

Investigation of the Effect of Geosynthetics on Climate-Induced Changes in Unsaturated Soil Behavior Using Non-Parametric Measure

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ABSTRACT

The expansive behavior of clayey soil in response to climate-induced changes in the soil water characteristic curve (SWCC) is a significant issue for many types of earth infrastructure. The application of geosynthetic material has been common to reduce the climate-induced changes in SWCC. Engineered turf, which is a composite geosynthetic material, has gained popularity for different earth systems to increase overall infrastructure resiliency. This paper's objective was to investigate engineered turf's effect on the climate-induced changes in SWCC at shallow depths in the field conditions using the statistical non-parametric measure: Spearman rank correlation coefficient (ρ_s). This research hypothesized that since the changes in soil moisture and suction would relatively be simultaneous for exposed ground under variable climate, thereby exhibiting a reasonable negative correlation between water content and suction, whereas the degree of simultaneity in the changes between water content and suction of the soil under the engineered turf would display arbitrary correlation. To test the hypothesis, two test beds, (1) a compacted clay bed (CCB) and (2) a compacted clay bed overlain by engineered turf (ETB), were constructed with expansive soil and instrumented with collocated moisture sensors and tensiometers identically to collect concurrent water content and suction data continuously. The analysis revealed that the estimated ρ_s values for CCB were almost -1.0 during different drying conditions indicating a very strong correlation. On the contrary, the estimated ρ_s values for ETB were $+0.79$ to -0.32 indicating an irrational to a weak correlation between ρ_s . The results indicated the engineered turf to be an effective barrier to climate-induced changes in SWCC.

INTRODUCTION

Background

Most of the earthen structures such as embankments, slopes, pavement subgrade, landfill covers, etc. remain in unsaturated condition. Soil water characteristic curve (SWCC) is an important relationship in the field of unsaturated soil mechanics that describes a correlation between matric suction (ψ) and moisture content (θ) within the soil mass (Fredlund and Rahardjo 1993; Lu and Likos 2004; Lu et al. 2010). The soil in unsaturated conditions is frequently subjected to changes in stress state due to transient wetting and drying climatic conditions (Fredlund and Rahardjo 1993; Rahardjo et al. 2019), the impact of which is reflected in the mechanical and hydraulic performance of these structures over time. This becomes especially

important in the context of problematic expansive soil. Expansive soils tend to exhibit shrink-swell behavior due to climate variations (Chan et al. 2015; Gallage et al. 2017). The variation in water content and matric suction during the periods of precipitation and evaporation affects the volume change response of the active clay of the earth structures. These volume changes can cause ground movements which may result in damage to the structures built on it, or the earth structure itself. As a result, they are a constant source of concern in the design and construction of earth structures (e.g., embankments, pavements, etc.) consisting of expansive soil. However, for geo-environmental structures such as sanitary landfills which are specially designed and built for the safe disposition of municipal solid wastes, the expansive soil is a good choice for final covers and liners because of its suitable hydraulic properties. Owing to the very low hydraulic conductivity of clays, especially swelling clays are the most suitable earth materials for the construction of impermeable liners and final covers in landfills. The very low permeability of swelling clays ($k_s \sim 10^{-9}$ m/s) as the compacted layers or Geosynthetic Clay Liners (GCL) (He et al., 2015) prevents the infiltration of precipitation through the final cover. Nonetheless, the impermeability characteristics of compacted swelling clays are subject to be compromised because of their susceptibility to extreme volume changes and desiccation cracking upon variations of water content and high thermal gradients in landfills (Yu and El-Zein 2019). As an alternative to the compacted clay cover, the water balance cover, also known as the evapotranspiration (ET) cover has been introduced into practice that works on the water store-release principle of soil. However, the post-construction natural processes such as freeze-thaw, wet-dry cycling, and plant root growth significantly alter the soil's hydraulic characteristics from its as-built condition and thereby degrade the cover hydrologic performance (Alam et al. 2019; Benson and Othman 1993).

