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Research Article

Hydraulic performance assessment of a multi-layered landfill cover system under constant water ponding

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The engineered multi-layered cover system (MLCS) is used to minimize rainwater infiltration into the wastes accommodated in near surface waste disposal facility (NSDF). It is important to assess the hydraulic performance of MLCS before deploying it in the field. For this purpose, an instrumented three-layered soil column representing MLCS was subjected to 1.5 m constant ponding head for 400 days. The variation of volumetric water content and soil water potential was monitored as a function of depth and time. The objective of the study is to understand the long-term hydraulic performance and rate of saturation of different layers of MLCS. Under constant water ponding, the time to saturation for 0.3 m in surface layer, 0.6 m in drainage layer and 1.0 m in hydraulic barrier layer was observed as 24, 223 and 262 days, respectively. The numerical analysis of the MLCS predicted comparable time duration of 25, 234 and 272 days, respectively. It was noted that the numerical simulation performed by using measured wetting hydraulic parameters matched well with the experimental observation. The importance of soil specific calibration of water content sensors to improve the accuracy of observations was demonstrated. Percentage error in the estimation of layer specific soil water storage, clearly indicates that the volumetric water content measurements using profile probe was marginally better than 5TM measurements.

Keywords: waste, disposal facility, cover system, sensor, numerical simulation, water infiltration

1 Introduction

Industrialization, population growth and urbanization results in the generation of municipal and hazardous waste which need to be safely contained. Engineered landfill or near surface disposal facility (NSDF) is an effective method of waste containment adopted in most of the countries in the context of environmental protection (Guerrero, Maas & Hogland, 2013; Laner et al., 2012; Ng et al., 2016; Turner, Beaven & Woodman, 2017). These NSDF after reaching its full capacity needs to be secured and isolated from the surrounding environment and ground water (Andreas, Diener & Lagerkvist, 2014; Benson & Khire, 1995; Hauser, Weand & Gill, 2001; Travar et al., 2015; Wu et al., 2017). To meet this goal, multi-layered cover system (MLCS) are constructed over NSDF to mitigate downward movement of rain water (percolation) into the impounded waste. Various types of cover system (compacted clay cover, capillary barrier cover, evapotranspiration cover, composite cover, etc.) are developed to satisfy the closure requirements of NSDF and climatic conditions (Abdolahzadeh, Lacroix Vachon & Cabral, 2011; Khire, Benson & Bosscher, 2000; McGuire, Andraski & Archibald, 2009; Parent & Cabral, 2006; Wijeyesekera, O'Connor & Salmon, 2001; Zhang & Sun, 2014; Zornberg, LaFountain & Caldwell, 2003). The past studies indicate that hydraulic characteristics of MLCS plays an important role in preventing environmental pollution. Landfill covers are exposed to varying hydraulic conditions associated with seasonal weather changes and vegetation growth. Therefore,

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it is important to understand the flow characteristics of unsaturated soil layers of cover system before deploying it in the field.

Field hydrology and water balance of these covers were investigated by previous researchers for identifying the governing factors resulting in water migration (Albright et al., 2004; Benson et al., 2007; Bohnhoff et al., 2009; Cuevas et al., 2012; Henken-Mellies & Schweizer, 2011; Nyhan, Shofield & Starmer, 1997; Ogorzalek et al., 2008; Zhan, Ng & Fredlund, 2007). Furthermore, field performance of these cover systems in various climate like arid, semiarid and humid is evaluated for exploring its physical strength to withstand the fatigue load imposed by changing atmospheric condition (Albright, Benson & Apiwantragoon, 2012; Albright et al., 2006; Barnswell & Dwyer, 2011; Benson, Daniel & Botwell, 1999; Benson et al., 2001; Chapuis, 2013; Kraus et al., 1997; Mijares, Khire & Johnson, 2012; Sadek, Ghanimeh & El-Fadel, 2007; Scanlon et al., 2005).

