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# Investigating Moisture Distribution Characteristics of Different Landfill Cover Soil at Shallow Depths Using Gaussian Distribution Analysis

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## ABSTRACT

One of the major purposes of landfill final covers is to minimize the infiltration of precipitation into the underlying waste. Deployment of conventional clay covers, geosynthetic clay liner, evapotranspiration (ET) covers, etc., has mostly been in practice to achieve the purposes. However, they have their shortcomings in the full attainment of the goals. In recent years, engineered turf has been introduced for landfill closure as a precipitation barrier to enhance cover performance. However, the field demonstration of engineered turf cover as the infiltration barrier is very limited. Soil moisture being one of the performance indicators of landfill covers, the objective of this study was to investigate moisture distribution characteristics of three distinct prototype landfill final cover systems: ET cover, compacted clay cover, and engineered turf cover, under in a humid subtropical climatic region. All the test covers (3 m × 3 m) were constructed side by side and were instrumented with moisture sensors at shallow depth (0.3 m depth). Descriptive statistics and histograms were used to summarize the features of the moisture distribution. Gaussian distribution theorem was used to investigate the spread out of the moisture data. In addition, the original moisture data were transformed to the standard normal distribution for a consistent framework for investigating the moisture variability of different covers. The analysis showed that 95% of the data were clustered around 0.173 to 0.238 $m^3/m^3$ at 0.3 m depth of engineered turf cover. On the contrary, the other two covers' soil had a similar wider spread out of moisture data ranging approximately from 0.041 to 0.34 $m^3/m^3$. Results obtained from this study indicated the efficiency of engineered turf cover as an effective barrier to precipitation.

## INTRODUCTION

### Background

One of the major objectives of a final cover system for landfills and other types of waste disposal sites is to minimize the infiltration of precipitation, thereby reducing percolation into the underlying waste mass. To minimize the percolation, the design of landfill cover systems is typically site-specific. Depending on the intended function of the final cover, the cover components can be a single-layer system to a complex multi-layer system. The typical final

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closure recommended by the Resource Conservation and Recovery Act (RCRA) of 1976 is the construction of low hydraulic conductivity (typical range between $1x10^{-5}$ and $1x10^{-9}$ cm/sec depending on the material type and construction method) compacted clay layer which acts as a barrier or resistive layer to prevent the infiltration of precipitation. These barrier layers are often constructed of compacted clay, geomembranes, geosynthetic clay liners, or combinations of these materials. However, the conventional compacted clay cover has several disadvantages, the most important of which is the climate-induced recurring wetting-drying, eventually, the formation of desiccation cracks due to extensive moisture loss, leading to potential infiltration of precipitation. The formation of cracks creates irreversible changes in the hydraulic properties of compacted clay and results in uncontrolled water flux (Gross et al. 2001). Therefore, the moisture variabilities in the soil due to environmental fluctuations cause the degraded performance of this type of cover.

Water balance cover, also known as evapotranspiration (ET) cover, has been an alternative to the conventional cover system. ET cover works on the principle of water balance in which it stores precipitation during rainfall events and releases the stored moisture to the environment during the dry period through evapotranspiration (Albright et al. 2004; Benson et al. 2002). In the ET cover, a high soil moisture value indicates that the stored water is approaching its storage capacity, thereby increasing the potential for percolation (USEPA, 2003). Thus, soil moisture is a critical indicator of ET cover performance. The post-construction natural processes such as freeze-thaw and wet-dry cycling, and pedogenesis processes significantly damage its as-built condition and thereby influence the cover hydrology by altering the soil's hydraulic characteristics (Benson et al. 1993; Alam et al. 2019), which, in turn, allow easy moisture intrusion that significantly affects the percolation rate (Khire et al. 1997; Ogorzalek et al. 2008). To overcome the shortcomings of ET and conventional covers in reducing precipitation infiltration, engineered turf covers have recently been introduced as the final closure. The engineered turf system may act as the precipitation barrier to reduce the moisture variabilities of the soil underneath. However, the field performance of engineered turf as the precipitation barrier has not been investigated yet.