Various methods have been proposed to reduce the swell-shrink potential and retain the low hydraulic conductivity of expansive soil such as excavation and replacement (Karatai et al. 2016), prewetting (Dafalla et al. 2017), water content control (Nelson et al. 2015), and soil stabilization and reinforcement using straw fibers (Qiang et al. 2014) and polyester fibers (Chaduvula et al. 2017). However, none of these methods have fully resolved the problems of expansive soil. In geoenvironmental engineering applications such as liners and final covers, small flaws in the system can cause significant environmental degradation. Additionally, cost, material availability, and time are other factors of existing methods of expansive soil treatment. Due to being practically impermeable, many waste containment facilities employ geosynthetic materials such as geomembrane, composite geosynthetics, and engineered turf. The geosynthetic material is intended to reduce the infiltration of precipitation into the underlying layer and reduce the change in the unsaturated soil properties, thus reducing the potential of soil shrink-swell behavior induced by climatic variability, eventually, controlling the percolation. However, field investigation of the effect of geosynthetics, especially engineered turf systems on unsaturated soil behavior is very limited in the literature.

Considering the importance of understanding the engineered turf system's ability to reduce the climate-induced changes in SWCC of the soil underneath, the objective of this study was to conduct a field investigation of the effect of engineered turf on the change in unsaturated soil behavior of clayey soil using a non-parametric measure: Spearman Rank Correlation Coefficient (ρ_s). The prediction of characterizing expansive soil behavior over time needs two components: (i) the range of water content or soil suction fluctuations as a function of time; and (ii) the constitutive law that links the soil state variables (i.e., water content, soil suction) (Briaud et al. 2003). Accordingly, it requires a large amount of data and analytics to effectively conclude,

especially for field-scale research. In this study, we analyzed a large volume of field data to investigate the change in unsaturated soil behavior at shallow depths (0.3 m) for (1) a compacted clay bed (CCB), and (2) a compacted clay bed overlain by engineered turf (ETB) for the comparative assessment of the effect of the engineered turf. The goal was to investigate how the in-situ SWCC would respond (degree of simultaneity of the changes in moisture content and suction) to the varying climatic conditions by developing the strength of correlation between moisture content and suction using Spearman's rank correlation coefficient for both the test beds. The weak or irrational correlation between water content and suction of the soil underneath the turf will be indicative of reduced hydrological responses of the soil under varying climates. It is to be noted that the objective of this study was not to illustrate the expansive characteristics of soil, rather the study attempted to investigate the effect of the engineered turf (laid over compacted clayey soil) on unsaturated soil behavior through field instrumentation and data analysis and its practicability.

Principle of Nonparametric Statistical Analysis

In statistics and probability theory, correlation determines the relationships between two random variables. The correlation coefficient is a measure that describes the degree of relationship between the two variables. Traditional parametric statistical correlation tests are widely used in various fields of research. However, it requires certain assumptions about the distribution of the population or sample. One of the basic assumptions in parametric statistical correlation tests is that the data must be normally distributed. Hence, parametric statistical analyses are conducted only after the assumptions are satisfied. However, if the principles are not satisfied because of the skewed distribution of the data or unknown data distribution because of a small population or sample size, parametric statistical techniques cannot be employed. In such cases, non-parametric statistical techniques are excellent alternatives. Non-parametric statistical correlation tests significantly differ from parametric tests because the non-parametric method considers positive or negative signs or the rank of data sizes instead of the original values of the data. Engineering variables, especially in geotechnical and geo-environmental engineering applications, are likely to have a non-normal distribution of data. In the context of field-monitored data, the data distribution may be more skewed or unknown because of extreme heterogeneities in the field conditions. Hence, non-parametric statistical correlation is essential in geotechnical and geo-environmental engineering. Non-parametric statistical techniques have various advantages such as less possibility to reach incorrect conclusions because data distribution assumptions are not necessary, are not greatly affected by outliers, and can be used even for small samples. Nonetheless, non-parametric statistical techniques have certain disadvantages. In the non-parametric method, actual differences in a population cannot be characterized, sometimes difficult to interpret data, have only a few analytical methods, and computation becomes complicated for a large population or sample, etc. The non-parametric analysis methods reduce the risk of incorrect conclusions but may have lower statistical power. In geotechnical engineering, where engineers deal with extreme heterogeneities in soil behavior, the non-parametric statistical tests seem to be more flexible than parametric tests.

