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Probability Distribution of Soil Suction of Engineered Turf Cover and Compacted Clay Cover

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Abstract. It is unlikely to predict the distribution of soil suction in the field deterministically. It is well established that there are various sources of uncertainty in the measurement of matric suction, and the suction measurements in the field are even more critical because of the heterogeneities in the field conditions. Hence it becomes necessary to probabilistically characterize the suction in the field for enhanced reliability. The objective of this study was to conduct a probabilistic analysis of measured soil suction of two different test landfill covers, compacted clay cover (CC) and engineered turf cover (ETC), under similar meteorological events. The size of the two test landfill covers was 3 m × 3 m (10 ft. × 10 ft.) and 1.2 m (4 ft.) in depth. The covers were constructed by excavating the existing subgrade, placing 6-mil plastic sheets, and backfilling the excavated soil, followed by layered compaction. Then the covers were instrumented identically with soil water potential sensors up to specified depths. One of the covers acted as the CC, and the other cover was ETC. In ETC, engineered turf was laid over the compacted soil. The engineered turf consisted of a structured LLDPE geomembrane overlain by synthetic turf (polyethylene fibers tufted through a double layer of woven polypropylene geotextiles). The sensors were connected to an automated data logging system and the collected data were probabilistically analyzed using the R program. There were significant inconsistencies in the descriptive statistical parameters of the measured soil suction at both covers under the same climatic conditions. Soil suction measured in the field ranged between almost 12 to 44 kPa in ETC, while it was in the range of almost 1 to 2020 kPa in the CC. The histogram and quantile-quantile (Q-Q) plot showed the data to be non-normally distributed in the field. A heavy-tailed leptokurtic (Kurtosis=13) distribution of suction was observed in the ETC with substantial outliers. In contrast, the suction distribution in CC was observed skewed to the right containing a thinner tail indicating an almost platykurtic distribution. The distribution of suction in the field under engineered turf was observed to be reasonably consistent with time compared to bare soil under the same meteorological events. The results obtained from this study revealed the engineered turf system to be an effective barrier to inducing changes in soil suction against climatic events.

Keywords: Engineered Turf, Unsaturated Soil, Instrumentation, Landfill Cover, Probability Distribution

1 Introduction

Landfill covers encountered in the field remain unsaturated for most of their service life. In the unsaturated state, the soil properties of landfill covers are substantially affected by changes in the degree of saturation and soil suction. Therefore, determining unsaturated soil properties is critical for designing and analyzing this geo-environmental infrastructure. Soil water characteristic curve (SWCC), which describes the relationship between pore water pressure and volumetric water content [1] is the fundamental concept of unsaturated soil mechanics. SWCC was earlier considered to be unique for a particular soil or static in nature. However, it is now well-established that various sources contributing to uncertainty in SWCC measurements, such as instrument types and measuring range, the initial soil density, hysteresis, temperature, and chemical composition of pore water, may lead to different curves for the same soil [2]. Moreover, in the natural field condition, matric suction measurement to determine in-situ SWCC of soil, especially vegetated ground, may have more uncertainties owing to variations in climate and soil conditions [3, 4].

There are two basic types of final cover systems: conventional and alternative or evapotranspiration (ET) covers. The conventional cover is built upon the concept of laying a low hydraulic conductivity compacted soil (clay) layer to prevent the infiltration of precipitation into the waste mass. Whereas the basic principle of ET cover is to store precipitation during rainfall events and release it to the environment during the dry period through evapotranspiration [5], thereby reducing the percolation rate. Both these covers have their advantages and shortcomings. However, compared to conventional covers, the performance of ET covers enhances with time [5]. In recent years, engineered turf covers have been introduced as an alternative to ET and

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conventional covers. Engineered turf covers have several advantages, such as ease of installation, applicability on steep slopes, reduced construction and operation cost, minimum maintenance requirements, and, most importantly, engineered turf can be an effective barrier to precipitation [6], thus controlled or no moisture movement in the waste as such it could potentially reduce the variability of matric suction of the soil under the turf.

