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Estimation of percolation of water balance cover using field scale unsaturated soil parameter

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Abstract. Water balance covers for landfill closure are used as a barrier which act with the natural processes to reduce percolation. The ideal performance of water balance cover is characterized by the minimal quantity of percolation. The rate of percolation of water balance cover largely depends on unsaturated soil behavior. In this study, percolation was evaluated through unsaturated soil parameters of six instrumented lysimeters. The field instrumentation included moisture sensors, tensiometers, rain gauge, dosing siphon, and pressure transducer. Soil water storage (SWS) capacity (S_A) was quantified from the soil water characteristic curves (SWCC) which were developed based on laboratory experiments and field instrumentation data. Required SWS (S_R) was also measured from the field monitoring results. Based on analysis, the relative storage ratio (S_R/S_A) was observed to be greater than unity (1) in most of the cases, indicating potential percolation. The S_R/S_A was also found competent to identify the lysimeter with higher quantity of percolations. The estimated percolation from the laboratory experimented and field generated SWCCs fairly resembled with the actual field measured percolation. The analyzed results also developed a framework to estimate the thickness of the cover storage layer required to manage percolation for the specific region of the study area.

Keywords: Landfill, Water Balance Cover, Percolation, Evapotranspiration, Runoff, Soil Water Storage, Unsaturated Soil, SWCC.

1 Introduction

Water balance cover, also known as evapotranspiration (ET) cover, is an emerging method for landfill closure. The three fundamental objectives of final cover of landfill: waste isolation, prevention of gas migration to the environment, and infiltration minimization of precipitation into the waste, are decently achieved by water balance cover compared to conventional cover system. Moreover, ET cover systems are easy to construct, have less maintenance cost, and expected to have improved performance with time [1]. The two major components of water balance cover system are soil and plant, where the soil functions to store precipitation while plants are the key means of removing the stored water through root water uptake process (evapotranspiration) during plant growing season under optimum field temperature. Thus, the infiltration of water into the waste is reduced by this natural environmental process.

Waste containment with final covers for landfills is primarily regulated through the Resource Conservation Recovery Act (RCRA) and the U.S. Environmental Protection Agency [2] in the United States. The RCRA and the USEPA conservatively recommend employing resistive barriers of low saturated hydraulic conductivity as final covers to limit percolation. However, now-a-days, the RCRA includes the provision of ET covers for waste containment upon successful field demonstration of ET cover, establishing greater long-term performance and minimal percolation rate than the conventional barrier layer. To comply with the RCRA regulation, many landfill operators and solid waste professionals are now verifying ET cover performance locally through field scale testing and establishing the necessity of employing ET cover for waste containment. Percolation is the major water balance component which is the decisive factor to choose water balance cover for any landfill in a region.

There are several methods available in literature that have been adopted by different researchers to measure the percolation from the field demonstration. The most common methods available in literature are water balance method, trend analysis, Darcy's Law calculations, tracer methods, and lysimetry method. However, the precision of the measured percolation in these methods varies significantly [3]. Trend analysis is the least precise method as it only relies on the water content data. Water balance method is the next least precise method which consists of measuring all other water balance variables. The mass balance equation to measure percolation using water balance method is shown below.

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$$P_r = P - ET - R - \Delta S \quad (1)$$

Where, P is precipitation, R is runoff, ET is evapotranspiration, and ΔS is the change in soil water storage during a fixed period. So, the precision of the measured percolation using the equation above is directly controlled by the quantities on the right side of Equation (1). Additionally, the precision may vary in humid, semi-arid, and arid regions [3]. Tracer method determines the depth of percolation, not the percolation rate. This method relies on several factors that cannot be reliably quantified in the field. Among the different methods to determine percolation rate, lysimetry method is the most precise one which quantifies percolation rate through direct measurement. Many field demonstrations of ET cover have been evaluated through lysimetry method. It is also reported from different research that large lysimeters (> 100 m^2) provide greater sensitivity. Though lysimetry method can sometimes cause an overestimation of percolation, it is the most ideal method to quantify percolation for ET cover system.