Spearman Rank Correlation Coefficient (ρ_s)

Spearman's rank correlation coefficient (ρ_s) test is a rank-based non-parametric measure of the strength and direction of the relationship between two independent variables without any

assumptions about the data distribution (Gauthier, 2001), except the only assumption of ρ_s is the dataset being ordinal and are monotonically related. Any dataset measured on an ordinal scale can be replaced by the corresponding rank of the dataset, and the estimated rank-based ρ_s implies the strength of association between two ranked variables to indicate the degree of agreement between the ranks of the two sets of variables (Myers et al. 2010). The ρ_s is a great tool for correlation analysis between two variables even after missing values. In field conditions, obtaining θ and ψ data is often challenging. Additionally, continuous field measurement of θ and ψ data may be interrupted because of malfunction of sensors and instrumentation, flawed installation, and damage of instrumentation after installation due to natural conditions, which is very common in the field. Hence, considering the data discontinuity in the field, ρ_s can be a great tool to measure the degree of correlation between θ and ψ at the field conditions. This research postulates that the changes in θ and ψ would relatively be simultaneous for CCB under variable climate, thereby, exhibiting a reasonable negative correlation (ρ_s) between θ and ψ . On the other hand, if the engineered turf is an effective barrier, the degree of simultaneity in the changes between θ and ψ of the soil of ETB would display an arbitrary correlation. For a sample size of N , the N number of raw data (A_i, B_i) are converted to their ranks (a_i, b_i), and Spearman's rank correlation coefficient (ρ_s) is calculated using the following equation.

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

where $d_i = x_i - y_i$, is the difference between ranks. The numerical value of the correlation coefficient (ρ_s), ranges between -1 and +1. This correlation coefficient indicates how the scores are related. In general, $\rho_s < 0$ implies a negative agreement and $\rho_s > 0$ implies a positive agreement between the variables. If the ρ_s value appears as 0, it indicates there is no agreement between the variables (no relationship between the variables at all). The closer the coefficient is to 1, the better the positive correlation (strong positive agreement between the variables), whereas the ρ_s value closer to -1 indicates a strong agreement in the negative correlation. The degree of strength of the correlation for the absolute value of ρ_s which is commonly followed is: (1) very weak ($0 \leq \rho_s < 0.2$), (2) weak ($0.2 \leq \rho_s < 0.4$), (3) moderate ($0.4 \leq \rho_s < 0.6$), (4) strong ($0.6 \leq \rho_s < 0.8$), and (5) very strong ($0.8 \leq \rho_s \leq 1.0$).

MATERIALS AND METHOD

Construction and Instrumentation

Two large-scale test sections of dimensions 3 m $\times$ 3 m were constructed side-by-side as shown in Figure 1. The existing subgrade where the test sections were constructed consists of high plastic clayey soil (CH). Based on the laboratory investigation of the collected samples, the fine fractions of the samples were found to be more than 70-90%. The liquid limit (LL) and plasticity index (PI) of the soil were found in the range between 52 to 71% and 27 to 39%, respectively. One test section was constructed as CCB, and the other was constructed as ETB.