Soil moisture is an important link between climatic factors and spatio-temporal variations due to the influence of different hydrological processes such as infiltration, runoff, evaporation, etc. (Huang et al. 2016; Liu et al. 2018). The response of soil moisture under climatic variability is specifically very important for landfill final cover systems since it is a critical indicator of landfill cover performance. It is well understood that various sources of uncertainty exist in the measurement of in-situ soil moisture because of the heterogeneities in the field conditions. Therefore, the deterministic approach of the in-situ measured soil moisture may have variable degrees of uncertainty. A probabilistic analysis of measured soil moisture could be more realistic to minimize the uncertainties in evaluating the moisture distribution. However, most field studies on landfill covers related to analyzing soil moisture variabilities induced by environmental factors are conducted using a deterministic approach. Therefore, it becomes necessary to probabilistically characterize the soil moisture distribution of landfill covers for enhanced reliability in the analysis.

To increase our knowledge of moisture distribution characteristics of soil under engineered turf and understand its potential applicability in the landfill as a moisture barrier in variable climatic conditions, a field test program was conducted to investigate the distribution of soil moisture in engineered turf cover. The moisture distribution characteristics were also evaluated for an ET and a compacted clay cover under identical climatic conditions for a comprehensive

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understanding and comparison between other cover types. This study aimed to probabilistically analyze the measured soil moisture of different covers at shallow depths (0.3 m) and demonstrated the field performance of different covers where moisture distribution was the performance indicator. Three test landfill covers of dimensions 3 m × 3 m were constructed side-by-side and moisture sensors were installed at 0.3 m depth to continuously measure volumetric moisture content ($\theta$). Descriptive statistics, histograms, and the Gaussian distribution theorem were used for data analysis. Additionally, the measured VMCs were standardized to a Standard Normal Distribution to form a consistent framework for investigating data variability.

## Gaussian Distribution

The normal, or Gaussian, distribution theorem is commonly used in science and engineering problems to evaluate probabilistic models to understand statistics and data variability, in general. When continuous data represent the responses due to natural events, such as changes in soil parameters induced by environmental factors (e.g., precipitation, temperature, etc.), they will likely take various frequency distributions. One of the distributions is the normal or Gaussian distribution, 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 probability density function (PDF) of the normal distribution is presented in Equation (1):

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

Where $\mu$ is the mean, and $\sigma$ is the variable's standard deviation. The distribution parameters $\mu$ and $\sigma$ are scale and shape parameters, respectively. Changing $\mu$ shifts the position of the distribution, whereas increasing $\sigma$ flattens the bell-shaped curve. The scale parameter ($\mu$) refers to the scaling of the x-axis, which does not affect the overall shape of the distribution. Although they behave differently for each distribution, scale, and shape parameters are useful for understanding how probability density changes with changing parameter values. A normal distribution is symmetric about the mean, median, and mode (all equal). It is widely understood that in a normal distribution, 68.3, 95.4 and 99.7% of data from a population or sample will fall within 1, 2, and 3 standard deviations ($\sigma$) from the mean ($\mu$), denoted: $\mu\pm\sigma$, $\mu\pm2\sigma$, and $\mu\pm3\sigma$. Alternatively, if the normal distribution concept is applied to certain random continuous variables, 68.3% of the data will be within 1 standard deviation from the mean of the variable, $\mu\pm\sigma$.

## Standard Normal Distribution (SND)

In probability statistics, there are infinite normal distributions (there is one for any choice of $\mu$ and $\sigma$). Hence, it is very common to standardize all the normal distributions to a unique SND. A random variable, $z$, with the standard normal distribution, has a mean of $0$ and a standard deviation of $1$: $z \sim N(0,1)$. Any distribution ($x$) can be transformed to the standard normal distribution ($z$): $x \rightarrow z$, which is a critical component of the engineering reliability analysis. Transformations between the standard normal space ($z$) and original space ($x$) provide a consistent framework for investigating data variability and interpreting the results. For any

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variable $x$, where $x \sim N(\mu,\sigma)$, normal distributions can be transformed into standard normal distributions by the following formula as presented in Equation (2).