Controlled experimental evaluation was carried out for understanding the performance of the cover system in the absence of real field data (Harnas et al., 2014; Kelln et al., 2006; Lee, Kassim & Gofar, 2011; Li et al., 2013; Melchior et al., 2010; Yanful, Morteza Mousavi & De Souza, 2006; Zhan et al., 2014). This was mostly accomplished by water infiltration columns (McCartney & Zornberg, 2010; Rahardjo et al., 2012; Tan et al., 2018; Yang, Rahardjo & Leong, 2006). Numerical simulation of column was performed using different software codes such as HELP, SEEP/W, VADOSE/W, LEACHM, UNSAT-H and HYDRUS (Aljaradin & Persson, 2015; Ibrahim, Mukhlisin & Jaafar, 2014; Indrawan, Rahardjo & Leong, 2007; Luellen & Brydges, 2005; Ribeiro et al., 2010). In the wake of erratic climatic conditions leading to heavy rainfall, which are normally encountered in tropical climate, it is important to understand the long-term hydraulic performance and progressive saturation of individual layers of MLCS. It is noted that most of the previous studies do not account for the long-term flow characteristics and progressive saturation of each layer in the cover system. Also, there are limited studies that incorporate low permeable hydraulic barriers in the controlled experiments of cover system. It is also important to evaluate the usefulness of numerical modelling for simulating the long-term hydraulic performance of the cover system. Such a study would help to understand the hydrological response of individual layers of cover system for a worst possible condition anticipated during heavy rainfall.

The main objective of this study is to evaluate the hydraulic performance of MLCS by conducting controlled laboratory study for long duration. This was achieved by constructing an instrumented three-layered soil column with its height comparable with the depth of field MLCS. The soil column was subjected to a constant ponding depth of water for progressive saturation of individual layers. The volumetric water content and soil water potential of each layers were simultaneously measured as a function of depth and time. Numerical simulation of the test column was performed to understand its adequacy for simulating long term hydraulic performance of the MLCS. It was noted that the observed and simulated time to saturation matched well for each layer of MLCS. The numerical simulation performed by using measured wetting hydraulic parameters matched well with the experimental observation under constant head condition.

2 Material and methods

Three soils, namely red soil (RS), medium sand (MS) and bentonite clay (BN) were used as surface layer, drainage layer and hydraulic barrier layer, respectively in the study. The soil RS was collected locally from hilly area, Guwahati, in north-east India. This is a medium plastic silty soil and qualifies the requirement of surface soil layer of cover system (USEPA, 1989, 1991). The sand MS used in this study is the construction sand available in north-east India and it satisfies the drainage layer criterion specified for cover layer. The hydraulic barrier layer is a red soil-bentonite mix designated as RB with its composition of 70% of RS and 30% of BN by dry weight. The soil BN used in this study was procured from Barmer, Rajasthan, India. It was ensured that the proposed mix qualifies the permeability criterion requirement ($<10^{-9}$ m.s^{-1}) of hydraulic barrier layer (USEPA, 1989, 1991). Addition of RS in hydraulic barrier is essential to ensure sufficient strength for the barrier layer. The basic physical, geotechnical and chemical properties of all the soils were investigated using standard laboratory procedures reported in the relevant ASTM or IS codes and presented in Table 1.

2.1 Profile probe

Profile probe (PP) (PR2/6-UM-3.0, Delta-T Devices Ltd., UK) consists of a rod housing six embedded sensors for monitoring volumetric water content (θ) at different depths of 0.1 m, 0.2 m, 0.3 m, 0.4 m, 0.6 m and 1.0 m when it is inserted into the soil column. A handheld moisture meter was used for scanning θ from the PP. The polycarbonate PP rod of 0.025 m diameter and 1.35 m length, transmits an electromagnetic field with 100 MHz wave frequency into the surrounding soil mass. Consequently, each profile probe sensor (PPS) measures dielectric constant (ε_a) for a cylindrical soil mass of 0.1 m radius and 0.05 m height (zone of influence). The measured ε_a is converted to θ using appropriate

calibration equation. Thus, PP can measure θ ranging from dry state (0%) to completely saturated state (θ_s) with an accuracy of ±6% for an operating temperature ranging from -20 °C to +60 °C. However, the accuracy of PPS measurements was improved up to ±1% based on soil specific calibration performed in house (Shaikh et al., 2018).

2.2 5TM sensor

The 5TM sensor (Meter Group, USA) are point sensors, which can simultaneously measure θ and temperature of the soil. Each of three prongs of the sensor generates electromagnetic field by an oscillating wave of frequency of 70 MHz to 100 MHz, which is transmitted into the surrounding soil mass to measure its ε_a. The measured raw ε_a are then converted into θ using Topp's equation (Topp et al., 1980). The sensor can thus measure θ in range of 0% to θ_s with a precision of ±3% for a temperature spanning from – 40 °C to 60 °C. However, measurement accuracy was improved up to ±1 % by utilizing soil specific calibration performed in house (Shaikh et al., 2019).