After excavating the test pit, each test section's subgrade bottom and sidewall were overlain by a 6-mil impermeable plastic sheet. Placing the plastic sheet along the sidewall was important to avoid intra-section moisture flow and ensure the soil's response to climatic events. Then the test pits were backfilled with the excavated soil. A few days after the backfilling, moisture sensors, and tensiometers were installed at co-located depths to closely monitor changes in

unsaturated soil behavior or SWCCs in the field test sections. The sensors installed at the test pits were connected to an automatic data logging system. This study analyzes the data obtained from the set of sensors installed at 0.3 m depth. A weather station was also installed at the site to capture the climatic parameters (e.g., precipitation, air temperature, etc.). Immediately after the instrumentation and smoothening of the top surface (of ETB), a structured LLDPE geomembrane (Figure 2) was placed, which was overlain by synthetic turf. The textured side was laid facing the ground. The synthetic turf was comprised of polyethylene fibers tufted through a double layer of woven polypropylene geotextiles and sand infill.



Figure 1. Construction activities and instrumentation.

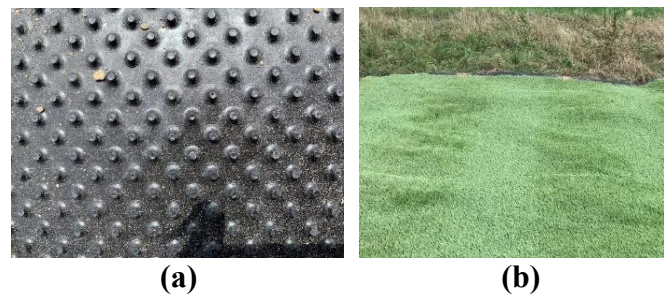


Figure 2. (a) Textured geomembrane layer (b) engineered turf.

Data Analysis

In this study, we investigated the degree of simultaneity of θ and ψ at 0.3 m depth for both test beds. Spearman's rank correlation coefficient (ρ_s) was used to investigate the degree of simultaneity by summarizing the strength of the correlation between the variables. During the field data monitoring, the wetting (sorption) SWCCs were observed significantly faster than the drying SWCCs (for the CCB). Consequently, almost all the data pairs of θ and ψ almost converged to the point of saturation (maximum θ and minimum ψ) during the sorption process producing no appreciable SWCCs. On the other hand, the drying (desorption) process was gradual and well-identified. Therefore, drying SWCC was considered for the ρ_s calculation. First, the data of θ and ψ from the CCB was identified at the times when the soil at 0.3 m was observed gradually drying. The CCB was required to be the standard to classify the data because the θ and ψ variabilities observed in the CCB had comprehensible distinction under climatic influences. The same timeframe was assigned for the ETB to identify corresponding data of drying. Three drying events were identified during the monitoring period indicated in Figure 3.

In the ρ_s calculation, all the observations (N) of the θ (X_i) and ψ (Y_i) pairs were considered, including the repetitive data (almost 24000 pairs). Though repetitive data is typically not

recommended in ρ_s calculation, however, to maintain consistency in the analysis, the data classified in the identified drying timeframe were used in the analysis. Additionally, the data repetition for both testbeds was not similar. On top of that, considering the repetitive data doesn't affect the Spearman rank correlation coefficient significantly. The X_i and Y_i data were converted to their ranks (x_i, y_i), and ρ_s was calculated using Equation (1).