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

where $x$ is a score from the original normal distribution, and $\mu$ and $\sigma$ are the original normal distribution's mean and the standard deviation, respectively. The SND is sometimes called the z distribution. A z-score always reflects the number of standard deviations above or below the mean a particular score is. The probability values of this distribution are known. The z distribution will be normal only if the original distribution is normal, but it is always possible to standardize a distribution of scores and give it normality.

## MATERIALS AND METHOD

### Construction and Instrumentation

The study was conducted at the Research Demonstration Farm of Prairie View A&M University in Waller County, TX, a climatologically humid subtropical region. The entire study area is a relatively flat surface. Three test sections: (1) engineered turf cover, (2) ET cover, and (3) compacted clay cover, of dimensions 3 m × 3 m and 1.22 m deep, were constructed side-by-side as shown in Figure 1(a). The side-by-side construction of the test sections was designed for them to experience identical weather conditions and consistency in the moisture distribution analysis. After excavating the existing subgrade, each test section was overlain by a 6-mil impermeable plastic sheet. The plastic sheet was also placed along the sidewall of the excavation and extended to almost 0.6 m along the top surface to avoid intra-section moisture flow. After placing the plastic sheet, all the test sections were backfilled with the excavated soil (Figure 1b) and compacted at 95% of maximum dry density with a sheep-foot roller. The initial gravimetric moisture content at the test sectios were in the range between 16 to 17%. For the ET cover, the top 0.3 m was compacted at a relatively lower compaction effort for plants to grow. Laboratory tests of samples collected from excavated soil classified the soil as high-plasticity Fat Clay with Sand (CH) according to the Unified Soil Classification System (USCS). After compacting all the test sections, moisture sensors were installed at 0.3 m (1 ft.) depth at each test pit (Figure 1c). In this study, TEROS 11 sensors were used. The TEROS 11 determines volumetric water content by measuring the dielectric constant of the soil using capacitance/frequency domain technology. Holes were drilled using a manual augur in each of the test section, and moisture sensors were pushed into the sidewall of the holes at the designated depth. After inserting the sensors, soils were backfilled and carefully compacted to avoid sensor damage and retain their functionality. The moisture sensors installed at the test pits were connected to an automatic data logging system. Following the instrumentation, native grass was used in the ET cover, and the compacted clay cover was left unseeded after compaction. In the engineered turf cover, a structured LLDPE geomembrane (Figure 1d) was placed after surface smoothening, followed by synthetic turf laying as shown in Figure 1(e). In the synthetic turf, polyethylene fibers were tufted through a double layer of woven polypropylene geotextiles and sand in-fill. Moisture data were collected for almost eight months for all the test sections. During the monitoring period, almost 329 mm rainfall were recorded with a relatively more frequency during late spring, and relatively less rainfall in summer.

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

**Figure 1. (a) Existing subgrade excavation, (b) backfilling after placing 6-mil plastic sheet, (c) moisture sensor installation, (d) structured geomembrane, and (e) synthetic turf.**

## RESULTS AND DISCUSSION

### Descriptive Statistics and Gaussian Distribution Analysis

Descriptive statistics and the histograms of in-situ soil moisture contents ($\theta$) are presented in Table 1 and Figure 2, respectively. It was observed from the table that there were significant discrepancies in the descriptive statistical parameters of the measured $\theta$ between the turf cover and the other two covers (compacted clay cover and ET cover) at 0.3 m depth. The range of the data of the clay cover and ET cover is quite similar (0.264 and 0.249, respectively). Cracks were observed in both the clay and ET covers that could lead to similar change in soil moisture at shallow depth. In contrast, the range of the turf cover (0.069) is distinguishably less than the other two at the identical atmospheric conditions at the equivalent depth, delineating a significant spread out of the $\theta$ in ET and clay covers. The degree of dispersion of $\theta$ was further measured by the standard deviation ($\sigma$). The $\sigma$ of measured $\theta$ for engineered turf cover (0.016) was considerably different from clay and ET covers (0.070 and 0.069, respectively). It is to be observed that the $\sigma$ of both clay and ET covers at 0.3 m depth is essentially the same, indicating a comparable performance of moisture distribution. The histogram plots may further explain this, as shown in Figure 2. In Figures 2(b) and 2(c), the frequency distribution of $\theta$ of clay and ET covers extends from drying to wetting, displaying multimodality distribution. However, there are differences in the $\theta$ distribution as observed in both these covers' central tendencies (mean, median, mode). These differences can be attributed to the presence of plant roots in the ET cover, formations of cracks in the clay cover and ET cover, and other heterogeneities. Nonetheless, the frequency distribution of $\theta$ of the clay and ET covers indicates the soil at 0.3 m depth of these two covers is highly responsive to climatic variations, which are understandable.