Field hydrology of ET cover soil is significantly influenced by the hydraulic properties of the soils, such as hydraulic conductivity and the soil water characteristic curve (SWCC). The percolation (infiltration of water) rate into the underlying waste is greatly affected by these hydraulic characteristics of the soil [4,5,6]. Typically, an ET cover produces greater quantity percolation and less surface runoff if the soil has higher saturated hydraulic conductivity (K_s) and SWCC with higher air entry suction (Ψ_a) [7,8,9]. Laboratory measured hydraulic properties of the cover soil are employed in the initial design of ET cover (required cover thickness) and as input parameters for modeling [5,9,10,11]. However, the hydraulic characteristics of the soil in the field do not remain invariable. Both the saturated and unsaturated hydraulic characteristics of the soil are subjected to change because of the post-construction natural processes (i.e., insect and animal burrowing, freeze-thaw cycling, wet-dry cycling, plant root growth and death, etc.), thereby influencing the cover hydrology significantly [4,12,13]. Therefore, designing ET cover considering only the initial laboratory assessed soil properties could be misleading. However, field measured unsaturated soil parameter may potentially provide a better resolution to predict the rate of percolation for water balance covers [14].

To address the effect of change in the unsaturated hydraulic properties of the soil on the percolation rate, this paper evaluates the directly measured percolation from six constructed lysimeters and compares with estimated percolation from SWCC parameters. Both laboratory generated and field constructed SWCCs were considered in the analysis. Required soil water storage (S_R) was estimated from the field water balance components. Soil water storage capacity (S_A) was computed from the SWCCs. The field based SWCCs were generated from the moisture sensors and tensiometer data. The sensors were installed co-laterally into the cover system. Relative storage ratio (RSR) was developed for the evaluation of percolation and field unsaturated soil behavior. The thickness of the cover storage layer was also evaluated from the field investigated water balance data.

2 Materials and Method

The study was conducted at the City of Denton municipal solid waste (MSW) landfill, Denton, Texas, which is geographically located in the semi-humid region. Six large-scale lysimeters were built side-by-side on top of an existing landfill cell as shown in Figure 1 below. The construction of the lysimeters started in June 2014, and it took approximately 5 months to complete the earth work, construction, and instrumentation.

Fig. 1. Location of the study area.

2.1 Test Section and Instrumentation

2.1.1 Description of Lysimeter

For this study, six large-scale lysimeters were constructed side-by-side. The dimensions of each lysimeter were 12.2 m x 12.2 m x 1.2 m (40 ft. x 40 ft. x 4 ft.). Three of the lysimeters were constructed on a 2% flat surface and the other three were constructed on 25% side slope section. The schematic of the constructed lysimeter is shown in Figure 2.

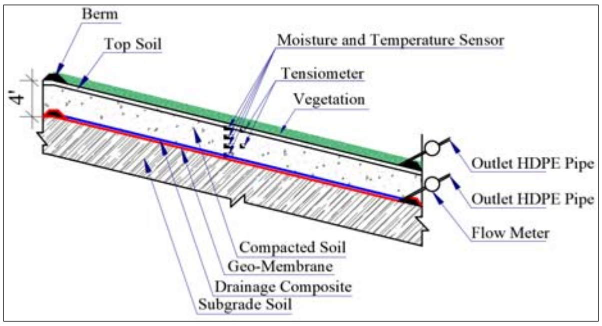

Fig. 2. Section of lysimeter.

The lysimeters were covered with 915 mm (36") of compacted storage layer (L), overlain by a 305 mm (12") vegetation surface layer. The surface layer was comparatively less compacted for efficient root growth into the cover. A geomembrane was placed on the excavated subgrade as well as along the sidewalls of the excavations. To collect the drained water (percolation) through the ET cover system, a percolation collection system (HDPE pipe) was installed along the lowest side of each lysimeter (Figure 2). The geomembrane was overlain by geocomposite drainage layer. Local clayey soil was then placed on the geocomposite layer. The soil was placed in three lifts and compacted at 95% of the maximum dry density (MDD) of the soil. Clay berms were constructed along the lysimeters' perimeter. After placing the surface layer over the compacted storage layer, the runoff collection systems (HDPE pipe) were installed. The water balance components were measured with automated monitoring system (e.g., percolation through rain gauge, runoff through dosing siphon, and pressure transducer). A weather station was installed at the site to monitor the environmental parameters such as rainfall, air temperature, wind speed, relative humidity, solar radiation, and barometric pressure.

2.1.2 Sensor Installation

To quantify the soil moisture, suction, and the soil water storage of the lysimeter soil, moisture and temperature sensors, and tensiometers were installed in each of the test sections as shown in Figure 3.

