty in unsaturated soil design considerations, probabilistic analysis of observed suction may be more practical to produce a reliable SWCC. The unsaturated soil design's dependability would be further improved by the probabilistic analysis. At the same time, it is equally important to characterize the unsaturated soil behavior on a large scale to incorporate more variabilities and data in the probabilistic characterization. Therefore, field investigation techniques that facilitate broader scale measurement of matric suction and moisture content are required to be implemented. Common methods to determine soil unsaturated parameters in the field are gravimetric methods (Van Reeuwijk 1992), time domain reflectometry (TDR) (Evett 2003), neutron probe and ground penetrating radar (Lunt et al. 2005), cosmic-ray neutron method (Andreasen et al. 2017), and electrical resistivity tomography (ERT) (Alam et al. 2019; Alam 2020). Every method has different pros and cons. However, the ERT method may be an effective method to characterize the field unsaturated soil behavior since this method does not require coring, has minimal disturbance to the soil body (electrode insertion only), yields information to a depth of several meters, covers a big area for investigation, and is repeatable.

The literature reports on several studies that used ERT to monitor soil suction in controlled laboratory settings, showing good correlations between ERT values and soil suction (Kong et al. 2017; Piegari & Di Maio, 2013) values and low noise levels, while field studies show only a modest correlation due to disturbance from uncontrolled environmental factors and other uncertainties. The very few field studies conducted to correlate electrical resistivity with moisture and suction, especially soil suction used primarily deterministic methods. Therefore, applying probabilistic methods in correlating or characterizing soil suction becomes crucial. The main objective of this study was to probabilistically evaluate the field distribution of soil suction using the ERT technique. Electrical resistivity testing was conducted on several test sections having a dimension of 12 m × 12 m × 1.22 m. Local fine-grained soil was used to construct the test sections. Instrumentation such as moisture and temperature sensors and tensiometers were installed at the site to monitor unsaturated soil parameters. However, in this study, analyses of only soil suction data are presented. Soil suction data and the corresponding resistivity data were first deterministically analyzed by simple scattered plots of these two variables. Then, the Spearman Rank Correlation measure was applied to check the statistical dependence between the two variables and visual data clustering, followed by the implementation of the simple Gaussian distribution theorem to correlate the soil suction with resistivity.

MATERIALS AND METHOD

Site Description, Instrumentation, and Field Testing

The study was conducted in North Texas at the City of Denton Municipal Solid Waste Landfill where six large test sections measuring 12 m by 12 m and 1.2 m deep, were built. The subgrade of an intermediate landfill cover was excavated, a geocomposite drainage layer was placed above a geomembrane layer at the subgrade bottom, and the soil was placed and compacted, during the building of the test sections. Each test section was equipped with tensiometers and moisture sensors to track the field SWCC. Figure 1 displays the test section's instrumentation. The top sensor was situated 305 mm from the surface, while the moisture sensors were spaced 228 mm apart. Figure 1 illustrates how far apart the tensiometers were from one another: 457 mm. All the sensors were connected through a data logger system for continuous monitoring of soil suction from the installed sensors. The soil used on the test sections had a fine fraction (clay and silt) in the range between 82% to 96%, while the plasticity index (PI) and liquid limit (LL) ranged from 26 to 33 and 51 to 60, respectively. According to the Unified Soil Classification System (USCS), laboratory test findings classified the soil as high plastic clay (CH).