Contrary to clay and ET covers, the histogram plot of $\theta$ at 0.3 m depth of turf cover exhibits a narrow distribution of $\theta$ (Figure 2a). The $\theta$ value is distributed between 0.15 to 0.22 $m^3/m^3$, where the mode is 0.21 $m^3/m^3$ with a frequency of 16359, which is almost 38% of the total population. Yet, the remaining 62% of $\theta$ variations occurred in a very narrow range. The measures of the central tendencies (i.e., mean, median, mode) of $\theta$ are almost equivalent (Table 1), which technically indicates the $\theta$ to be normally distributed at 0.3 m depth of the turf cover. However, Skewness and kurtosis values of the measured $\theta$ exhibit non-normality. The skewness (-2.389) of $\theta$ suggests the $\theta$ distribution under the engineered turf was highly skewed to the left or negatively skewed. This is also confirmed by the PDF of the normal distribution of $\theta$ as shown in Figure 3. Additionally, the kurtosis of $\theta$ is considerably higher for turf cover. Usually, kurtosis greater than 3 indicates a leptokurtic distribution of data that contains very long and skinny tails and data peakedness. Additionally, the leptokurtic distribution indicates the likelihood of substantial outliers. The histogram in Figure 2(a) also confirms the heavy-tailed $\theta$ distribution

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(tailed to the left) under the engineered turf, and the $\theta$ data are potentially clustered (peaked) around the central tendency (≈0.21 $m^3/m^3$ ) with a significant outlier. However, the outliers' dispersal is very confined as understood by the vertiginous PDF of the turf cover compared to the flattened PDFs of clay and ET covers shown in Figure 3.

**Table 1. Descriptive Statistics**

| Descriptive Statistics | Engineered Turf Cover | Compacted Clay Cover | ET Cover |
|---|---|---|---|
| Mean (μ) | 0.206 | 0.200 | 0.181 |
| Standard Error | 7.9E-5 | 3.3E-4 | 3.3E-4 |
| Median | 0.210 | 0.194 | 0.175 |
| Mode | 0.210 | 0.121 | 0.175 |
| Standard Deviation ($\sigma$) | 0.016 | 0.070 | 0.069 |
| Sample Variance | 0.0003 | 0.0049 | 0.0048 |
| Kurtosis | 4.437 | -1.259 | -0.202 |
| Skewness | -2.389 | 0.252 | 0.889 |
| Range | 0.069 | 0.264 | 0.249 |
| Minimum | 0.153 | 0.102 | 0.096 |
| Maximum | 0.222 | 0.366 | 0.345 |
| Count | 43408 | 43408 | 43408 |
| Confidence Level (95.0%) | 0.000154 | 0.000658 | 0.000656 |

