Investigating Sub-soil Moisture Variation of Engineered Turf Cover for Landfills Through Field Instrumentation

Md. Jobair Bin Alam(✉) and Maalvika Aggarwal

Prairie View A&M University, Prairie View, TX 77446, USA
mdalam@pvamu.edu

Abstract. Understanding the moisture distribution pattern and associated suction variability of soil in response to environmental loading (e.g., precipitation, temperature) is important. However, there is a lack of understanding of the spatial variability of moisture and suction in different final cover systems. In this study, the spatial correlations between soil moisture and suction data from field instrumentation are examined using Spearman's rank correlation test of three different types of landfill final cover systems: evapotranspiration (ET) cover, conventional clay cover, and engineered turf cover, under identical atmospheric conditions. In addition, box and whiskers plots were used to investigate the distribution of the field-measured data under environmental fluctuation. As observed from the box plot, soil moisture displayed maximum spatial heterogeneity in clay cover and very less in the engineered turf cover under identical environmental conditions. The ET cover exhibited a very strong spatial correlation of moisture and suction as indicated by the highly significant Spearman's rank correlations (r_S) ranging from −0.88 to −0.93. The clay cover showed a strong to moderate correlation ($-0.51 < r_S < -0.74$) between the spatial distribution of moisture and suction. On the other hand, the engineered turf cover displayed poor agreement of the spatial moisture-suction distribution implying the soil under the engineered turf is relatively non-responsive under environmental variability compared to clay and ET cover. The preliminary findings from this study showed engineered turf's capacity to maintain more moisture stability of the turf under the humid subtropical climate than other landfill covers.

Keywords: Engineered Turf · Landfill Cover · Spearman's Rank Correlation

1 Introduction

1.1 Background

A landfill final cover is a multi-layered system composed of various materials. The final cover is constructed over the landfill to achieve three primary goals: waste isolation from the environment, infiltration minimization (reduce moisture intrusion from precipitation in the soil), and control of fugitive gas (CH_4) emissions [1]. Hence, the final cover system of landfills is one of the major components of engineered landfills, and failure or

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poor performance of the final cover may lead to significant environmental contamination. There are two basic types of final cover systems: conventional and alternative or evapotranspiration (ET) covers.

A conventional or prescriptive cover consists of several layers, such as compacted clay or geosynthetic clay liner (GCL), geomembrane, drainage, and topsoil layers [2, 3]. The main concept of a conventional cover is to construct a low hydraulic conductivity compacted soil (clay) layer to prevent the infiltration of precipitation into the waste mass. This layer has been termed the barrier layer or resistive layer. The cover systems with barrier layers are also referred to as resistive covers [4]. However, the conventional cover or resistive barrier has disadvantages, the most important of which are soil erosion or crack formation, leading to performance reduction with time and eventually environmental degradation. This type of cover is also associated with high cost and difficulty of construction [5]. The compacted soil layers desiccate due to extensive moisture loss (increased soil suction) and form cracks in the cover which, in turn, create irreversible changes in the cover soil and result in uncontrolled water flux. As such, compacted clay layers often fail to fulfill the objective of controlling precipitation infiltration.

ET covers, also known as Water Balance covers are increasingly being considered for the final closure of landfills for their enhanced performance compared to the conventional cover system. 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 [6, 7]. Therefore, both soil and plant become crucial components of the ET cover system, unlike the compacted clay cover where the soil is the main component that acts as a resistive layer to control moisture movement. It is also a cost-effective solution for waste containment [8]. Most importantly, the performance of ET covers enhances with time [6]. However, the performance of ET covers largely depends on site-specific factors. The field hydrology of ET covers is strongly influenced by soil hydraulic properties. The post-construction natural processes such as freeze-thaw cycling, wet-dry cycling, plant root growth, and animal burrowing significantly alter the soil's hydraulic characteristics (e.g., hydraulic conductivity, soil water characteristic curve) from its as-built condition and thereby influence the cover hydrology [9, 10]. Hence, over time, the changed hydraulic properties of ET cover soils allow easy moisture intrusion that significantly affects the percolation rate [11–13]. Therefore, though, ET covers offer better performance compared to conventional covers, they are not fully capable to reduce moisture intrusion, and eventually reducing percolation.