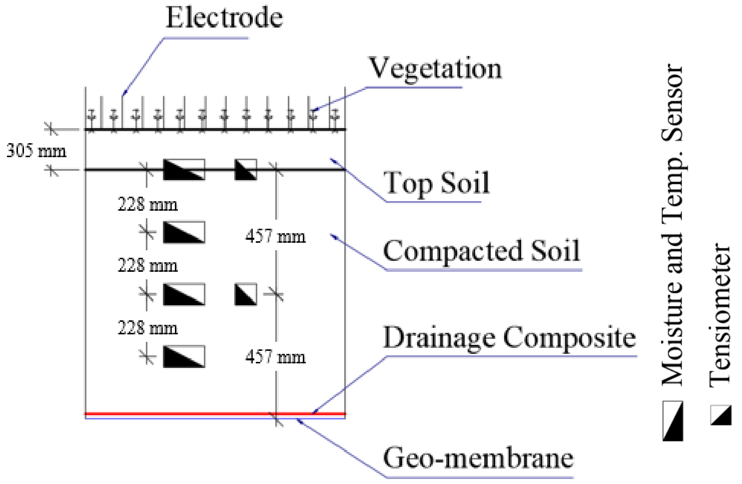

Figure 1. Schematic of instrumentation

Throughout the investigation period, the electrical resistivity tomography (ERT) approach was used to probabilistically characterize matric suction. The Advanced Geosciences Institute (AGI) produced programmable eight-channel resistivity equipment that was employed in this investigation. 28 electrodes in total, spaced 152 mm apart, were employed in a transect spanning 4116 mm across the sensor positions (Figure 2). To ensure that the resistivity profile is created within the 1.2 m cover and does not overlap with the geomembrane layer resting on the subgrade (bottom of cover), a narrow electrode spacing was used. Raw resistivity data was retrieved along the sensors' location. Every time the resistivity readings were recorded from the apparatus, temperature adjustments were done. Using the 2D dipole-dipole analyzing array, Earth Imager 2D software was used to analyze the raw resistivity data. For uniformity, the 2D resistivity profile's scale was fixed from 0 to 100 in all tomography.

Figure 2. Field setup with resistivity meter and testing

Gaussian Distribution and Non-Parametric Spearman's Rank Correlation

In scientific and engineering challenges, the normal, or Gaussian, distribution theorem, is frequently used to assess probabilistic models to comprehend statistics and data variability in general. Continuous data are likely to take on different frequency distributions when they reflect the reactions resulting from natural occurrences, such as modifications in soil characteristics brought about by environmental conditions (such as temperature, precipitation, etc.). The normal, or Gaussian, distribution also referred to as the bell-shaped distribution is one of the distributions. Numerous probabilistic sciences as well as geotechnical and geophysical engineering challenges have been assessed using the normal distribution. Equation (1) presents the probability density function (PDF) of the normal distribution for a random variable x.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \tag{1}$$

where σ is the standard deviation of the variable and μ is the mean. Here, μ and σ represent the scale and shape parameters, respectively. The engineering reliability analysis requires the transformation of any distribution (x) into the standard normal distribution (z): x→z. The original space (x) and the standard normal space (z) can be transformed to create a consistent framework for analyzing and understanding data variability. Equation (2) presents the method of converting normal distributions into standard normal distributions for any variable x, where $x \sim N(\mu,\sigma)$.

$$z = \frac{x-\mu}{\sigma} \tag{2}$$

Spearman rank correlation is a non-parametric measure of statistical dependence between two variables without any dependence (Gauthier 2001). It assesses how well the relationship between two variables can be described using a monotonic function. Unlike Pearson correlation, which measures linear relationships, Spearman correlation can capture non-linear associations as well. This research postulates that soil resistivity and matric suction will exhibit a rational positive correlation. After converting the N raw data (Ai, Bi) to their rankings (ai, bi) with a sample size of N, Equation 3 is used to calculate Spearman's rank correlation coefficient (ρ_s).

$$\rho_s = 1 - 6\frac{\sum {d_i}^2}{N(N^2-1)} \tag{3}$$

where the rank difference is expressed as di = xi - yi. The correlation coefficient's (ρ_s) numerical value falls between -1 and +1. The relationship between the scores is shown by the correlation coefficient. A negative agreement between the variables is indicated by $\rho_s < 0$ and a positive agreement is shown by $\rho_s > 0$. The closer the coefficient is to 1 or -1, the better the positive or negative correlation.