RESULTS AND DISCUSSION

Field Variations of Moisture and Suction

The changes in θ and ψ under the field climatologic variabilities are presented in Figure 3. During the monitoring period (February 2022 to July 2022), several precipitation events of different intensities and duration, and temperature fluctuations were observed which influenced the change in the θ and ψ in the CCB as observed in Figure 3. The sharp rises in θ are an indication of immediate soil wetting due to rainfall events. Unlike the sharp rises in θ due to rainfall, the rate of drying was relatively slow. The air temperature during the monitoring period was in the range of 55 to 85°F covering a moderately cold to high summer temperature. The change in ψ was also similar to the change of θ , especially in the wetting process when the matric suction rapidly dropped to almost 0.4 kPa (apparently indicating fully saturated condition) after significant rainfall events. During the drying of the soil, the rate of increase of ψ was relatively faster than the rate of change (decrease) of θ . It is to be noted in Figure 3 that qualitatively, both θ and ψ had synchronized variation at 0.3 m depth of CCB. In other words, the degree of simultaneity of θ and ψ is quite factual. In contrast to CCB's θ and ψ variation at 0.3 m depth, the soil of ETB at the same depth demonstrated almost straight paths of propagation, especially the θ profile. The initial θ measured at the inception of data monitoring of the ETB was nearly 0.21 m³/m³ and demonstrated that the soil was unaffected by the climatic influences as indicated by the almost flat θ profile. The ψ profile at 0.3 m depth of ETB further supports the phenomenon of the soil being reasonably non-responsive to climatic variabilities. The ψ for ETB ranged between almost 12 to 39 kPa throughout the monitoring period exhibiting a low degree of dispersion (coefficient of variation 25%). On the other hand, the ψ for CCB ranged between 0.4 to 1933 kPa at identical climatic conditions with a very high degree of dispersion (coefficient of variation more than 100%). Comparing the patterns of changes in the SWCC (change in θ and ψ) for both the testbeds at 0.3 m depth under identical atmospheric conditions, the CCB exhibited distinct significance of its unsaturated soil behavior than the ETB.

Evaluation of Spearman's Rank Correlation Coefficient (ρ_s) and In-Situ SWCC

The Spearman's rank correlation coefficient (ρ_s) was estimated to investigate the concurrent changes in θ and ψ (field SWCC) for the exposed ground (CCB) and the soil under the engineered turf (ETB), and how closely they are associated. The plots of the ranks of θ and ψ identified from the three drying conditions (D-1 through D-3) for CCB and ETB are presented in Figures 4(a) and 4(b), respectively. As projected, Figure 4(a) demonstrates the negative relationships between the ranks of θ and ψ indicating the CCB's delicate response to the soil's unsaturated behavior at 0.3 m depth. Here the relatively small rank plot of D-2 compared to D-1 and D-3 is because of the short drying duration (Figure 3). However, all the rank plots exhibit negative relationships. One fact to be pointed out in Figure 4(a) is the disuniting of the ranks

from its path around 4500 to 7000 observations for D-3, where it is observed that at a specific rank of ψ , there were multiple ranks of θ . This phenomenon was also observed in D-1. Density-based data clustering revealed that almost all those deviated ranks were near the field air entry value (AEV) of approximately 13 kPa. We anticipate that the non-consideration of the repetitive data would have removed these. The estimated ρ_s values are presented in Table 1. The ρ_s values were almost -1.0 indicating a very strong correlation between θ and ψ . In other words, the change of θ and ψ was concurrent which is theoretically justified.