2.3 TEROS 21 sensor

The TEROS 21 sensor (Meter Environment, USA) is used to measure soil water potential or suction (ψ) in the range of 9 to 100,000 kPa (as stated by the manufacturer) with an accuracy of ±10%. The sensor consists of a water content sensor and a porous substrate with a known moisture release curve. The water content sensor measures the water content of the porous substrate after its equilibration with the surrounding soil. The moisture release curve is then utilized to convert the obtained water content into soil suction based on the factory calibration procedure. An Em50 data logger (Meter Group,

Table 1 Basic properties of soils used in the study

Properties	Soil material (designation)			
	medium sand (MS)	red soil (RS)	bentonite (BN)	70% RS + 30% BN (RB)
General				
Specific gravity, G	2.68	2.65	2.88	2.72
Hygroscopic water content (%)	2	5	11	7
Saturated hydraulic conductivity ($m.s^{-1}$)	4.23E-5	2.9E-9	3.9E-12	2.0E-10
Specific surface area ($m^2.g^{-1}$)	–	55	348	143
Linear shrinkage (%)	–	2	3	2
Free swell index (%)	–	10	686	213
Particle size distribution				
% of gravel (>0.00475 m)	0	0	0	0
% of coarse sand (0.002–0.00475 m)	13	17	0	12
% of medium sand (0.000425–0.002 m)	70	16	0	11
% of fine sand (0.000075–0.000425 m)	15	16	5	13
% of silt (0.000002–0.000075 m)	2	19	31	23
% of clay (<0.000002 m)	0	32	64	41
Atterberg's limits				
Liquid limit (%)	–	42	295	117
Plastic limit (%)	–	22	42	28
Shrinkage limit (%)	–	21	11	18
Plasticity Index (%)	–	20	253	89
Standard compaction				
Optimum moisture content, OMC (%)	–	20	33	23
Maximum dry density, MDD ($g.cm^{-3}$)	–	1.73	1.34	1.59
Chemical				
Soil pH value (at 28.5 °C)	–	6.85	9.15	7.54
Organic content (%)	–	0.48	0.22	0.40
Cation exchange capacity ($meq.100\ g^{-1}$)	–	8	27	14

USA) is employed for recording continuous measurements of 5TM and TEROS 21 sensor.

2.4 Instrumentation of test column

The test column fabricated in this study consist of polyvinyl chloride (PVC) cylinder of 0.3 m internal diameter and total height of 1.2 m. The soil column accommodates three layers of cover system, the hydraulic barrier layer, drainage layer, and surface layer designated as BL, DL, and SL respectively. Schematic diagram of the soil column is presented in Fig. 1 and the details of soil layers and instrumentation is listed in Table 2. For ease of placing the soil layers, the soil column has four detachable portions of 0.3 m height. O rings were provided at the joints between two cylindrical portions and commercially available sealants were applied for preventing leakage of water. The bottom of the soil column consists of a percolation collection chamber. A thin walled access tube of 0.027 m internal diameter and 1.2 m height was placed and secured vertically along the longitudinal axis of the soil column. Hydraulic barrier layer (BL) of 0.4 m thickness was placed by compacting the soil mix RB to its maximum dry density (MDD) and optimum moisture content (OMC) as detailed in Table 1. For uniform density, each layer was divided into multiple layers of 0.05 m height and the soil was compacted using 2.6 kg rammer.