The soil at 0.3 m depth of clay and ET covers had significantly lower skewness values (rightly skewed) (Table 1) than turf cover. The skewness of $\theta$ distribution of the ET cover is slightly higher than the clay cover. Both distributions have negative kurtosis indicating a platykurtic distribution with a flatter peak and thinner tail. The PDFs of these two covers' $\theta$ are fairly resembling (Figure 3) compared to the turf cover. It can further be explained using the Gaussian distribution's location (μ) and shape (σ) factors. Differences in the effect of Gaussian location and shape factors for measured $\theta$ are visible in Figure 3. Soil moisture content as the continuous random variable, the Gaussian distribution parameters of the measured $\theta$ can be notated as $\theta \sim N(\mu, \sigma)$. The Gaussian distribution parameters of the three covers at 0.3 m depth: $\theta_{(Turf)} \sim N(0.206, 0.016)$, $\theta_{(Clay)} \sim N(0.200, 0.070)$, and $\theta_{(ET)} \sim N(0.181, 0.069)$ exhibit distinctions under identical meteorological conditions. The shape parameter (σ) of clay and ET covers are considerably higher than the turf cover, which indicates the flatter shape of the Gaussian curves of these two covers (Figure 3). The location parameter (μ) is also not substantially different, as noticed in Figure 3 (peak of each curve). The PDF of the measured $\theta$ of turf cover at 0.3 m depth demonstrates that under the field atmospheric conditions, soil moisture would potentially be distributed around 0.206 $m^3/m^3$. However, the $\theta$ at the inception of data collection is very important here as a different value of initial $\theta$ may shift the distribution's location. It is to be noted that the initial $\theta$ of the turf cover at the beginning of data collection was 0.21 $m^3/m^3$. The $\theta$ distribution of clay and ET covers at the same depth would be highly variable because of the substantial impact of the natural atmospheric conditions and post-construction processes of cover soil such as wetting-drying, root growth, crack formations, etc.

Based on the parameters of descriptive statistics, it was observed that the degree of dispersion of soil volumetric moisture content data at 0.3 m depth for clay and ET covers was significantly higher than the engineered turf cover under identical climatic conditions. The results imply that the engineered turf might effectively reduce the soil moisture variation at shallow depths and consequently controlled or no percolation. It is anticipated that under an engineered turf, the soil moisture at a depth deeper than 0.3 m would have a similar distribution to 0.3 m depth as investigated in this study. Accordingly, an engineered turf cover could be a better solution for landfill closure in extreme climates. However, it requires further study to confirm this notion.