In recent years, attempts have been made to overcome the shortcomings of ET covers and conventional covers by introducing engineered turf covers. Engineered turf covers are increasingly being accepted by landfill owners due to the ease of installation, applicability on steep slopes, reduced construction and operation cost, minimum maintenance requirements, and most importantly controlled moisture movement in the waste, eventually controlled or no percolation. As such engineered turf cover can be a viable option for landfill final closure from a technical advantage and economic point of view. However, the long-term performance of such type of cover systems needs to be validated with extensive field studies [14]. To the best of the authors' knowledge, the sub-soil moisture variation, and its associated change in soil suction below engineered turf have not been investigated yet. Considering the importance of understanding the spatial and temporal variability of the moisture and suction under an engineered turf, the objective of this study was to investigate the moisture and suction variation of the cover soil below an engineered turf through field instrumentation. In addition, a relative comparison of moisture-suction variability among the turf cover, ET cover, and compacted clay cover was performed under identical environmental conditions. The moisture-suction variability was conducted using descriptive statistics: boxplot explanatory analysis and the spatial correlation of simultaneous changes of the moisture and suction was evaluated using Spearman's rank correlation coefficient.

1.2 Spearman's Rank Correlation Coefficient

In statistics and probability theory, correlation is a method of analyzing relationships between two variables. The correlation coefficient is a measure that identifies the degree of association between two variables. It is to be noted that the correlation coefficient calculation is not intended to identify the causal relationship between variables. There are various types of correlation coefficient measures such as Pearson's correlation coefficient, Spearman's rank correlation coefficient, and Cramer's correlation coefficient, etc. Among the different correlation coefficient measures, the most commonly-used correlation coefficients are Pearson and Spearman. However, Pearson's correlation coefficient is used to identify the linear correlation between two variables. Moreover, Pearson's correlation coefficient is calculable only when both variables are present. Therefore, Pearson's correlation coefficient is not useful when there are missing values. On the contrary, Spearman's rank correlation coefficient can perform better than Pearson's because it calculates the basic rank of variables even if there are missing values. Since continuous field measurement of moisture content and matric suction may be interrupted because of sensors' malfunctioning which is very common in the field, this paper uses Spearman's rank correlation coefficient to measure the degree of correlation between moisture and suction at the field condition.

Spearman's rank correlation test is a rank-based test for correlation between two independent variables without any assumptions about the data distribution [15]. However, the only assumption of Spearman's rank correlation is that the data must be at least ordinal, and scores on one variable must be monotonically related to the other variable. Spearman's rank correlation coefficient (r_s) is a non-parametric measure of the correlation between the variables, using ranks to calculate and measure the correlation. Any dataset measured on an ordinal scale can be replaced by the corresponding rank of the dataset, and the r_s value estimated based on the ranks implies the strength of association between two ranked variables to indicate the degree of agreement between the ranks of the two sets variables [16]. 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 (r_s) is calculated using the following equation.

$$r_s = 1 - 6\frac{\sum d_i^2}{N\left(N^2 - 1\right)} \tag{1}$$

where $d_i = a_i - b_i$, is the difference between ranks. The numerical value of the correlation coefficient (r_s), ranges between -1 and $+1$. This correlation coefficient indicates how

(a) (b) (c) (d)

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

the scores are related. In general, $r_s < 0$ implies a negative agreement and $r_s > 0$ implies a positive agreement between the variables. If the r_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 r_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 r_s which is commonly followed is: (1) very weak ($0 \leq r_s < 0.2$), (2) weak ($0.2 \leq r_s < 0.4$), (3) moderate ($0.4 \leq r_s < 0.6$), (4) strong ($0.6 \leq r_s < 0.8$), and (5) very strong ($0.8 \leq r_s \leq 1.0$).

2 Materials and Method

2.1 Description of Study Area

The study was conducted in a subtropical climatic region in South Texas. Three large-scale test sections were excavated with dimensions of 3 m × 3 m (10 ft. × 10 ft.) and 1.22 m depth as shown in Fig. 1(a). The excavated soils from the test sections were predominantly fine-textured. The three test sections were constructed as (1) ET cover using native vegetation, (2) compacted clay cover, and (3) engineered turf cover. The test sections were constructed side-by-side, ensuring that each test section is 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, and it extended to approximately 0.6 m (runout length) along the top surface. To allow water to flow under gravity and prevent the accumulation of water in the test pits after heavy rainfall, the bottom of the excavated pit was sloped by 2% and a sand strip was placed at the sloping end.