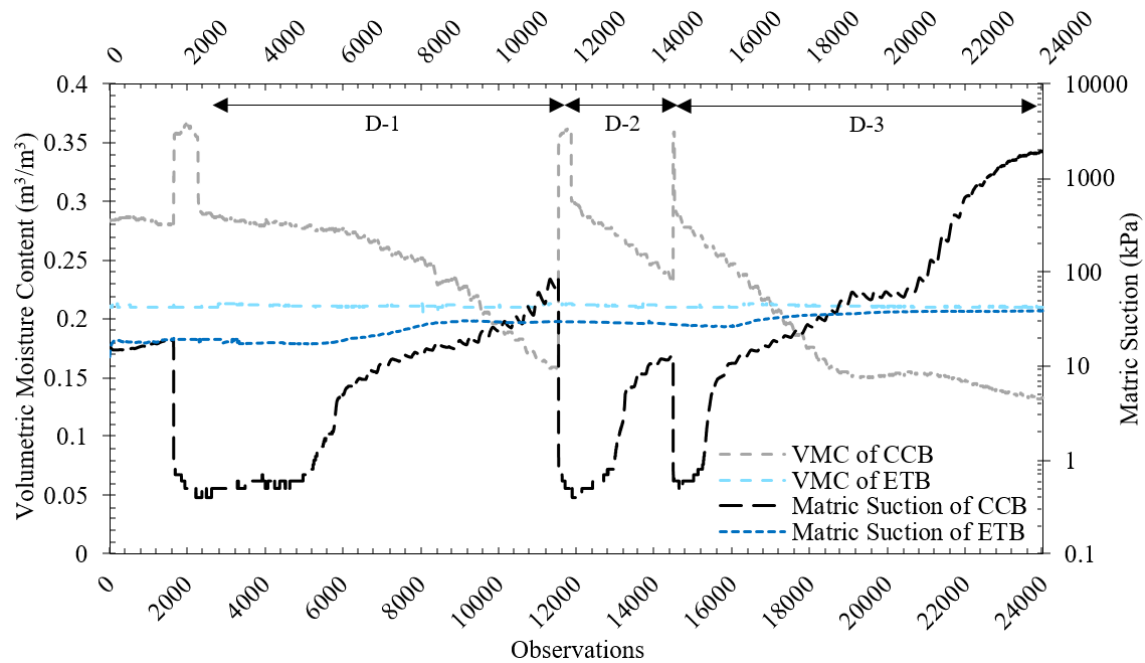


Figure 3. Field variation of soil moisture and suction

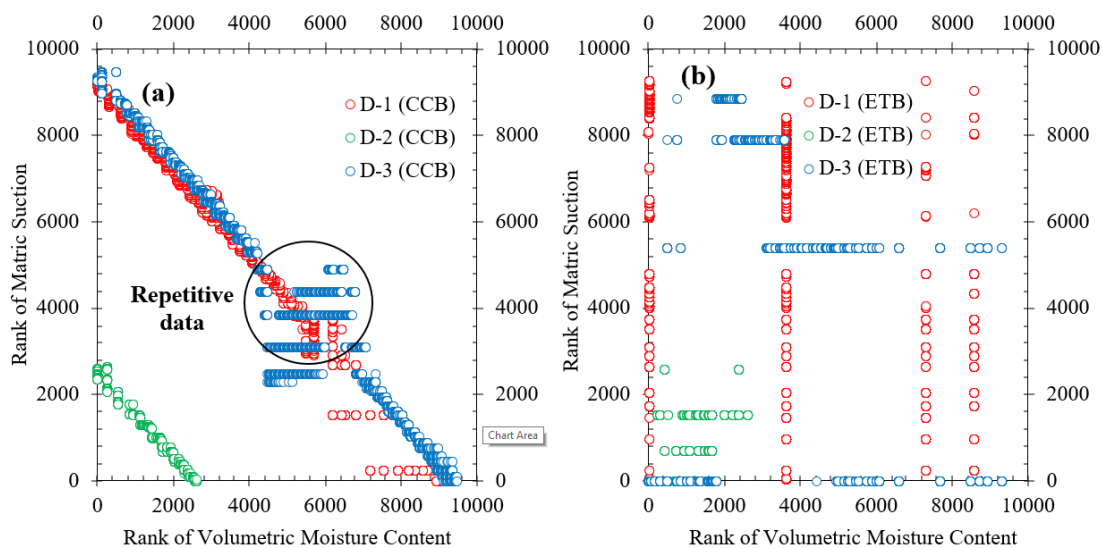
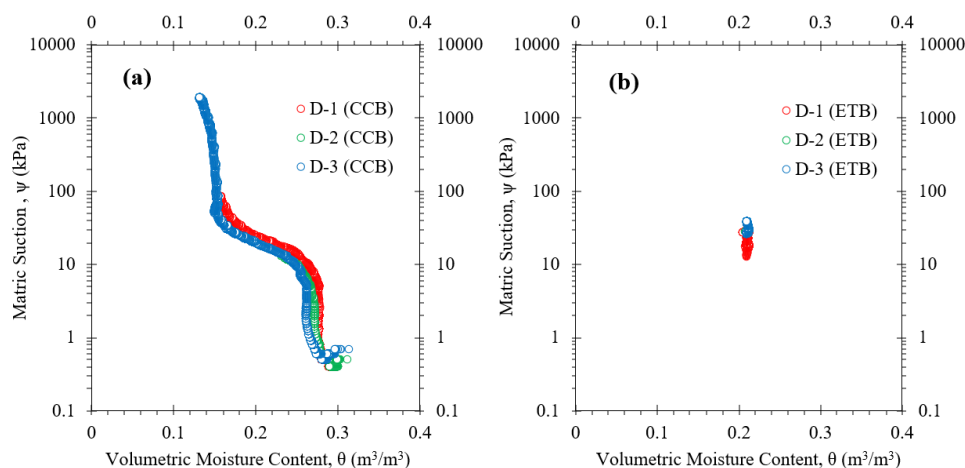