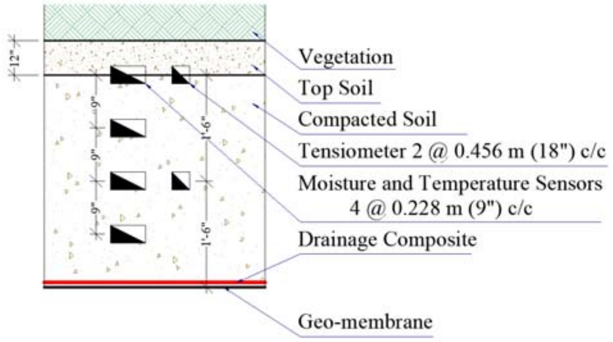

Fig. 3. Instrumentation detail.

The sensors were installed every 228.6 mm (9") depth, where the first sensor was installed at the top of the storage layer (305 mm or 12" below the surface). Two tensiometers were installed 456 mm (18") apart as shown in Figure 3 co-located with the moisture and temperature sensors. The co-existence of the tensiometers and moisture sensors in the lysimeters led to generating the field soil water characteristic curves.

2.1.3 Vegetation

Vegetation within all the lysimeters were native grasses such as a mix of native trails, perennial wildflower mix, and caliche; mix of upland switchgrass, perennial wildflower mix, and caliche; and Bermuda grass and hulled common Bermuda grass (grade 90/80). The test sections were intentionally planted with these three different types of grasses to evaluate the effect of different vegetation on the performance of ET cover. Each flat section lysimeter and the corresponding sloped section lysimeter were seeded with identical vegetation.

2.2 Soil Properties

Soil samples were collected from all the lysimeters at different depths during construction of the ET covers. Disturbed soil samples were collected and shipped to the laboratory for the geotechnical testing. The physical and hydraulic characterizations of the soil were performed following the ASTM standards. Laboratory investigations of the cover soil completed in this study included grain size distribution (ASTM D 422-63), specific gravity (ASTM 854-14), Atterberg limits (ASTM D 4318), Standard Proctor Test (ASTM D 698), hydraulic conductivity (ASTM D 5084) and soil water characteristic curve (ASTM D 6836).

2.2.1 Physical and Hydraulic Soil Properties

Based on the laboratory investigation of the collected samples from the lysimeters, the soil was classified as high plastic clay (CH) according to the Unified Soil Classification System (USCS). The percent passing through No. 200 sieve ranged from 80% to 86% for all the soil samples. Clay fraction of the soil was found in the range between 38% and 42%. Optimum moisture content (OMC) and maximum dry density (MDD) were found 17 to 17.8% and 16.85 to 17 kN/m^3, respectively. The soil was subjected to a hydraulic conductivity test in a flexible wall permeameter. The soil samples were compacted to 95% MDD at its dry side. The saturated hydraulic conductivity of the soil ranged from 1.2×10^{-7} cm/sec to 1.5×10^{-6} cm/sec with a geometric mean of 5.85×10^{-7} cm/sec.

2.2.2 Soil Water Characteristic Curve (SWCC)

SWCC was measured following the standard test method using the pressure cell apparatus (Fredlund SWCC device) and Chilled Mirror Hygrometer (CMH). WP4 Dewpoint Potentiometer was used for the CMH test. Only drying SWCCs were measured in this study. CMH was used to determine the volumetric moisture content (θ) at higher suction (Ψ) levels, while the pressure cell apparatus was used to determine the suction-moisture (Ψ-θ) relation at higher moisture contents. Around 8 to 12 measurements were made to develop the Ψ-θ relationship of the soil. Soil sample was compacted at 95% maximum dry density and subjected to SWCC. The variation of the volumetric moisture content with the matric suction for the specimen is shown in Figure 4. The experimental data points were fitted with van Genuchten [15] sigmoidal function to define the SWCC. The equation of the function takes the following form. The fundamental SWCC properties are given in Table 1.

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=\frac{1}{[1+(\alpha\Psi)^n]^m} \tag{2}$$

Table 1. Fundamental features of SWCC of ET cover soil

SWCC parameters at 95% MDD	
Saturated Volumetric Water content, (θ_S), %	39.74
Air entry value, AEV (ψ_a), KPa	120
Residual water content (θ_r), %	12.30

van Genuchten's curve-fitting model parameters for the SWCC, based on the RETC code of the soil are presented in Table 2.