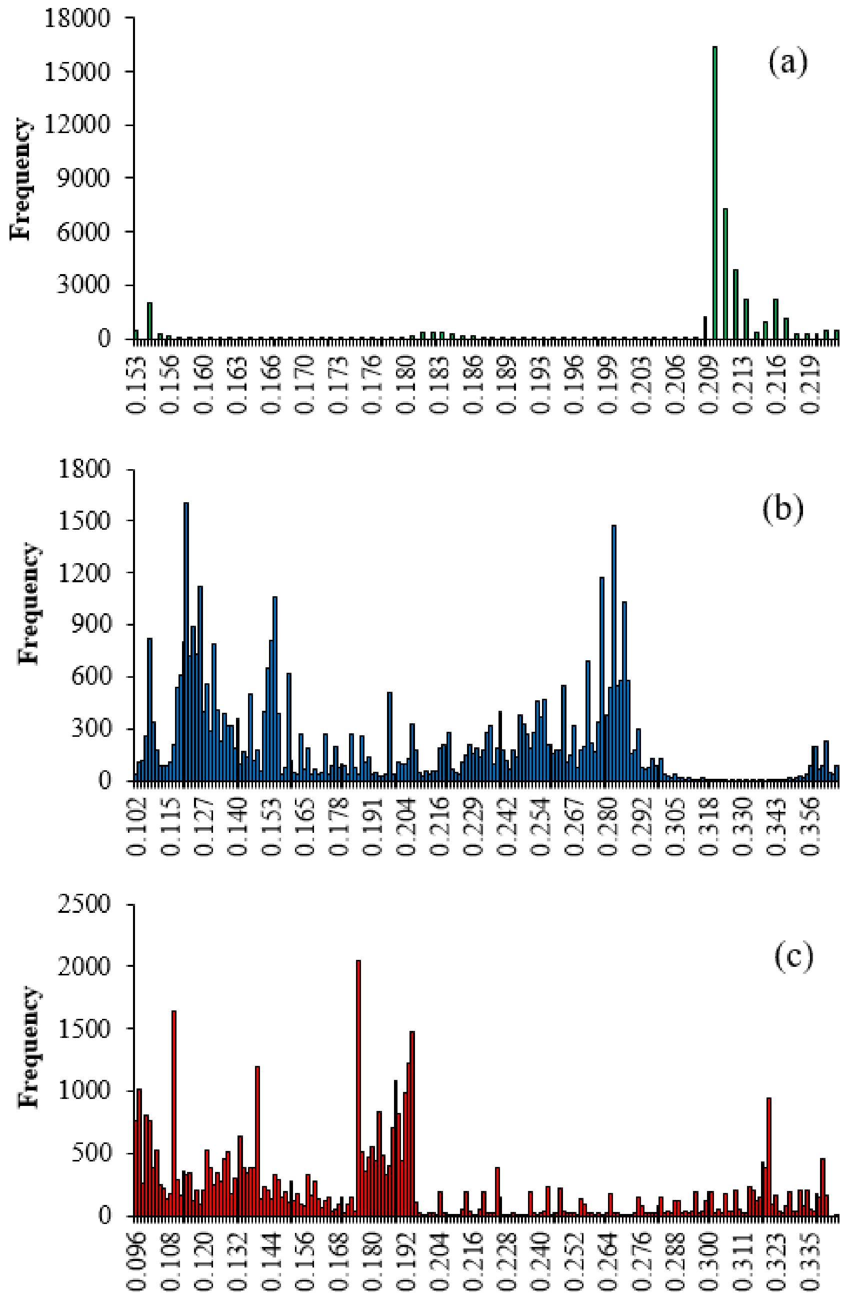


**Figure 2. Histogram of VMC (a) engineered turf cover, (b) compacted clay cover, (c) evapotranspiration cover**

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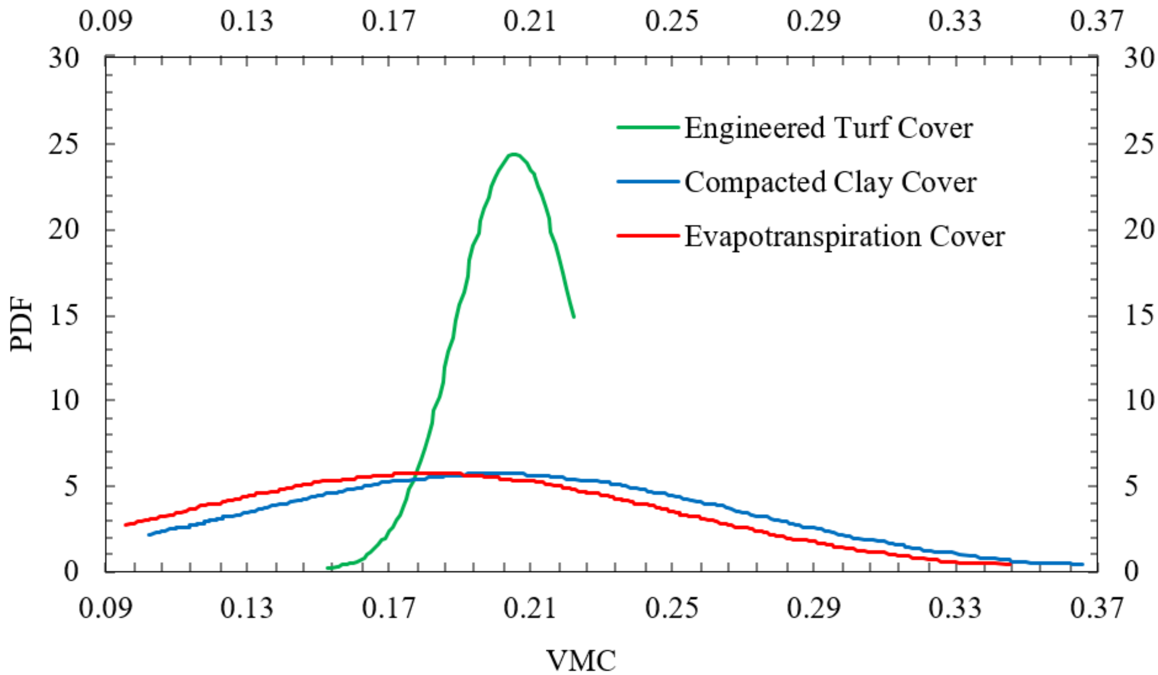