Most field studies on landfill covers related to the analysis of matric suction induced by environmental factors have been conducted using a deterministic approach. The probabilistic approach has been adopted in many design analyses of various geotechnical infrastructures [7, 8, 9] but is very limited in analyses of landfill cover hydrology. For risk analyses, reliability considerations, and other types of probabilistic assessments, the temporal and spatial variability in unsaturated soil parameters is generally described by a probability distribution. A field study [4] showed the variability in soil suction in bare and vegetated soil on slopes. It was inferred that the variation of suction induced in bare and vegetated soils is quite uncertain due to environmental variability. Thus, probabilistic analysis of measured suction could be more realistic to minimize the uncertainties in design considerations of unsaturated soil. The probabilistic analysis would further enhance the reliability of unsaturated soil design.

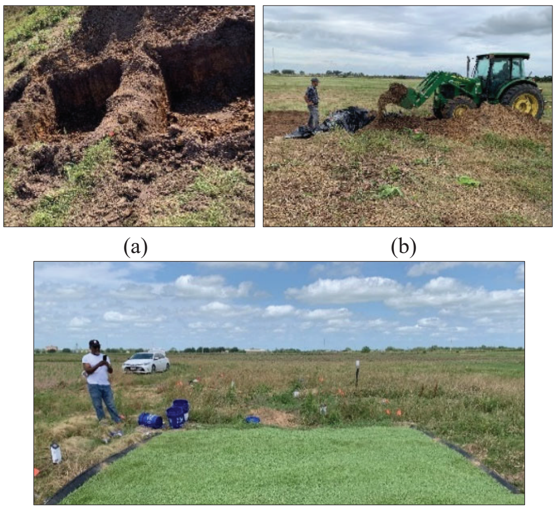
The dataset related to the distribution of soil suction under an engineered turf at variable environmental conditions is minimal. To the best of the authors' knowledge, soil's matric suction distribution below engineered turf at field conditions has not yet been investigated to test its efficacy as a barrier to precipitation and other environmental factors. To improve our understanding of field matric suction distribution at variable climatic conditions, a field test program was conducted to measure the distribution of soil suction in engineered turf cover (ETC). The soil suction distribution of a compacted clay cover (CC) was also evaluated for a comparative assessment. This study aimed to: (1) probabilistically analyze the measured soil suction of ETC and CC (at shallow depth: 0.3 m) using R software, thus investigating the effect of engineered turf on soil suction distribution under variable atmospheric conditions, and (2) demonstrate the importance of probabilistic analysis of measured suction for the design considerations of unsaturated soil cover.

Two test landfill covers of dimensions 3 m × 3 m (10 ft. × 10 ft.) and 1.2 m (4 ft.) in depth were constructed side-by-side, where one test cover acted as the CC and the other cover as ETC. Both the covers were instrumented identically with soil water potential sensors for the continuous measurement of soil suction. The measured values of suction were processed through descriptive statistics and probabilistic analysis for each cover under natural drying and wetting. The normal distribution (Gaussian distribution) theorem was used for the probability distribution of soil suction along with their standard parameters (mean, standard deviation). Other statistically significant parameters (range, skewness, and kurtosis) of soil suction measured during the field monitoring period were also evaluated.

2 Materials and Method

2.1 Construction of the Test Cover

The study was conducted in a subtropical climatic region in South Texas. Two large-scale test sections were excavated with dimensions of 3 m x 3 m (10 ft. x 10 ft.) and 1.22 m depth, as shown in Figure 1(a). The excavated soils from the test sections were predominantly fine-textured. According to ASTM D2487-11: the Unified Soil Classification System (USCS), the soil was classified as high-plasticity Fat Clay with Sand (CH). The two test sections were constructed as (1) compacted clay cover (CC), and (2) engineered turf cover (ETC). The test sections were constructed side-by-side, ensuring that each test section was subjected to identical weather conditions. An impermeable 6-mil plastic sheet was laid over each excavated subgrade bottom. Moreover, to prevent moisture flow within the sections, the plastic sheet was also placed along the excavation's inner sidewall, extending to approximately 0.6 m (runout length) along the top surface. The bottom of the excavated pit was sloped by 2%, and a sand strip was placed at the sloping end to allow water to flow under gravity and prevent water accumulation in the test pits after heavy rainfall. After the plastic sheet was placed at the bottom and inner wall, the excavated fine-grained soil was backfilled (Figure 1b) to the two test sections and compacted with a sheep-foot roller. Following the backfilling, extensive instrumentation was implemented to monitor the soil's hydraulic and climatic parameters. In the engineered turf cover, a structured LLDPE geomembrane was placed after surface smoothening, followed by the laying of synthetic turf (Figure 1c). In the synthetic turf, polyethylene fibers were tufted through a double layer of woven polypropylene geotextiles and sand in-fill.