RESULTS AND DISCUSSION

Throughout the monitoring period (two years), a monthly field ERT test was conducted. However, during the summers, the ERT test was conducted weekly since the summers had notable high temperatures and precipitation with variable frequencies and intensities. The ERT profiles at the same transect are shown in Figure 3. Only two contrasting ERT profiles are presented here: one on June 23, when high temperatures were maintained for an extended period without rain, and another on July 19, which was carried out the day following significant rainfall. There is a noticeable difference in resistivity profiles between the two in the same transect. As indicated by the red contour in Figure 3(a), the top 304.8 mm to 457.2 mm of the subsurface display a high resistivity zone. Because the resistivity values at the bottom of the profiles are lower than those in the top 304. 8 mm to 457.3 mm (approximately), this suggests the presence of moisture and consequently reduced suction. The resistivity contour in Figure 3(b) changed from a concentrated red contour to virtually green to blue, indicating a considerable fall in resistivity value and moisture incursion into the soil following precipitation events.

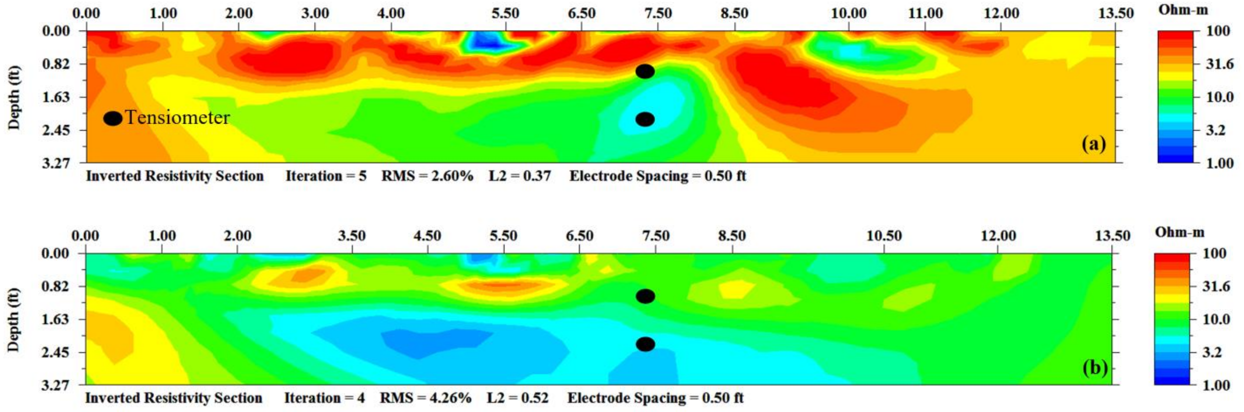

Figure 3. Resistivity imaging result for (a) 23rd June 2016 (b) 19th July 2016

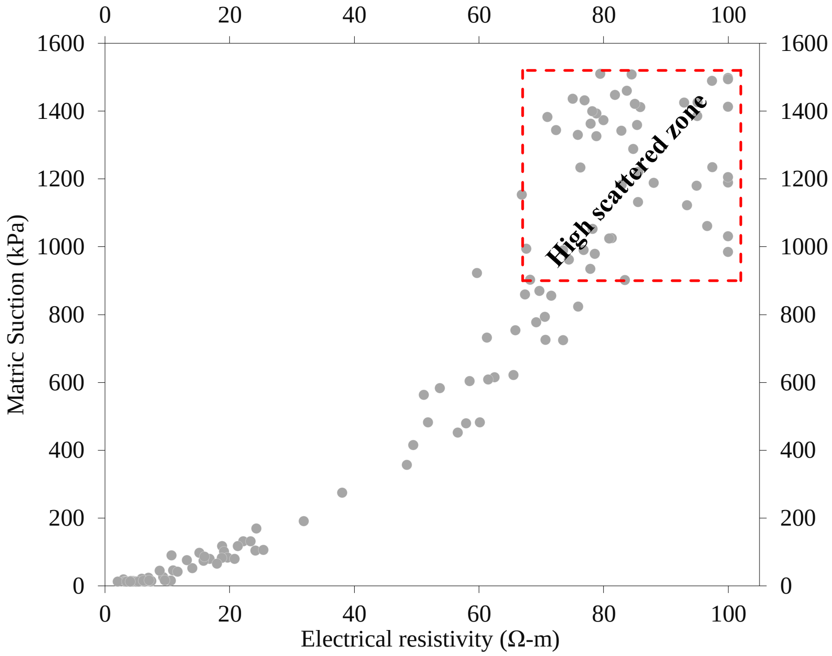

Figure 4. Plot of matric suction and electrical resistivity

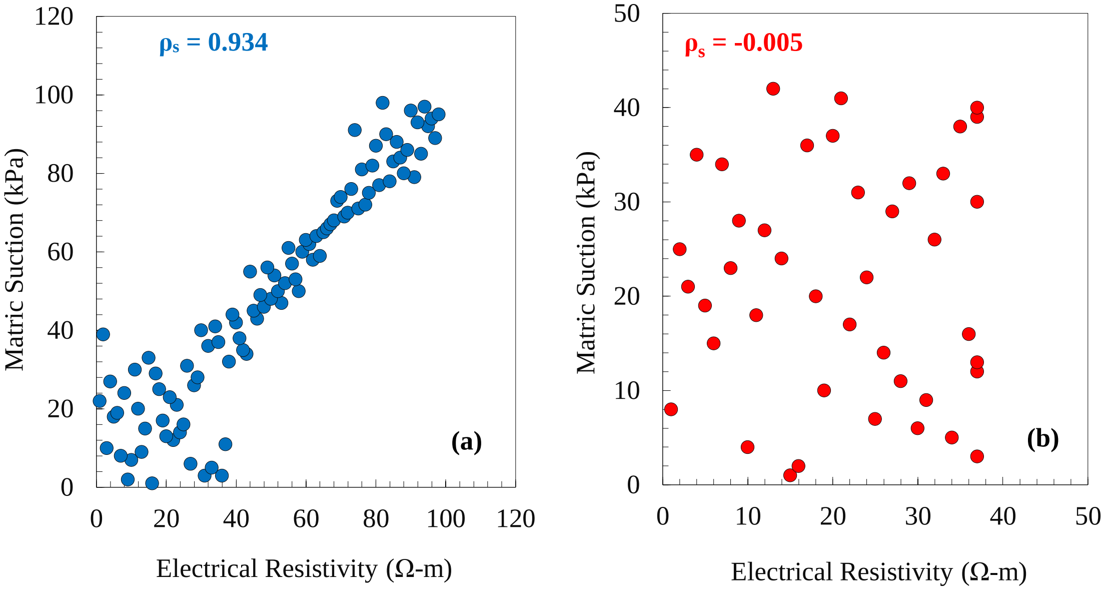

Figure 5. Rank plots of resistivity vs matric suction (a) resistivity 0 to 70 Ω-m (b) resistivity less than 71 to 100 Ω-m

From the ERT profiles, concurrent resistivity values were extracted from the depths where tensiometers were installed to determine the electrical resistivity response at different soil suctions. The relationship between resistivity and suction is presented in Figure 4. An expected proportional relationship was observed between the two measured parameters. Matric suction increased with an increase in soil resistivity in a non-linear manner. However, it is observed from the figure that the data points at lower resistivity values are more clustered compared to the data points at higher resistivity values, where the data are more dispersed. The