The drainage layer (DL) of 0.3 m height was constructed by loosely

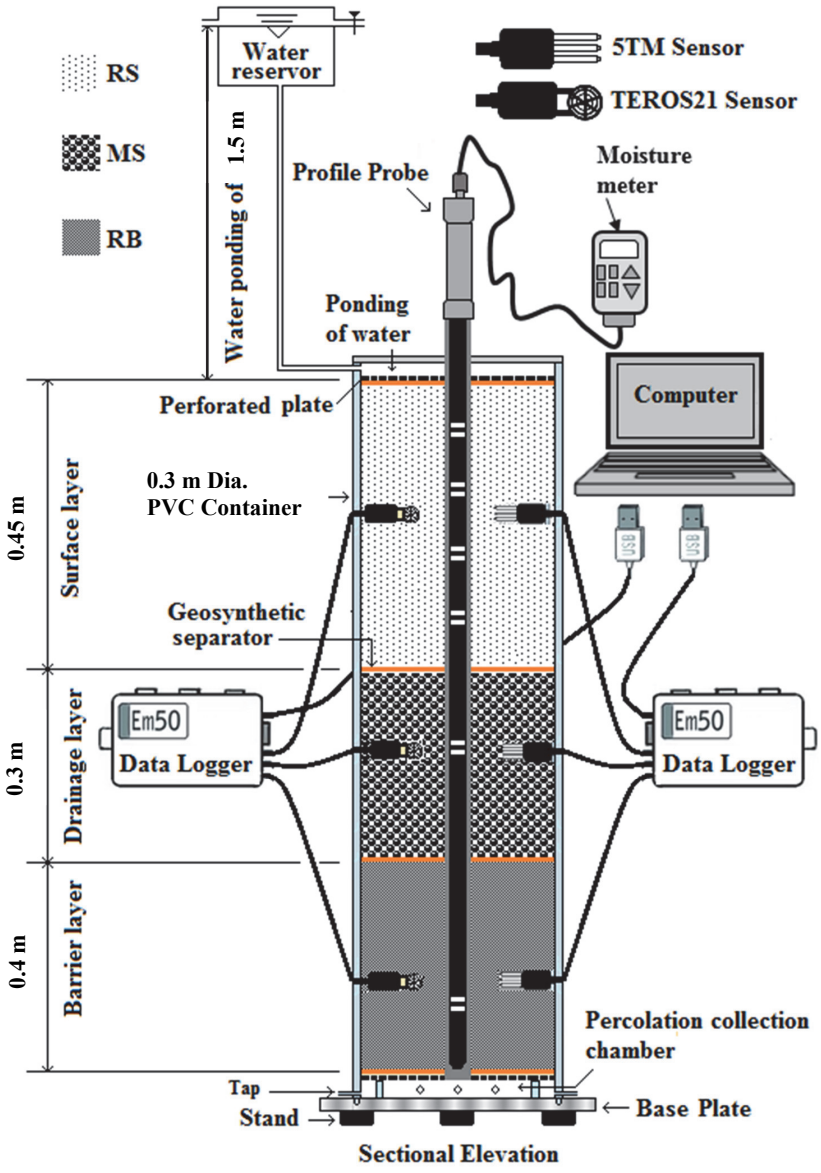


Figure 1 Schematic diagram of the experimental soil column

compacting medium sand (MS) on top of BL. This was overlain by surface layer (SL) of 0.45 m height by compacting RS to its MDD and OMC. The 5TM and TEROS 21 sensors were placed at the middle of each layer during compaction. Two diametrically opposite holes were provided for connecting the sensors to their data loggers. Sufficient care was taken to prevent water leakage by applying sealants. The top 0.05 m

Table 2 Details of instrumentation of soil column for the study

Cover layer (thickness)	Soil material		Sensor device employed (depth in m)
	name (designation)	source	
Surface layer (0.45 m)	red soil (RS)	locally available	PPS1 (0.1), PPS2 (0.2), PPS3 (0.3), PPS4 (0.4), 5TM (0.3), TEROS21 (0.3)
Drainage layer (0.3 m)	medium sand (MS)	locally available	PPS5 (0.6), 5TM (0.6), TEROS21 (0.6)
Barrier layer (0.4 m)	red soil-bentonite mix (RB)	mixture of 70% of red soil and 30% of bentonite	PPS6 (1.0), 5TM (1.0), TEROS21 (1.0)

height of the column act as reservoir for ensuring uniform 1-D flow of water into the soil layers. A thin layer of sealant was applied at the interface between the access tube of PP and the soil surface and also at the side boundary to minimize preferential flow of water. The fully erected soil column was subjected to constant water ponding depth of 1.5 m at its top. The PP was inserted into the access tube for scanning θ at 0.1 m, 0.2 m, 0.3 m, 0.4 m, 0.6 m and 1.0 m depths of the soil column. PPS measurements were conducted thrice in a day and their average was considered as measured daily θ. At depths of 0.3, 0.6 and 1.0 m, θ was measured by 5TM and ψ was measured by TEROS 21 sensor. The daily average of these measurements was considered for this study. The variation of θ and ψ in each layer subject to downward percolation of water were monitored as a function of depth and time for 400 days.