Table 2. van Genuchten curve-fitting parameters of cover soil

Parameter	Value
α	0.0031
n	1.6
m	0.375

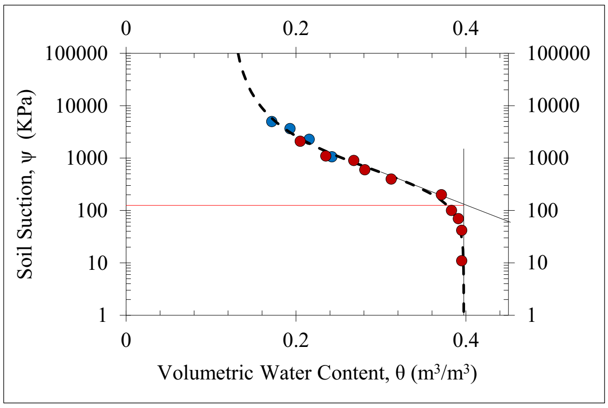

Fig. 4. SWCC of lysimeter soil.

2.3 Soil Water Storage (SWS) Assessment

Soil water storage (SWS) is one of the significant design components which largely depends on the cover soil properties (e.g., soil type, grain size distribution, SWCC). The soil characteristics determined in the laboratory do not necessarily remain constant throughout its service life. The fluctuating climatic conditions (freeze-thaw cycling, wet-dry cycling, etc.) alter the soil behavior significantly [4,12,16,17] and ultimately affect the storage capacity of the soil cover. Hence, both laboratory investigated, and field monitored soil properties were evaluated. The following sections describe the laboratory and field measurement methods of soil water storage capacity.

2.3.1 Available Soil Water Storage Capacity (S_A)

Available soil water storage capacity (S_A) of the cover soil was computed using the following equation as described by Benson [18].

$$S_A = L\ (\theta_{FC} - \theta_{WP}) \tag{3}$$

Where, L is the thickness of the cover storage layer, θ_{FC} and θ_{WP} are the field capacity and wilting point water content [19], respectively. The θ_{FC} is the water content at which the soil can no longer hold moisture and is estimated from the SWCC as the volumetric moisture content (VMC) at matric suction, $\psi = 33$ kPa. The θ_{WP} is the water content at which plant transpiration ceases. The θ_{WP} is estimated as the VMC at matric suction, $\psi = 1500$ kPa. However, the parameters θ_{FC} and θ_{WP} are reported to be variable at different climatological conditions, especially in arid and semi-arid region. The θ_{WP} has been found as high as 5 to 7 MPa [20]. In this study, the θ_{FC} and θ_{WP} were computed from the laboratory measured SWCC following the method described by [18]. The field capacity and wilting point measured from one of the lysimeter soil is shown in Figure 5 where θ_{FC} is 0.41 (41%) and θ_{WP} is 0.188 (18.8%). The θ_{FC} ranged from 39.5% to 42.2%, and θ_{WP} varied from 18.8% to 22.6% for all the lysimeter soil.

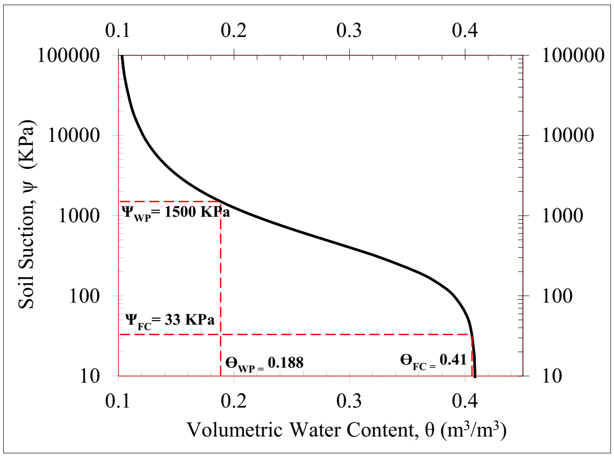

Fig. 5. Field capacity and wilting point of cover soil.

2.3.2 Required Soil Water Storage Capacity (S_R)

Required soil water storage (S_R) was computed for each meteorological year during the study period (2015, 2016, and 2017). The S_R was computed for all the lysimeters using the procedure outlined in [19]. The procedure described by Albright [19] is a holistic approach to determine S_R as all the water balance components are considered in the approach. The S_R was computed using Equation 4 as shown below.

$$S_R = \sum_{m=1}^{6} \Delta S_{FW,m} + \sum_{m=7}^{12} \Delta S_{SS,m} \tag{4}$$

Where, $\Delta S_{FW,m}$ is monthly accumulation of soil water storage in fall and winter. In the study location, fall and winter are considered from October through March. The $\Delta S_{FW,m}$ was calculated using Equation 5.