resistivity values exceeding approximately 70 Ω-m indicate high degrees of dispersion. Therefore, from the deterministic plot of resistivity and soil suction based on field testing, the 70 Ω-m resistivity value was observed to be the threshold point between the high-scattered zone and the relatively congregated zone or the low-scattered zone (resistivity < 70 Ω-m). The responses of soil suction from the tensiometer readings at the resistivity values higher than 70 Ω-m distributed between approximately 900 kPa to 1600 kPa. For a statistical comprehension and significance of the dependence between the two variables in the identified zones, the Spearman Rank Correlation Coefficient (ρ_s) was determined. The plots of the ranks of resistivity and suction identified in the two zones are presented in Figure 5. As projected, Figure 5(a) demonstrates the positive relationships between the ranks of resistivity and suction indicating that resistivity and soil suction have a meaningful correlation at resistivity values less than 70 Ω-m. The ρ_s values were almost 0.934 indicating a very strong correlation between resistivity and soil suction in the low-scattered zone. On the other hand, in the high-scattered zone, the ρ_s (-0.005) exhibited no relatable relationship between resistivity and soil suction. The rank plot of the high-scattered zone is portrayed in Figure 5(b) where the ranks of resistivity and soil suction are randomly scattered with an uninterpretable pattern. Hence, based on the field results and non-parametric statistical evaluation, it is understandable that the deterministic evaluation of soil matric suction using ERT in the field conditions will produce reduced precision due to different degrees of scatteredness. This scattered distribution of soil resistivity and suction may be incurred from uncertainties or factors such as frequent changes in climatic patterns, root-induced changes in soil properties, soil cracks, etc., which are almost impossible to quantify or address in the variable field conditions. Therefore, being deterministic in evaluating soil suction in the field using ERT may not be suitable. Consequently, the probabilistic soil suction and resistivity characterization becomes crucial for field site characterization.