2.5 Numerical simulation

The vertical flow of water through the experimental soil column was numerically modelled using finite element HYDRUS 2D code (Šimůnek, Šejna & van Genuchten, 1998). Hydrus solves modified Richard's equation of water flow through unsaturated or saturated soil media. The details of geometry, boundary conditions, and finite element (FE) mesh of the soil column is shown in Fig. 2A. The mesh sensitivity study presented in Fig. 2B indicates that FE mesh size less than 0.03 m has no significant effect on obtained results. Hence, a 0.03 m triangular FE mesh was considered for subsequent numerical modelling. Hydraulic properties of RS, MS and RB were determined in the study as input parameters for numerical analyses. These properties comprise residual volumetric water content (θ_r), saturated volumetric water content (θ_s), van Genuchten parameters α and n, saturated hydraulic conductivity (K_s), and pore connectivity parameters (l). The K_s was determined in the laboratory by conducting falling head test (ASTM D5084-03). Pore connectivity parameter, l was considered to be 0.5 for all soil materials based on previous literature (Mualem, 1976).

The hydraulic parameters θ_r, θ_s, α and n were determined in three ways: (1) the parameters were obtained from neural network prediction (Rosetta Lite V. 1.1 2003) based on percentage of sand, silt and clay fraction of the soil (Wosten et al., 1999) (2) parameters determined from drying soil water characteristic curve (SWCC) measured by dew point potentiometer (WP4-T, Decagon Devices Inc., USA) (3) parameters obtained from measured wetting SWCC obtained from 5TM and TEROS 21 readings during water infiltration. Table 3 details three different sets of estimated hydraulic parameters designated as PHP, DHP and WHP for predicted, drying and wetting, respectively. These hydraulic properties were assigned separately in the numerical simulations to understand its