(a) (b)

(c)

Fig. 1. (a) excavation of the test pits (b) soil backfilling after a 6-mil plastic sheet placed on the bottom of the excavation floor and inside the side wall of excavated pits (c) textured geomembrane layer placed over the smoothen compacted layer overlain by engineered turf

2.2 Instrumentation

Soil water potential sensors (TEROS 21: Meter Group) were installed at the desired depth (0.3 m from the ground surface) in the field test covers to monitor the negative pore-water pressure (matric suction). The TEROS 21 which is a porous block sensor was calibrated at a saturated state (≈0 kPa), at a dry state (≈−100,000 kPa), and four points between 0 and −100 kPa, resulting in an accuracy of ± (10% of reading + 2 kPa). A 4-inch hand augur was used to drill holes in both covers (Figure 2), and at 0.3 m depth, sensors were installed. After the installation, the holes were backfilled with the excavated soil and carefully compacted. A weather station was installed at the site (Figure 2d) to monitor the climatic parameters (e.g., precipitation, air temperature, relative humidity, wind speed, solar radiation, and vapor pressure). The sensors and weather station were equipped with automatic data logging systems. The data loggers were programmed to record and store data every five minutes.

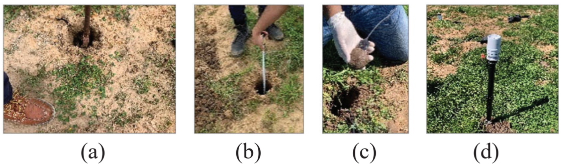


Fig. 2. (a) drilling using hand-auger (b) depth measurement (c) sensor installation (d) weather station

2.3 Statistical Analysis

When continuous data represent natural events, such as a change in soil parameters induced by environmental factors, they will likely take various frequency distributions. One of the distributions is a normal or Gaussian distribution that is also known as the bell-shaped distribution. The normal distribution has been used to evaluate many probabilistic sciences and geotechnical and geo-environmental engineering problems. For a random variable *x*, the function of the normal distribution is presented in the following equation (Equation 1):

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

Where μ is the mean and σ is the variable's standard deviation. The distribution parameters μ and σ are scale and shape parameters, respectively. Changing μ shifts the position of the distribution, whereas increasing σ flattens the bell-shaped curve that is such an iconic symbol of the normal distribution.

The first step in evaluating the distribution of the instrumentation-based suction dataset was examined by histogram to identify significant asymmetries, discontinuity of data, and any multimodal peaks. Estimators of symmetry and kurtosis of the dataset were also calculated that represented the shape of the histogram, dislocation of data to left or right (skewness), and peakedness or flattening of the data. Additionally, the dataset's quantile-quantile (Q-Q) plots were introduced to assess the normality of the field suction data. In general, Q-Q plots are more reliable for large-scale samples to examine the normality of data to reduce type II errors [10, 11]. This study observed more than 36,000 data (population size). However, a significant amount of duplicate data was observed. For example, after any precipitation event, the suction of CC soil at 0.3 m depth was reduced to 0.5 kPa and prevailed for several hours, as recorded every five minutes from the data logger. Similarly, different values of higher soil suction were constantly recorded in the data logger during prolonged summer with no precipitation events. Duplicate data was also observed in the ETC. While it is important to analyze the temporal in-situ distribution of soil suction under the variable climate, maintaining a unique dataset may be critical in soil suction analysis for robustness in statistical interpretation. The duplicate observations were removed from the dataset (using the R program) to analyze with unique sets of soil suction data. Nonetheless, the sample size was still large, and the Q-Q plots were introduced to investigate the data distribution for increased sensitivity.