After the plastic sheet was placed at the bottom and inner wall, the excavated fine-grained soil was backfilled (Fig. 1b) to all the test sections and compacted. 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 (Fig. 1c) was placed after surface smoothening, followed by the laying of synthetic turf (Fig. 1d) over it. In the synthetic turf, polyethylene fibers were tufted through a double layer of woven polypropylene geotextiles and sand infill. Local grass seed was seeded on the top surface of the ET cover.

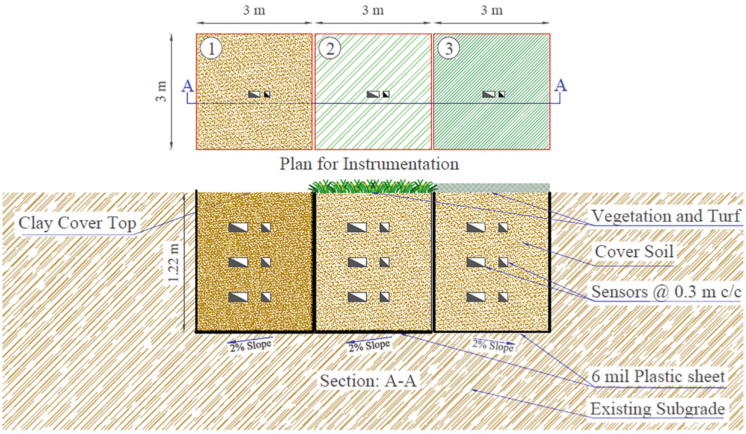

Fig. 2. Instrumentation plan and section.

2.2 Soil Characteristics

The soil samples were collected from each test section during the excavation period. All the samples were laboratory characterized by the American Society for Testing and Materials (ASTM) standards. More than 70% of the soil was fine fractions based on the wet sieve analysis. It was found that the liquid limit (w_L) and plasticity index (IP) of the soil were around 52% and 27%, respectively. The soil was classified as high-plastic clay (CH) by the Unified Soil Classification System (USCS). The results from the Standard Compaction Test demonstrated that the maximum dry density ($\gamma_{d(max)}$) was between 16.7 to 17.3 kN/m^3 and the optimum moisture content (OMC) was found between the range of 15 to 16.5%.

2.3 Instrumentation

Numerous moisture sensors and tensiometers were installed at varying depths in the field test sections to monitor the volumetric moisture content (VMC) and the negative pore-water pressure (suction). Figure 2(a) shows the plan and the section of the instrumentation. Moisture sensors were installed at every 0.3 m (1 ft.) interval. Tensiometers were also installed at every 0.3 m depth to measure the soil suction. Both the moisture sensors and tensiometers were installed at co-located depths to investigate the change in moisture and the associated change in soil suction. A weather station was installed at the site 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.

2.4 Data Analysis

In this study, we investigated the variation of moisture and soil suction at three different depths. Box and whisker plot was used to investigate the spread out of the moisture and soil suction data (total of 34567 observations for each measurement) at different depths to compare the distribution between different cover types under identical climatic conditions. Spearman's rank correlation coefficient (r_s) was used to investigate the correlation between moisture content and soil suction synchronized under the influence of environmental variabilities at every measurement depth by summarizing the strength of the correlation between the variables. The change in soil moisture content and the corresponding change in soil suction is referred to as the soil water characteristic curve (SWCC). So, how the field SWCCs would respond (degree of simultaneity of the changes in moisture content and suction) to the fluctuating climatic conditions was investigated using Spearman's rank correlation coefficient. In the field conditions, it is very likely for hysteresis of the SWCC. The difference between the drying and wetting SWCC curves is referred to as the hysteresis of soil. During the field data monitoring, the wetting SWCCs were significantly faster than the drying SWCCs. Consequently, it was very difficult to effectively classify the data set for the wetting SWCCs. Therefore, drying SWCC was considered for the r_s calculation. The data of VMC and suction from all the covers at the three different depths were identified at a particular time when the soils were observed gradually drying. In the r_s calculation, the total number of concurrent observations (N) of the VMC (A_i) and suction (B_i) pairs were different for the three covers at different depths (after removing all the repetitive data). The A_i and B_i data were converted to their ranks (a_i, b_i), and Spearman's rank correlation coefficient (r_s) was calculated using Eq. (1).