$$\Delta S_{FW,m} = P_m - \beta_{FW} \times PET_m - \Lambda_{FW} \tag{5}$$

Similarly, $\Delta S_{SS,m}$ is monthly accumulation of soil water storage in spring and summer (April through September). Equation 6 shown below was used to compute the $\Delta S_{SS,m}$.

$$\Delta S_{SS,m} = P_m - \beta_{SS} \times PET_m - \Lambda_{SS} \tag{6}$$

In Equations 5 and 6, P_m and PET_m are the monthly precipitation and potential evapotranspiration (PET) for the corresponding mth month, respectively. The β parameter represents the ET to PET ratio for fall-winter (FW) or spring-summer (SS) conditions. The PET was computed using Penman-Monteith equation presented in [21]. The Λ element in the equation is the residual water balance components (i.e., surface runoff, percolation, and internal lateral flow, if any) for the FW or SS conditions. It is to be noted that in this study percolation was not included in the residual component (Λ), rather it was attempted to evaluate the percolation using the S_R. Albright [19] provided specification for β parameter for snow and frozen ground conditions. However, the effect of snow is very negligible in the location of the study area.

2.3.3 Measurement of S_A from Field SWCC

The available soil water storage (S_A) based on the field SWCC of the cover soil was computed using Equation 3. The thickness of the storage layer (L) in Equation 3 is constant during the computation of S_A, and the θ_{FC} and θ_{WP} were calculated from the field generated SWCCs. The field SWCCs were developed based on the co-located instrumentation data for each of the monitoring year. The response of soil suction at different moisture contents from the co-located sensors are shown in Figure 6.

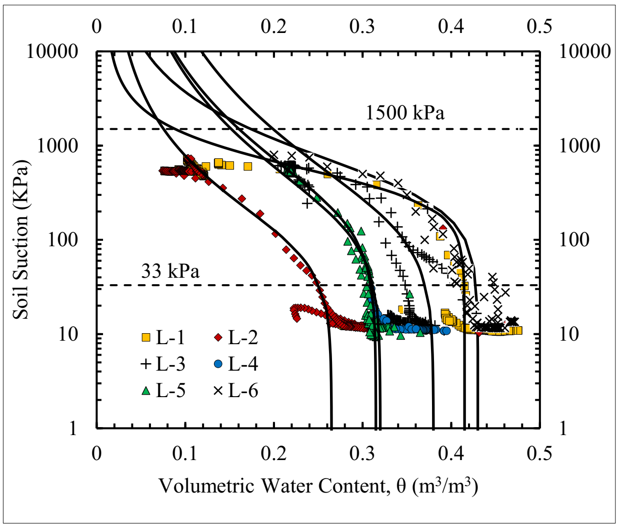

Fig. 6. Field SWCCs of different lysimeters fitted with van-Genuchten equation.

It is to be noted that many data points were recorded from each of the test sections, and hysteresis in the field was observed. However, only those unique data points which constitute the average fair propagation paths of the field SWCCs are shown in the figure. The field SWCCs obtained only in the year 2015 are shown in Figure 6. A curve fitting program was developed to fit the field data with van-Genuchten empirical model using Equation 2 as plotted in Figure 6. The θ_{FC} and θ_{WP} of the field generated SWCCs were estimated following the similar process of laboratory produced SWCCs as described in section 2.3.1. A clear distinction is observed among different lysimeters' field moisture-suction behavior. The θ_{FC} moisture content varied from 0.262 to 0.422 m^3/m^3, while the θ_{WP} ranged from 0.075 to 0.198 m^3/m^3. Consequently, the storage capacity of different cover soil varied, and percolation occurred accordingly. Though all the test sections received equal amount of precipitation and had been through identical environmental conditions, their pore water pressure development was different because of differences in initial in-situ compaction and variation in the plant properties [4, 16]. The field capacity of soil generally decreases with an increase in soil density. During construction, it was observed that the in-situ density of lysimeter 2 soil was comparatively greater than other test sections' density. As a result, the θ_{FC} of L-2 in 2015 was found significantly less. The field measured percolation of L-2 was also found relatively lower than other lysimeters in 2015.

2.3.4 Relative Storage Ratio (RSR), S_R/S_A

Relative storage ratio (RSR) is defined as the ratio of required soil water storage to available soil water storage (S_R/S_A) for a given meteorological year. The RSR is an effective indicator of soil water status and drainage or percolation of the cover profile. Each of the six lysimeters was evaluated using the RSR. The lower value of RSR ($S_R/S_A < 1$) indicates negligible percolation as the cover has adequate capacity to store precipitation. On the contrary, percolation is anticipated if the RSR exceeds the unit value ($S_R/S_A > 1$) because the water to be stored from precipitation is larger relative to the storage capacity of the cover profile. For a given meteorological year, when $S_R/S_A>1$, the quantity S_R-S_A indicates the approximation of annual percolation rate.