3 Results and Discussion

3.1 Field Distribution of Matric Suction

The response of soil matric suction at 0.3 m depth under variable atmospheric conditions is presented in Figure 3 for both the ETC and CC. The graphical portrayal in Figure 3 presents the change in soil suction at variable precipitation. It is observed from Figure 3 that the initial matric suction at both covers was around 15 kPa at the inception of data recording. It was noticeable that the soil of the CC cover was delicately responsive under different rainfall events. As can be seen from the figure, the soil suction for CC cover at 0.3 m depth dropped to almost 0.3 kPa after most of the rainfall events. Then, soil suction started to rise again after different rainfall events. The sensors used in this study recorded the lowest suction to be almost 0.3 kPa. None of the suction readings in any sensors used exhibited 0 kPa suction during the wet condition of the soils.

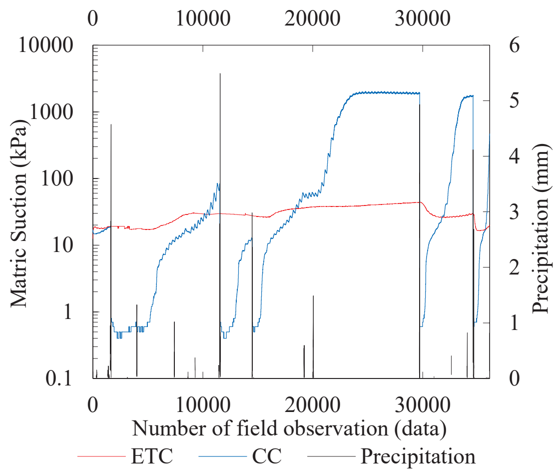


Fig. 3. Matric suction variation at 0.3 m depth

It is to be noted that though the CC cover had been intended for no plants to grow, a few months after construction, the soil had germination of local grass incurred from natural processes. During the prevailing elevated temperature and when there were no rainfall events, the suction at 0.3 m depth for the CC cover sustained at almost 2000 kPa. Contrary to the matric suction distribution in CC cover, the suction profile of the soil under the engineered turf was noticeably insignificant, as an almost flat propagation was observed (Figure 3). Throughout the monitoring period, the suction ranged from 12 kPa to almost 44 kPa, implying that the capillary actions of soil under the turf were negligibly induced. Therefore, the changes in matric suction induced by environmental factors under the turf were insignificant, indicating the engineered turf to be an effective barrier to environmental factors.

3.2 Descriptive Statistical Analysis

Descriptive statistics and the histogram of field-measured matric suction observations are presented in Table 1 and Figure 4, respectively. It was observed from the table that there were significant discrepancies in the descriptive statistical parameters of the measured soil suction at both covers. The measures of the central tendency (e.g., mean, median) of both ETC and CC indicate a substantial variability of soil suction under the same meteorology. The first parameter to notice in Table 1 is the range of the data, which delineates the spreading out of the suction at the in-situ conditions. The range of ETC was 31.6, which is significantly lower than the range of CC (2019.3), implying the negligible impact of the change in suction under the engineered turf at the environmental conditions. The degree of dispersion of soil suction was further measured by σ and variance coefficient (C_V). The σ of measured suction for ETC ($\sigma_{ETC} = 2.9$) and CC ($\sigma_{CC} = 667.7$) was considerably different. The C_V also shows a significant variation in measured soil suction. According to the degree of variation, $C_V \leq 0.1$ represents weak variation, $0.1 < C_V < 1$ represents medium variation, and $C_V \geq 1$ reflects strong variation. The C_V was found to be 0.1 and almost 0.8 for ETC and CC, respectively. The C_V value indicates that soil suction of CC is attributed to medium variation. However, compared to the matric suction variability of ETC, the CC could reasonably be assumed to retain a strong variability of soil suction at the in-situ conditions.