**Figure 3. Normal distribution of the measured soil moisture**

## Standard Normal Distribution (SND)

The $\theta$ data for all three covers was transformed to the standard normal space from the original space to develop a consistent framework for investigating the $\theta$ variability, comparison, and interpretation. The standard normal distribution (SND) plots of three different covers are presented in Figure 4. The figure also presents the data distribution within four standard deviations concerning the mean of individual cover ($\mu \pm 4\times\sigma$). Significant discrepancies are observed in the $\theta$ distribution between the engineered turf cover and the other two covers (ET and Clay cover). In the engineered turf cover, almost 95% of the $\theta$ data at 0.3 m depth are within a narrow range of 0.173 to 0.238 $m^3/m^3$, as presented in Figure 4a (shaded green area), also presented in Table 2. On the contrary, the clay and the ET cover showed a wide dispersal of $\theta$ and have a similar SND presented in Figures 4b and 4c, respectively. In the clay cover, 95% of the $\theta$ data are within 0.06 to 0.34 $m^3/m^3$ (shaded blue area), and in the ET cover, 95% of the $\theta$ data are within 0.041 to 0.321 $m^3/m^3$ (shaded red area). Moisture distribution within 2 and 3-standard deviations ($\mu\pm2\sigma$ and $\mu\pm3\sigma$) for clay and ET covers display the variation of $\theta$ from almost residual condition ($\theta_r$) to saturated condition ($\theta_s$). It is to be noted that the unsaturated characterization of the soil in the laboratory indicated the soil's $\theta_r$ and $\theta_s$ in the range between 0.09 to 0.13 $m^3/m^3$ and 0.39 to 0.42 $m^3/m^3$, respectively. For the soil under the engineered turf, 99.7% of the $\theta$ data remained constricted between 0.156 to 0.255 $m^3/m^3$ at $\mu\pm3\sigma$, and reasonably far from the $\theta_r$ and $\theta_s$ of the soil. This indicates the engineered turf's ability to retain a moisture equilibrium condition of the soil underneath, where the moisture equilibrium condition is referred to as the insignificant variation of soil moisture under climatic variations.

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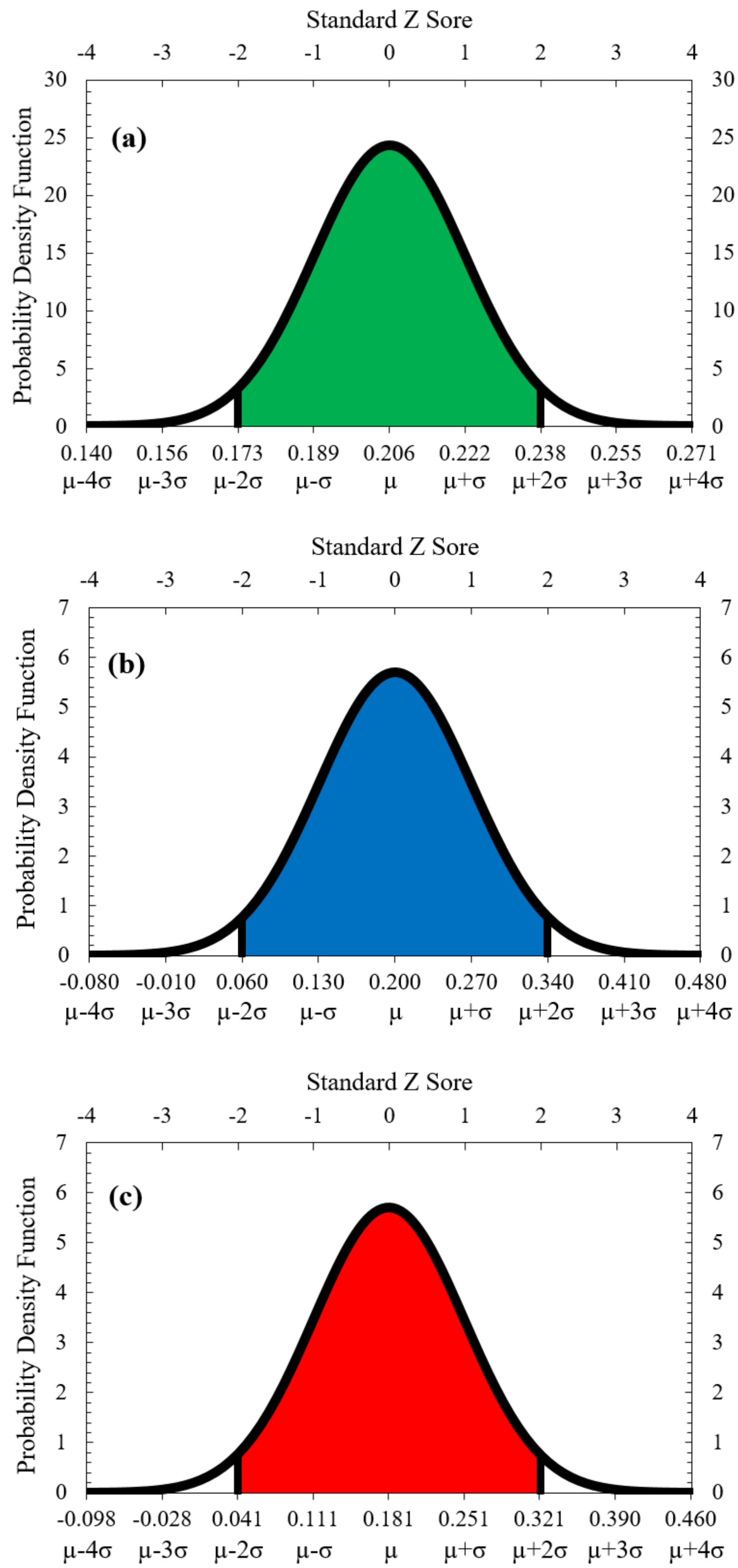