The resistivities from 70 to 100 Ω-m were divided into 6 small-ranging groups, and the soil suction values within the small groups were probabilistically characterized. The median resistivity values of these groups are listed in Table 1.

Table 1. Fitting parameters of field resistivity

Median Resistivity (Ω-m)	Most probable Suction (kPa)	Standard Deviation
72.5	955.28	23.51
77.5	1057.0	24.54
82.5	1163.1	21.84
87.5	1235.8	36.65
92.5	1362.7	25.54
97.5	1457.5	38.54

The 2D plot of probability density functions of soil suction is shown in Figure 6. Differences in probability distributions for measured soil suctions are visible among the PDFs. It is clear that increasing resistivity causes an increase in soil suction, therefore, the PDF shifted rightward or increased in the scale factor. Also, the probability of the PDFs gradually increased towards its direction to the right, though the probability differences between the PDFs were not significant. Two of the PDFs correspond to the median resistivities: 87.5 Ω-m and 97.5 Ω-m show discrepancies. These discrepancies can be described from the Gaussian shape factor: standard deviations (σ) of the analyzed data. The Gaussian distribution parameters of the measured suction (as the continuous random variable) can be notated as $\Psi \sim N(\mu, \sigma)$. The Gaussian distribution parameters of the two PDFs at 87.5 and 97.5 Ω-m median resistivities were: $\theta_{(87.5)} \sim N\ (1235.8,\ 36.65)$ and $\theta_{(97.5)} \sim N\ (1457.5,\ 38.54)$ which exhibited distinctions than the other PDFs (also presented in Table 1). The σ for other PDFs ranged from 21 to almost 25 (Table 1). Accordingly, the two PDFs had more spread out of the suction data. The median resistivity values were correlated with the most probable soil suction and plotted in Figure 6. A linear relationship was observed contrary to the non-linear deterministic plot of the two field-measured variables presented in Figure 4.