3 Results and Discussion

3.1 Effect of Precipitation on Moisture and Suction Distribution

Significant moisture and suction variation patterns were observed under the fluctuating environmental conditions in the three different types of cover. The response of VMC and soil suction at 0.3 m depth is presented in Fig. 3(a). It was noticeable that the soil of the compacted clay cover and ET cover were delicately responsive under different rainfall events. As can be seen from the figure that the VMC spiked up to 0.35 m^3/m^3 at rainfall events of around 3 to 6 mm. After any rainfall events, the VMC gradually decreased from the peak until the next rainfall event was observed. The clay cover was relatively more responsive than the ET cover (Fig. 3a). It is to be noted that though the compacted clay cover had no plants seeded after the construction, a few months after construction, the clay cover had unintended germination of local grass incurred from natural processes. Contrary to the moisture distribution in clay and ET cover, the VMC profile of the soil under the engineered turf was almost flat. At 0.3 m depth, the VMC consistently prevailed at almost 0.21 m^3/m^3 throughout the monitoring period. This signifies that the moisture distribution from precipitation under the turf was inconsequential indicating the engineered turf to be an effective moisture barrier.

A similar phenomenon was observed in the change of soil suction under the precipitation events as shown in Fig. 3(b). Soil suction for clay and ET cover at 0.3 m depth dropped to almost 0.3 kPa after the rainfall events. It is to be noted that the tensiometers used in this study showed the lowest suction to be almost 0.3 kPa. None of the suction readings in any tensiometers used exhibited 0 kPa suction during the wet condition of

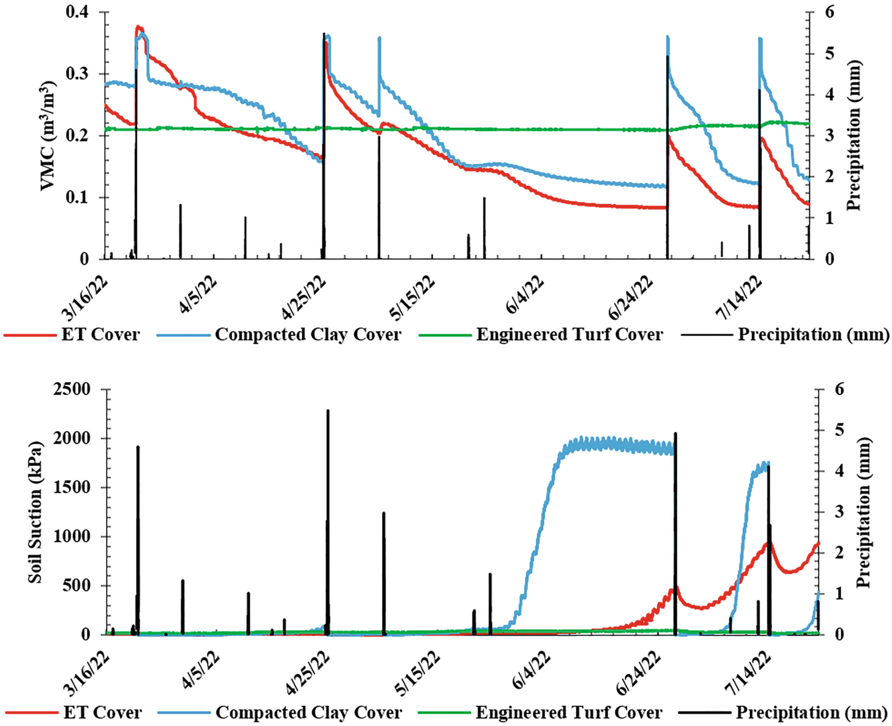

Fig. 3. (a) Moisture and (b) suction variation of three different types of cover at 0.3 m depth

the soil (after precipitation). The discernible changes in suction in the clay and ET cover soil were observed from late May 2022 when the atmospheric temperature started to rise. From June 06 to June 27 of 2022, there were no rainfall events and the suction at 0.3 m depth for the clay cover sustained at almost 2000 kPa and dropped to 0.3 kPa after the rainfall event on June 27, 2022. Then it started to rise again. The changes in suction in the ET cover soil were similar to the clay cover, however, numerically the suction values were significantly lower than the suction in the clay cover at 0.3 m depth. Compared to ET and clay covers, the changes in suction were noticeably insignificant under the same environmental conditions. The suction ranged from 15 kPa to almost 44 kPa throughout the monitoring period. Therefore, based on the moisture and suction profile of the three different covers, it can be inferred that the engineered turf can effectively be a barrier to precipitation. However, it is important to investigate the durability and resiliency of engineered turf exposed to the environment for a long time to test its efficiency as a flawless barrier to moisture.