Table 1. Descriptive statistics of matric suction (0.3 m)

Descriptive Statistics	ETC	CC
Mean	28.9	792.7
Standard Error	0.05	10.1
Median	29.1	641.9
Standard Deviation	2.90	628.9
Sample Variance	8.75	395552.9
Kurtosis	13.1	-1.30
Skewness	-0.31	0.60
Range	31.6	2019.3
Minimum	12.5	0.4
Maximum	44.1	2019.7
Count	3452	3736

Figures 4(a) and 4(b) also show Gaussian probability density functions (PDF) of measured suctions (at 0.3 m depth) for ETC and CC, respectively. Differences in the effect of Gaussian location (μ) and shape (σ) factors for measured suctions are visible between ETC and CC. Matric suction (ψ) as the continuous random variable, the Gaussian distribution parameters of the measured suction can be notated as $\psi \sim N(\mu, \sigma)$. The Gaussian distribution parameters of the two-test cover at 0.3 m depth, $\psi_{(ETC)} \sim N(28.9, 2.9)$ and $\psi_{(CC)} \sim N(792.7, 628.9)$ exhibit significant distinctions under identical meteorological conditions. The σ_{CC} parameter is considerably higher than the σ_{ETC} which is indicative of the flatter shape of the Gaussian curve of CC than the ETC. The location parameter (μ) was also substantially different as noticed in Figure 4. The PDF of the measured soil suction of ETC at 0.3 m depth demonstrates that under the field atmospheric conditions, soil suction would potentially be distributed around 28.9 kPa given that the initial matric suction is near 15 kPa. On the contrary, the matric suction distribution of CC at the same depth would be rather volatile because of the substantial impact of the natural atmospheric conditions.

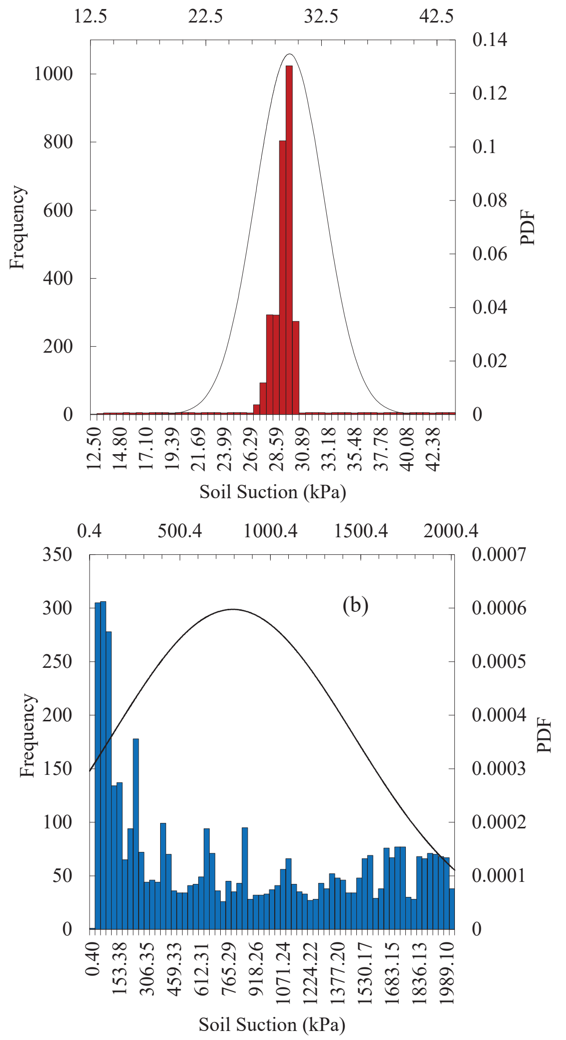


Fig. 4. Probability density function (PDF) and histogram of matric suction measured at 0.3 m depth (a) ETC (b) CC