3 Results and Discussion

The analysis in this research was administered to evaluate the percolation rate from the soil's unsaturated soil behavior and field observation. Additionally, the required thickness of the storage layer was evaluated based on the field observation.

3.1 Evaluation of Relative Storage Ratio (RSR)

The average S_A computed from the laboratory measured SWCC was 182.07 mm (7.17"). However, the S_A calculated from the field generated SWCC (S_A at the in-service condition) for different lysimeter was found to have an array ranging between 146.30 mm (5.76") and 215.79 mm (8.49"). It was observed that the S_A had relatively increased value in the year 2016 and 2017 than in 2015. This can be attributed to the pedogenic changes in the soil [4, 18, 22]. Additionally, the initial field compaction, moisture content, crack formation in the cover surface and differences in the plant root growth also influenced the field soil behavior [4]. The required soil water storage (S_R) was computed for all the lysimeters in each of the monitoring years. The range of S_R was found 163.15 mm (6.42") to 278.96 mm (10.98"), averaging 221.19 mm (8.71"). It is to be noted that the S_R was comparatively less in the year 2017 than the other two years because the annual precipitation in 2017 at the study area was less compared to that in 2015 and 2016. So, the cover soil had to manage less quantity of water in 2017. Therefore, annual precipitation is an influential factor for hydraulic management of cover soil. The annual precipitations were 1219.45 mm, 1562.35 mm, and 950 mm, respectively in 2015, 2016 and 2017. Here, per annum analysis was conducted from October to September. Each lysimeter soil was evaluated using the relative storage ratio (S_R/S_A). The S_R/S_A ratios are plotted in Figure 7. It is observed from Figure 7 that almost all the lysimeters had S_R/S_A ratio greater than one (1), implying potential percolation. The S_R/S_A ratios shown in Figure 7 are for S_A generated from the field SWCCs. The field observation of the lysimeters through the rain gauge also indicated substantial amount of percolation. The S_R/S_A was found to be in the range between 1.16 and 1.53 for 2015, and 1.22 and 1.57 for 2016. The S_R/S_A values for the year 2017 were found less (0.95 to 1.28) as relatively less quantity of annual precipitation was recorded by the weather station in 2017. On average, S_R/S_A ratio was 1.28>1 for the three years monitoring period. It signifies that for the given environmental conditions, percolation is likely to occur. The higher the ratio of S_R/S_A, the more percolation is anticipated. This fact was also observed consistently from the analyses. The field measured annual percolation for lysimeters 4 and 5 was found comparatively greater than other lysimeters in all the years as listed in Table 3. The S_R/S_A was also found relatively higher, 1.4 to 1.57 for lysimeters 4 and 5 in 2015 and 2016. This shows the S_R/S_A ratio to be a useful indicator to anticipate the degree of percolation. The broad-spectrum investigation of S_R/S_A signifies the unsaturated soil behavior of ET cover to govern the cover performance.

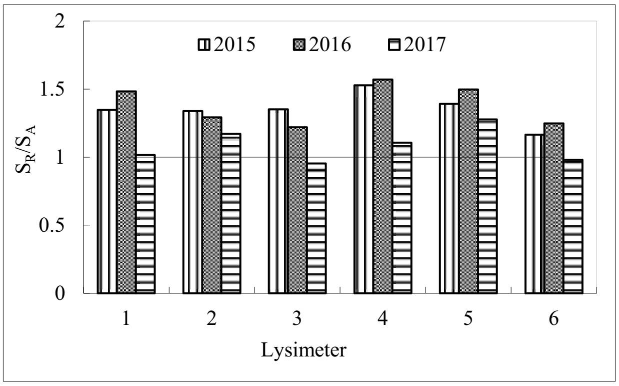

Fig. 7. Relative storage ratio for different lysimeters from field measured SWCC.