**Figure 4. SND (a) engineered turf cover (b) compacted clay cover (c) ET cover**

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**Table 2. Percent variation in the distribution of soil moisture for different cover types**

| Standard Normal Distribution | Gaussian Parameter | Engineered Turf Cover | Compacted Clay Cover | Evapotranspiration Cover |
|---|---|---|---|---|
| | ***N(μ,σ)*** | ***N(0.206,0.016)*** | ***N(0.200,0.070)*** | ***N(0.181,0.069)*** |
| ***μ±σ (68.3%)*** | μ+σ | 0.222 | 0.270 | 0.251 |
| | μ−σ | 0.189 | 0.130 | 0.111 |
| ***μ±2σ (95.4%)*** | μ+2σ | 0.238 | 0.340 | 0.321 |
| | μ−2σ | 0.173 | 0.060 | 0.041 |
| ***μ±3σ (99.7%)*** | μ+3σ | 0.255 | 0.410 | 0.390 |
| | μ−3σ | 0.156 | -0.009 | -0.028 |

## CONCLUSION AND PRACTICAL SIGNIFICANCE

Soil moisture content is a critical design parameter of the landfill's final cover system. It is important to characterize the soil moisture distribution of cover soil in field conditions to help landfill operators and owners reduce risks and improve management based on the closure objectives of landfill covers specified in terms of hydraulic performance. The major objective of this study was to investigate moisture distribution characteristics of different types of landfill final cover systems under identical atmospheric conditions. To accomplish this objective, in-situ soil moisture data obtained from the instrumented sensors from the three covers at shallow depths (0.3 m) was analyzed in a probabilistic framework. The results from this study indicated a negligible change in soil moisture in engineered turf cover at 0.3 m depth throughout the monitoring period. The degree of dispersion of soil moisture was significantly higher for the compacted clay cover and ET cover than for the engineered turf cover. The probability density function of the turf cover produced a considerably slender bell curve with higher kurtosis and skewness. The standardization (standard normal distribution) of the soil moisture data also revealed that almost all the soil moisture data (within 3-standard deviation or 99.7%) would be in the range between 0.156 to 0.255 $m^3/m^3$ for engineered turf cover, while between almost 0 to 0.4 $m^3/m^3$ for the clay and ET cover, indicating noteworthy changes in soil moisture in these two covers than in the engineered turf cover at similar climatic conditions. Based on the results obtained in this study, engineered turf cover shows encouraging results and can be a climate-adaptive solution for landfill closure to control percolation. Engineered turf system can also be beneficial in reducing the major degradation of exposed geomembrance such as ultraviolet radiation, elevated temperatures, and atmospheric oxidation.

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