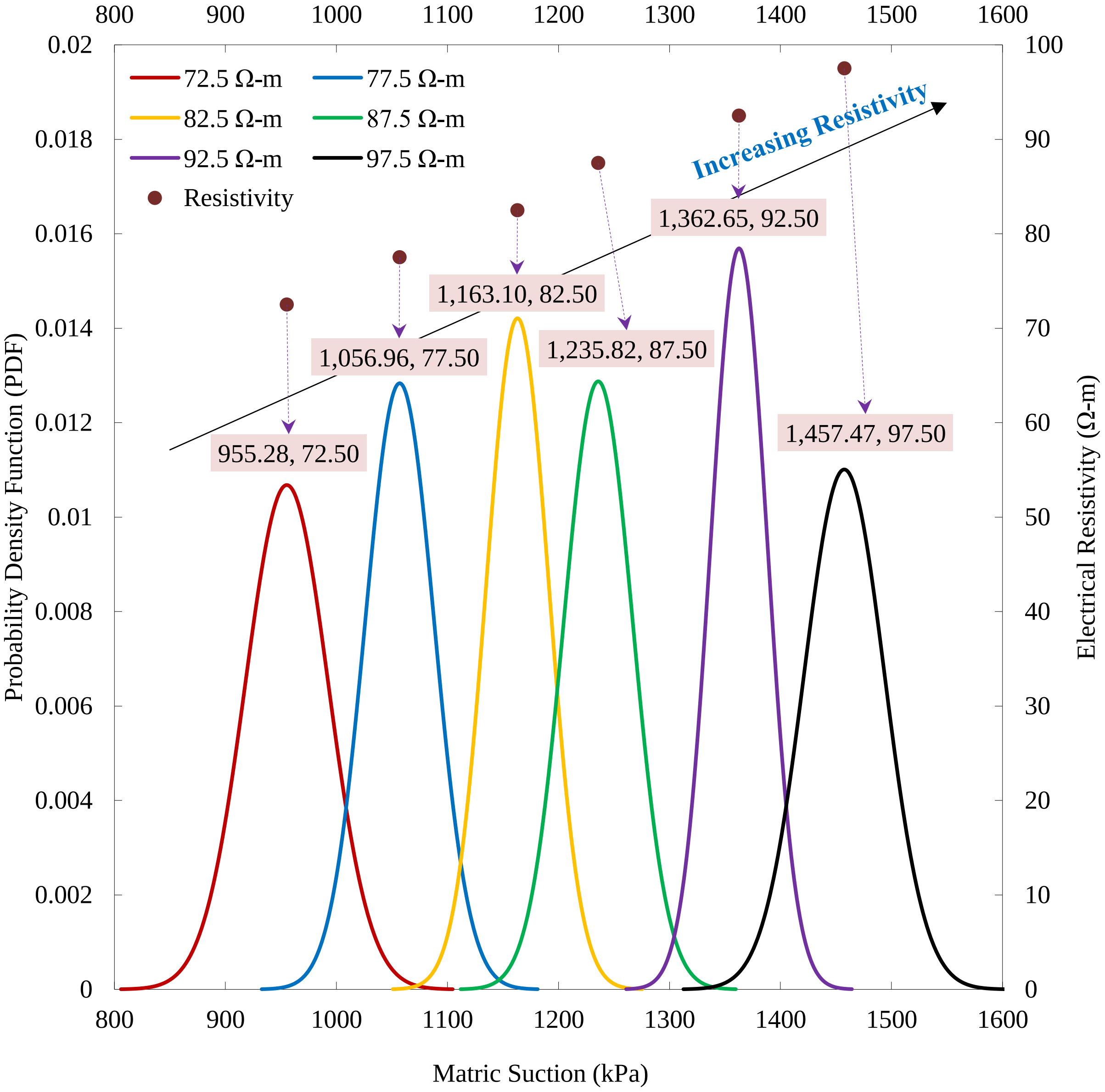

Figure 6. Probability density functions of soil suction in various resistivity

CONCLUSION

Under field conditions, it is almost impossible to characterize the soil suction distribution in a deterministic manner. Furthermore, different variables in field circumstances that impact the suction distribution are particularly difficult to assess in a large earth infrastructure. Understanding the distribution of the key constitutive variable: soil suction is critical in geotechnical engineering practice. Thus, an accurate and broader scale estimate of soil suction is important, accordingly constituting the SWCC. However, since the distribution of soil suction varies under field conditions, deterministically characterizing suction distribution in the field is supposed to be atypical. Therefore, probabilistic analysis is practically the ideal option for identifying the suction distribution in the field. For probabilistic analysis, sufficient data points are crucial to increase the reliability of the probabilistic model. Electrical resistivity tomography is one of the best options for producing ample spatial and temporal data in the field. In this study, a simple but efficient probabilistic approach: Gaussian distribution analyses was conducted using field monitoring suction and resistivity data to correlate soil suction with resistivity. The field-monitored data were first deterministically analyzed. The Spearman Rank Correlation Coefficient was used to check the statistical dependence between the two variables. Based on the analyses from the study, soil suction, and resistivity were highly scattered at higher resistivity (>70 Ω-m). Probabilistically, the soil resistivities (>70 Ω-m) were reasonably correlated with suction. The study revealed the importance of the probabilistic correlation of unsaturated soil variables (soil suction) with geophysical parameters (soil resistivity).

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