Table 3. Field measured annual percolation (mm)

Lysimeter	Field Percolation 2015	Field Percolation 2016	Field Percolation 2017
1	62.99	58.42	53.12
2	42.67	49.53	63.22
3	58.67	66.04	52.63
4	72.89	68.58	49.85
5	74.93	71.12	68.32
6	60.96	53.34	59.63

3.2 Computation of Percolation

The annual percolation for all the lysimeters was approximated using the difference between S_R and S_A, and the estimated percolation was compared with the field measured percolation. The comparison graph is plotted in Figure 8. The estimated values of annual percolation from SWCCs (both laboratory established, and field generated) reasonably fit with the annual percolation of 2015 and 2016. However, the annual percolation measured from laboratory measured SWCC slightly underestimated the percolation values (Figure 8b). One of the reasons behind this is that the SWCCs are measured in a controlled environment in the laboratory; however, the unsaturated hydraulic properties changed when exposed to the environment [4]. The results plotted in Figure 8(a) are reasonably evenly distributed along the 45° inclined straight line, indicating a relatively good agreement between the estimated and field measured values compared to that in Figure 8(b). So, the field generated SWCCs portray a more realistic field hydraulic behavior of soil cover and should be incorporated in the design process. It is to be observed that the annual percolation data for the year 2017 shows clear discrepancies. These discrepancies possibly occurred because of the less quantity of annual precipitation in 2017. Consequently, the cover soil had to manage less water compared to that in 2015 and 2016. The annual precipitation is crucial in the computation of the S_R parameter as it affects the annual percolation estimation. Nonetheless, the field measured annual percolations in 2017 were close to that in the other monitoring years as shown in Table 3. This is because of the precipitation intensity and existence of desiccation cracks in the cover soil [16, 23]. Additionally, annual precipitation in 2017 (950 mm) is considered as heavy rainfall year (wet precipitation year) to cause percolation, even though the rainfall quantity is less than the 2015 and 2016 annual precipitation data.

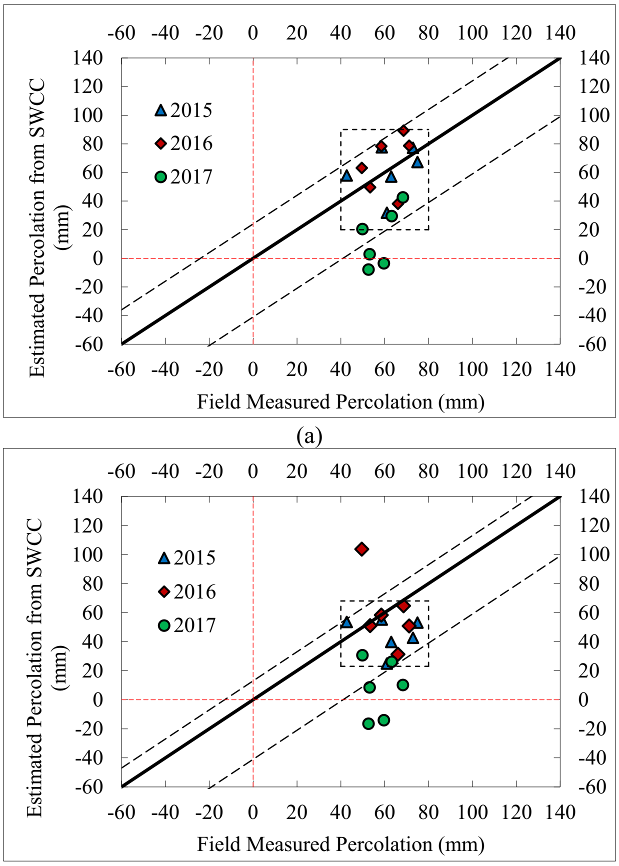

Fig. 8. Comparison of field measured percolation and estimated percolation from (a) field SWCC (b) laboratory SWCC.

3.3 Evaluation of Storage Layer Thickness

From the analysed field data, attempts were made to evaluate the thickness of the cover storage layer. Since, the quantity S_R-S_A implies percolation, the percolation equation takes the simple linear form as defined by the following Equation (7).

$$P_r = S_R - L \times (\theta_{FC} - \theta_{WP}) \tag{7}$$

Based on the field investigation, the S_R was found 163.15 mm (6.42") to 278.96 mm (10.98"), with an average of 221.19 mm (8.71"). So, three curves were generated to evaluate the thickness of the storage layer based on the field investigation. The magnitude of (θ_{FC} – θ_{WP}) indicates the slope of Equation 7. The slope of the equation was determined from the field measured SWCCs and was assumed the average (0.1903) of the three years' monitoring data. The linear plots of the equations are shown in Figure 9.