Figure 4. Scatterplot of ranks of θ and ψ (a) CCB, (b) ETB, and field plot of SWCCs (c) CCB, (d) ETB

Table 1. Spearman Rank Correlation Coefficients (ρ_s) for different drying

Field Drying (D)	<i>Spearman Rank Correlation Coefficient (ρ_s)</i>	
	CCB	ETB
1	−0.99537	−0.30378
2	−0.99609	+0.79050
3	−0.97134	−0.32099

On the other hand, in the soil at 0.3 m depth of ETB, the ρ_s exhibited an irrational to weak correlation (Table 1), also portrayed in Figure 4(b) where the ranks of θ and ψ are randomly scattered with an uninterpretable pattern. For D-1 and D-3, the estimated ρ_s were -0.30 and -0.32, respectively, demonstrating a weak correlation. This could practically be theorized because of a significant amount of lag time in coupling the θ and ψ . Most noticeably the ρ_s value appeared to be +0.79 of D-2. Conceptually, the θ and ψ are inversely correlated, meaning soil suction decreases with the increase in moisture or vice versa. Therefore, a positive ρ_s value correlating the θ and ψ is theoretically unjustifiable. However, the analyses with the real-time data obtained in cycle D-2 practically demonstrated the positive ρ_s correlation. Therefore, the field meteorological events didn't influence in changing θ and ψ of the soil under the engineered turf. This could further be comprehended from the field-coupled SWCC plotted in Figure 5. Figure 5(a) presents the desorption plot of the field SWCC of the CCB that occurred at 0.3 m depth. It is observed that all the drying paths retained a clearly defined sigmoidal shape with two SWCC asymmetries displaying the different boundary conditions of SWCC (i.e., boundary effect stage, transition stage, and residual stage). On the other hand, with the data obtained in the same time frame as CCB, the SWCC plot of the soil at 0.3 m depth of the ETB technically exhibited a point in the semi-logarithmic scale. To further understand the correlation of θ and ψ of ETB and its distribution, θ and ψ data of the ETB are plotted in the arithmetic scale in Figure 6. It is observed that the θ is constricted around 0.204 to 0.213 m^3/m^3 , and the ψ between almost 15 to 40 kPa with different degrees of dispersion as indicated by the significantly lower coefficient of determination ($R^2 = 0.03$ and 0.06 , for D-1 and D-3, respectively). For D-2 (Figure 6b), though the R^2 ($R^2 = 0.61$) indicates relatively a moderate relation between θ and ψ , however, the positive slope of the regression curve is not supposedly justified.