Skewness and kurtosis values of the measured soil suction for both covers also exhibited discrepancies, especially the kurtosis. Generally, the skewness values between -0.5 and 0.5 are considered fairly symmetrical. The skewness between -1 and -0.5 (negatively skewed) or between 0.5 and 1 (positively skewed) indicates a moderately skewed distribution. The skewness < -1 or > 1 implies data are highly skewed, negatively, or positively, respectively. The skewness value of ETC (-0.31) suggests the suction distribution under the engineered turf was fairly symmetric concerning the mean. This was also confirmed by the almost equal values of the mean and median of the ETC (Table 1). Additionally, the PDF superimposed on the histogram presented in Figure 4(a) indicates reasonable normality of matric suction distribution under the engineered turf. However, the kurtosis value of ETC was considerably higher. Generally, a kurtosis value greater than 3 indicates a leptokurtic distribution of data that contains very long and skinny tails. The leptokurtic distribution also indicates the likelihood of the occurrence of outliers. The histogram superimposed with the heavy-tailed PDF of the ETC suggests that the matric suction distribution under an engineered turf would potentially be clustered around the central tendency with a significant outlier. However, the data range, R=31.6 (max = 44.4 kPa and min =12.5 kPa) of ETC indicates the outliers' dispersal is very confined. Contrary to the ETC, the soil at 0.3 m depth of CC had a skewness value of 0.6 indicating the distribution to be rightly skewed. It is also observed from the histogram presented in Figure 4(b). Another indication of the right-skewed distribution of the CC is the higher value of the mean than the median. Figure 4(b) seems to be a multimodal histogram even after the elimination of the duplication. However, it can be considered as a right-skewed unimodal distribution. The high-frequency matric suction values are clustered in the lower magnitude indicating the soil at 0.3 m depth of CC had more wetting events (precipitation) or longer wet periods than dry events. The kurtosis value of CC (-1.3) was less than 3 signifying a platykurtic distribution that has a lower tail and most of the data points are present in high proximity to the mean.

Based on the parameters of descriptive statistics, it was observed that the degree of dispersion of matric suction data at 0.3 m depth for CC was significantly higher than ETC under identical climatic conditions. The results imply that the engineered turf might be a good barrier to climate-induced changes in soil suction at shallow depths.

3.3 Quantile-Quantile (Q-Q) Plot

It is improbable that the distribution of matric suction in the field under variable climatic conditions will be normal. Nonetheless, in this study, the quantile-quantile (Q-Q) plot was used to determine the degree of non-normality of the matric suction distribution. The Q-Q plots for both ETC and CC are presented in Figure 5(a) and 5(b), respectively. If the matric suction in the field was distributed normally, the data should be in line with its normal Q-Q distribution plot. However, an extreme non-linearity is observed for both ETC and CC. The matric suction distribution in ETC is more non-normal than the CC indicated by ETC's comparatively lower coefficient of determination (R^2) value ($R^2_{ETC} = 0.5931$). The shape of ETC's Q-Q plot indicates the data's peakedness, which was also confirmed by the histogram plot and the kurtosis value. Though the coefficient of determination of CC (R^2_{CC} = 0.8871) is almost 89% (Figure 5b), it does not necessarily signify that the matric suction data of CC is normally distributed. The distribution parameters can be inferred from the slope and intercept of the Q-Q plots. The data corresponding to the CC shows a slope of 628.93 and an intercept of 792.67, implying normal distribution parameters of μ=792.67 and σ=628.93 (Figure 5b). Similarly, the normal distribution parameters for ETC are μ=28.9 and σ=2.28. Here, the slope of the Q-Q plot of ETC (σ_{ETC}=2.28) is less than the calculated standard deviation (σ=2.9) implying the considerable non-linear fit of the quantiles as indicated by the lower R^2 value.