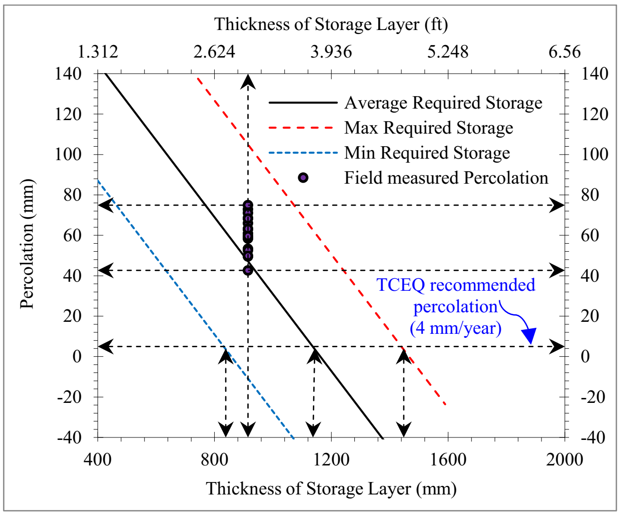

Fig. 9. Design thickness of storage layer.

As shown in Figure 9, an inverse relationship is observed as projected. The annual percolation reduces with an increase in the storage layer thickness. The thickness of the storage layer for all the lysimeters was 915 mm (3'), with 305 mm (1') thick surface layer for vegetation growth. During the field investigation period, the annual percolation was recorded approximately 42 to 75 mm (Table 3) for all the test sections under the identical environmental conditions at the study area. So, it may be expected that ET covers will potentially generate around 42 to 75 mm of annual percolation in this region with a storage layer thickness of 915 mm constructed with high plasticity clayey soil. The guideline for allowable percolation set by Texas Commission on Environmental Quality (TCEQ) for ET cover is limited to 4 mm/year [24]. However, based on the field investigation, it is apparent that limiting the annual percolation to 4 mm will necessitate to increase the thickness of the storage layer. So, a general summary developed based on the field investigation as shown in Figure 9 could improve future design to anticipate the annual percolation and the associated thickness of the ET cover for this region. The plots in Figure 9 identify the required thickness of the water storage layer for potential annual percolation. Considering the average and maximum required storage (S_R) for a given year, the thickness of the storage layer required to limit the annual percolation to less than 4 mm is 1143 mm (3.75') to 1448 mm (4.75'). Considering maximum S_R and given that 305 mm (1') is required for surface layer for vegetation growth, the depth of ET cover becomes 1753 mm (5.75') to limit percolation less than 4 mm/year, which can be proved to be economically impracticable. The developed charts in Figure 9 provide a baseline to estimate the required storage layer thickness of ET cover constructed with high plasticity clayey soil for a specific annual percolation. The results obtained from this evaluation on cover thickness based on the field results establish the impact in design and construction of water balance cover in the region of North Texas.

4 Conclusion

Instrumentation data describing the water balance and the unsaturated hydraulic properties from the field-scale lysimeter has been presented for the semi-humid region of North Texas. The key water balance performance indicator of the ET cover system is percolation. The fundamental concept of water balance covers is to promote evapotranspiration and increase water storage capacity, thus limiting percolation. The amount of annual percolation significantly depends on the annual precipitation and cover soil's water storage capacity. The storage capacity exclusively depends on the unsaturated hydraulic properties of the soil and design thickness. Based on this study, the following inferences can be realized.

1. Annual precipitation greatly influences the required storage of the cover soil, eventually the annual percolation. The evapotranspiration component of water balance is limited for a specific region, and surface runoff greatly depends on the saturated hydraulic conductivity of the soil and precipitation intensity. Ultimately, it is the annual precipitation which regulates the water balance distribution.
2. The unsaturated soil behavior greatly controls the soil water storage capacity. The field capacity and wilting point water content are the primary design parameters to determine the storage capacity of the soil. The RSR is a great indicator of potential percolation and degree of occurrence. Therefore, SWCC determination is an important step in the ET cover design process.
3. The field investigated results clearly demonstrated the change in the unsaturated soil behavior when exposed in the field condition. The annual percolation measured from the SWCCs were reasonably close to the field measured annual percolation, especially the field generated SWCCs. Therefore, the hydraulic properties can be adjusted to field condition before design for reliable water balance cover in the future.
4. The thickness of the cover storage layer, also the ET cover depth, can be assessed for a specified annual percolation range. Realizing the environmental behavior

of a specific region and the local soil's unsaturated parameter (θ_{FC} and θ_{WP}), the thickness of the storage layer can be estimated. So, the unsaturated hydraulic parameters of soil evidently impact the ET cover performance.

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