**Figure 5. Field plot of SWCCs (a) CCB, (b) ETB**

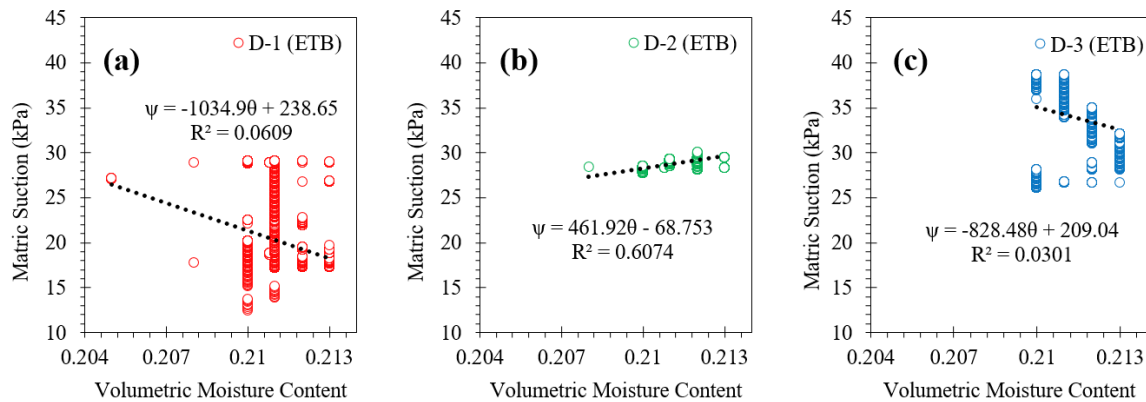


Figure 6. Augmented plots of SWCC of ETBs in arithmetic scale

The statistical significance for ρ_s exhibited a significance level of less than 0.05, which led to the rejection of the null hypothesis, and there is an exact correlation between θ and ψ for CCB. It signifies that the changes in θ and ψ were instantaneous in CCB which were comprehended by the realistic SWCC constitution in the field. On the other hand, the soil at 0.3 m depth of the ETB produced a non-interpretable SWCC indicating an inconsequential influence of climatic conditions on the soil beneath the engineered turf.

This research hypothesized the changes in unsaturated soil behavior can be evaluated using the non-parametric test: Spearman Rank Correlation Coefficient, and to evaluate the effect of engineered turf on the impact of the climatic variabilities affecting soil unsaturated behavior using this non-parametric measure. The analysis demonstrated the hypothesis to be satisfactory. In the era of big data, where a significant amount of data is gathered during field investigation in different engineering applications, the efficient and quick data analysis of field-instrumented data can provide deep insight and create value in the design and management of civil infrastructures.

CONCLUSION AND PRACTICAL SIGNIFICANCE

Soil moisture and suction data obtained from field instrumentation at 0.3 m depth of two testbeds: (1) a compacted clay bed, and (2) a compacted clay bed overlain by engineered turf have been statistically analyzed and presented in this study. The non-parametric Spearman's rank correlation coefficient was used to test the hypothesis of this research by determining the correlation strength between the two state variables for both test beds at identical depths. The unsaturated soil response of the compacted clay bed was significantly responsive to climatic variation. The Spearman's rank coefficient showed that soil moisture and suction are very strongly correlated ($\rho_s \approx 1$) indicative of simultaneous changes in soil moisture and suction. This was also realized by the realistic constitution of SWCC of the compacted clay bed. On the other hand, no justifiable correlations ($\rho_s \approx -0.30$ to $+0.79$) were observed for the compacted clay bed overlain by engineered turf. The SWCC plots were also concentric in the pattern where no meaningful interpolation could be made. Therefore, the field data and analytics demonstrated engineered turf to be resilient to climate-induced changes in unsaturated soil behavior. In practice, engineered turf has been used as a combination of synthetic turf and geomembrane underneath. However, future research may endeavor the applicability of the synthetic turf only for technical efficiency along with a cost analysis with the geomembrane integrated engineered turf.

There is a huge amount of both structured and unstructured data that is gathered and stored in the field of geotechnical and geo-environmental engineering. Data analysis can give the engineers the power to make use of the data generated which is difficult to collect and analyze manually in an effective way. Without a method of precise verification and analysis, all data is useless. The availability of a large amount of field monitoring data obtained in this study has enabled us to take advantage of analytically characterizing the in-situ unsaturated soil behavior. Though the outcome of this study is site-specific, the analytical method applied in this study using the simple non-parametric statistical test with a relatively large dataset provided valuable insight. In addition, the non-parametric test applied in this study can also be significant where there is an interruption in data collection. Future research demands investigating the field SWCCs for both exposed ground and engineered turf at shallow and deeper depths with massive data and developing a unique prediction model with various machine learning models.

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