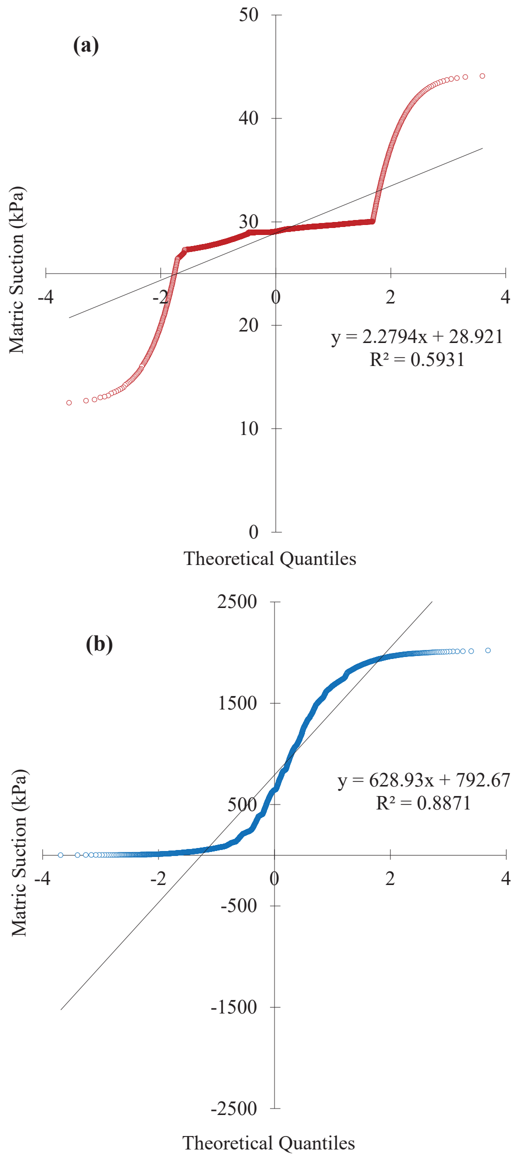


Fig. 5. Quantile-Quantile (Q-Q) plot of measured matric suction @ 0.3 m depth (a) ETC (b) CC

4 Implication of Probability Distribution

Testing the normality of data is a precondition for interpolation and analyzing the data feature because only the normal distribution leads to valid interpolation. This is especially important in geotechnical and geo-environmental engineering because of relatively significant uncertainties in the field conditions. Any data distributed non-normally will necessitate an appropriate transformation of the data before the interpolation is made or it requires selecting other distribution models (e.g., Weibull, Log-normal, Gamma, Gumble, etc.) whose quantiles fit linearly with the data. The major objective of this study was to investigate the impact of engineered turf on the changes in the in-situ soil suction and how the soil suction is distributed in the cover at shallow depths. In this study, the matric suction distribution in the field conditions of both engineered turf cover and clay cover showed a higher degree of non-normality, meaning the matric suction data measured in the field needs transformation or selection of different distribution models for prediction or interpolation. This study revealed the efficiency of engineered turf as the barrier to climate-induced changes in soil matric potential. However, future study demands more rigorous analysis of field-measured matric suction data to develop prediction models. Also, there is a need to consider the time-dependent or seasonal probability distribution of matric suction and moisture content for landfill final covers for conducting any hydrologic or seepage analysis over time.

5 Conclusion

This study evaluated the matric suction distribution of engineered turf cover and compacted clay cover under indistinguishable field conditions in a probabilistic framework. The suction data were collected from installed porous block sensors at both covers at the same depths. The data collected from field instrumentation were statistically analyzed using the R program. Descriptive statistics and the Gaussian distribution theorem were utilized for data explanation. The results from the study indicated a negligible change in matric suction in engineered turf cover at shallow depth (0.3 m) throughout the monitoring period. However, the clay cover underwent noteworthy changes in matric suction, indicating the engineered turf to be the barrier to environmental factors. The degree of dispersion of matric suction was significantly higher for the compacted clay cover than the turf cover. The distribution of suction was non-normal for both covers, which was expected because of the heterogeneity in the in-situ conditions and climatic fluctuations that were confirmed by the histogram, probability density function, and Q-Q plots. Based on the results obtained in this study, engineered turf shows encouraging results to reduce the potential for climate-induced changes in the unsaturated soil behavior at shallow depths. However, it is essential to continue monitoring the matric suction data for a few more years and more rigorous analysis with the long-term data. It is equally important to investigate the changes in the unsaturated soil behavior under an engineered turf at a relatively deeper depth for more applicability of engineered turf as the barrier to environmental factors for landfill final covers, especially in regions that are characterized as humid and tropical.

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