The changes in VMC and suction at 0.6 m and 0.9 m depths were also recognizable for clay and ET cover like the change in 0.3 m depth. However, for the turf cover, the changes were like the trend that occurred at 0.3 m depth. The variation of moisture and suction of different covers' soil at different depths are explained in Fig. 4 through the standardized box and whisker plot. It is noticeable from Fig. 4(a) that the soil moisture of the clay and ET cover at 0.3 m depth are more spread out which was also intelligible from

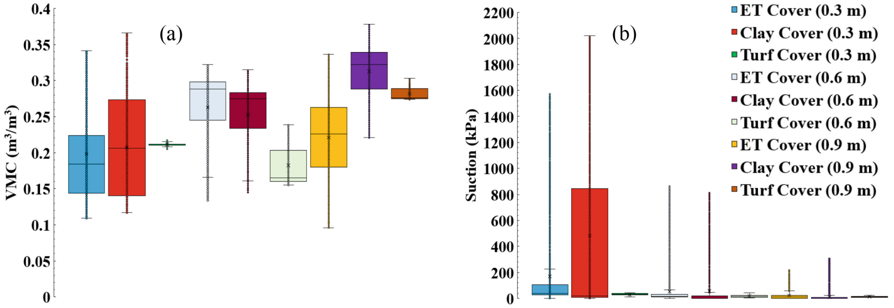

Fig. 4. Box and whisker plot of the measured (a) volumetric moisture content and (b) suction.

the time series plot in Fig. 3(a). 25% of the moisture data (out of 34576 observations) were in the upper end of the whisker (0.225 to 0.34 m^3/m^3), and 25% of data were in the lower end whisker (0.11 to 0.14 m^3/m^3), and 50% data were in the range between 0.14 to 0.225 m^3/m^3. Therefore, there was noticeable soil moisture variation in ET cover at 0.3 m depth. The moisture data in the clay cover was even more spread out at 0.3 m depth. 50% of the data were in the upper end of the box (widely ranging from 0.21 to 0.37 m^3/m^3), and 50% of the data were in the lower end (median to minimum value) (0.12 to 0.21 m^3/m^3). However, the degree of dispersion of moisture content of turf cover is narrowed from 0.205 to 0.22 m^3/m^3 including a few outliers. Outliers are the observation in a data set that is numerically distant from the rest of the dataset. It indicates the change in soil moisture (0.3 m) in response to environmental fluctuation was substantially low as almost all the moisture data are clustered near the mean moisture content.

At 0.6 m depth, the degree of dispersion of moisture data was not as wide as it occurred at 0.3 m depth for clay and ET cover. The soil of ET cover at 0.6 m depth had 50% moisture data ranging from 0.165 to 0.29 m^3/m^3 excluding the outliers. The clay cover had a similar distribution of ET cover at 0.6 m depth. At 0.9 m depth also had a wide degree of dispersion for both clay and ET cover (Fig. 4a). However, the ET cover soil had relatively more spread out of the moisture data than the soil of clay cover at 0.9 m depth. Based on the box plot analysis, it can reasonably be inferred that the soil of ET cover and clay cover is highly responsive to rainfall and evapotranspiration up to a depth of 0.9 m. In contrast, the soil of turf cover at 0.6 m and 0.9 m depths had a significantly lower degree of dispersion of the moisture data. The box plot of turf cover at 0.6 m depth shows a little spread out of the moisture data, however, not significant as clay cover or ET cover at the same depth. Therefore, from the statistical distribution of the moisture data, it is obvious that the soil under an engineered turf is unresponsive to environmental variation.

In Fig. 4(b), the box plot of soil suction shows that the soil of ET and clay cover at 0.3 m depth had a significant spread out of the data due to the closer proximity of the environment. At 0.3 m depth of ET cover, the maximum value was around 210 kPa, and the distribution of outliers ranged from 210 to 1560 kPa. An understandable reason could be observed in Fig. 3(b). Soil suction visibly started to rise in the summer of 2022 (mid-June of 2022) and continued to vary until the end of the monitoring period. However, from the beginning of the monitoring period until mid-June, which is almost

2/3 of the monitoring period, the soil consistently had very low soil suction. So, the median value tended to be near 40 kPa. In clay cover at 0.3 m depth, though no outliers were observed, 25% of the data were on the upper end of the whisker between 840 to 2040 kPa (wide range of distribution), and 75% of data were in the lower end (minimum to the upper quartile) ranging from 0.3 to 840 kPa, out of which 50% data spread out from the lower to upper quartile. On the other hand, the suction data at 0.6 m and 0.9 m depth, and at all depths of turf cover had a constricted distribution. However, for clay and ET cover at 0.6 m and 0.9 m depth, a good number of outliers were observed indicating the environmental conditions (precipitation and high summer temperatures) are influencing suction at deep soil layers. So, the boxplot-based suction data distribution indicates the soil of ET and clay cover are subject to high variation, especially at shallow depth (up to 0.3 m depth) as compared to turf cover.

3.2 Evaluation of Spearman's Rank Correlation Coefficient

The Spearman's rank correlation coefficient (r_s) was estimated to investigate the concurrent changes in soil moisture and suction (field SWCC), and how closely they are associated. The estimated r_s values of three different cover types at different depths are presented in Table 1. Theoretically, moisture and suction are inversely correlated, meaning soil suction decreases with the increase in moisture or vice versa. As projected, a negative coefficient value was observed for all depths except at 0.6 m depth of turf cover where the r_s value appeared to be +0.558. Both theoretically and practically, there is no physical meaning of a positive correlation between moisture and suction. However, based on the response of moisture and suction in the turf cover, it seems that a non-equilibrium condition exists, implying either there is a significant amount of lag time, or the hydrological parameters do not have the influence of field meteorological events. From the previous discussion, as the turf appeared to be an effective moisture barrier, the soil under the turf was technically unresponsive to climatic conditions. Therefore, a random data clustering or data convergence occurred in the turf cover soil. Additionally, the r_s values (Table 1) at 0.3 m and 0.9 m depths of turf cover suggest that there is a very weak to weak correlation between moisture and suction signifying a high degree of discordance. On the other hand, for ET and clay cover, the r_s exhibited a moderate to very strong correlation. For clay cover, at a shallow depth (0.3 m), a strong correlation was observed. However, at 0.6 m and 0.9 m depths, a moderate correlation was identified. At different depths of ET cover, a strong to very strong correlation was observed indicating a faster response time of the changes in the concurrent moisture and suction or field SWCC during field meteorological events at all depths.

In this study, the statistical significance for r_s presented a significance level of reasonably less than 0.05. Therefore, the null hypothesis was rejected, and there is an exact correlation between moisture content and soil suction (for ET and clay cover). Also, it indicates that the changes in soil suction and moisture content are instantaneous in ET and clay cover and are anticipated to constitute realistic SWCCs with variable degrees of uniformity at varying depths, and the turf cover soil would potentially have irrational SWCCs at varying depths due to the non-influence of climatic conditions on the soil beneath the engineered turf.

Table 1. Spearman's rank correlations coefficient between the VMC and soil suction.

Depth (m) [feet]	Spearman's Rank Correlation Coefficient (r_S)		
	Compacted Clay Cover	Engineered Turf Cover	Evapotranspiration (ET) Cover
0.3 [1]	−0.739	−0.229	−0.919
0.6 [2]	−0.583	0.558	−0.877
0.9 [3]	−0.508	−0.486	−0.931

4 Conclusion

Moisture and suction data obtained from field instrumentation of three different types of landfill cover have been statistically analyzed and presented in this study. Descriptive statistic: box and whisker plots were used to investigate the degree of dispersion of the data under identical climatic conditions. The non-parametric Spearman's rank correlation coefficient was used to determine the correlation strength of the spatially distributed moisture and suction data (SWCC). Based on the analysis, the soil of ET cover and clay cover is highly responsive to climatic variation, and soil under the engineered turf showed a steady state condition in terms of moisture and suction variation indicating the engineered turf to be an effective barrier to precipitation. The Spearman's rank coefficient showed that spatially the moisture and suction for ET and clay cover are moderate to very strongly correlated, especially the ET cover soil indicating a realistic development of SWCCs. No justifiable correlations were observed for engineered turf cover soil. In the future, further analysis will be conducted with continuous monitoring of the moisture and suction data to assess the efficacy of engineered turf exposed to the environment for a long time. Also, field SWCCs need to be constituted for different cover types at varying depths to evaluate different unsaturated soil models on the hydrologic parameters.

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