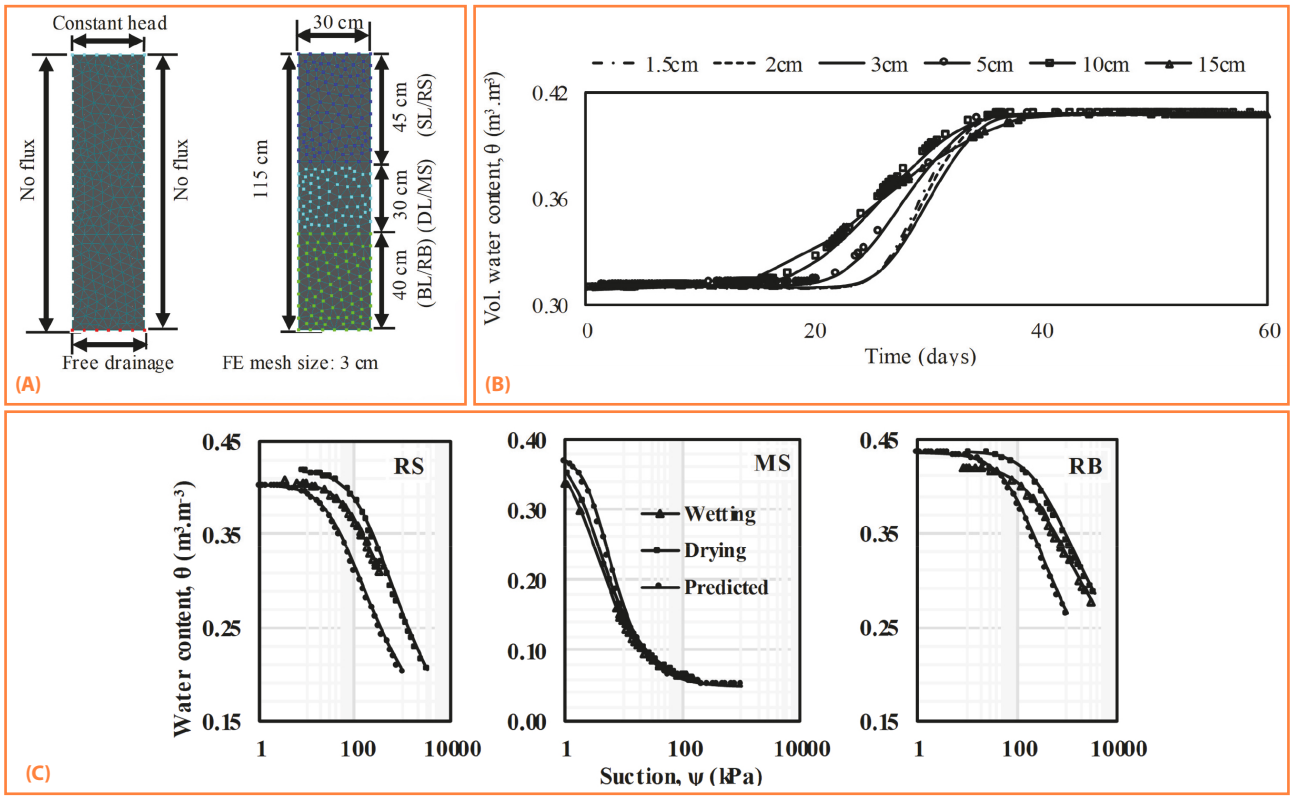


Figure 2 (A) Geometry and boundary conditions used in numerical analysis, (B) Mesh convergence study (C) Predicted, drying and wetting soil water characteristic curves for RS, MS and RB

Table 3 Hydraulic parameters of the soil materials assigned in numerical analyses for the study

Layer (material)	Designation	Hydraulic parameters						θ_i
		θ_r	θ_s	α	n	K_s	l	
SL: Surface layer (RS)	WHP	0.061	0.406	0.00001	1.23998	0.0001209	0.5	0.308
	DHP	0.062	0.419	0.000005	1.30978	0.0001209	0.5	0.308
	PHP	0.076	0.404	0.000023	1.30000	0.0001209	0.5	0.308
DL: Drainage layer (MS)	WHP	0.039	0.369	0.000498	1.78391	0.0183168	0.5	0.060
	DHP	0.040	0.381	0.000408	1.80731	0.0183168	0.5	0.060
	PHP	0.049	0.379	0.000259	2.06211	0.0183168	0.5	0.060
BL: Barrier layer (RB)	WHP	0.076	0.421	0.000004	1.21201	0.0000173	0.5	0.330
	DHP	0.077	0.438	0.000003	1.23110	0.0000173	0.5	0.330
	PHP	0.086	0.436	0.000011	1.28160	0.0000173	0.5	0.330

Note: WHP – wetting hydraulic properties, DHP – drying hydraulic properties, PHP – predicted hydraulic properties, θ_r – residual volumetric water content ($m^3.m^{-3}$); θ_s – saturated volumetric water content ($m^3.m^{-3}$); α (m^{-1}) and n – van Genuchten parameters; K_s – saturated hydraulic conductivity (m/day); l – pore connectivity parameter; θ_i – initial volumetric water content ($m^3.m^{-3}$)

appropriateness in modelling the progressive saturation of the layered soil column. The details of the three SWCCs (predicted, drying and wetting) of RS, MS and RB were presented in Fig. 2C. A constant ponding head of 150 cm was assigned at the top of SL. No flux boundary conditions were chosen at vertical sides of soil column. A free drainage boundary condition was selected at the base of column model. Table 3 also presents the average values of initial θ (θ_i) measured by the water content sensors separately in each layer of the test column. The numerical flow simulation estimates θ and ψ with depth and time for the abovementioned initial and boundary conditions, which was compared with the measured results from the respective sensors placed in the soil column.

3 Results and discussion

The instrumented column shown in Fig. 1 was monitored continuously to measure the variation in θ and ψ as a function of depth and time for studying the hydraulic performance of individual layers of MLCS. Fig. 3A shows the θ variation measured by PPS with time at depths of 0.1 m, 0.2 m and 0.4 m in surface layer. Fig. 3B compares θ measured by 5TM and PPS at 0.3 m, 0.6 m and 1.0 m depths in SL, DL and BL, respectively. The main objective of these figures is to show the importance of corrective calibration of sensors for precise measurements of θ. Referring to Fig. 3A, there is a significant difference in θ variation before and after calibration of PPS, even though the trend remains the same. It can be noted that the initial measurements of PPS fall below the expected actual value in some cases. At 0.4 m, the measured θ before calibration was found to be higher than the theoretical θ_s. The theoretical θ_s is equal to porosity and it is computed from the measured mass-volume relationship shown in Eq. 1. It may also be noted that measured θ_s after calibration is marginally less than the theoretical value. This is expected due to the presence of entrapped air and has been reported in the previous studies (Brooks & Corey, 1966; Touma, Vachaud & Parlange, 1984; Wang et al., 1997).

$$\theta_s = 1 - \frac{\rho_d}{G\rho_w} \quad (1)$$

Table 4 Measured time to deviation from initial condition and time to saturation (in days)

Layer	Depth (m)	PPS		5TM		TEROS21	
		t_d	t_s	t_d	t_s	t_d	t_s
SL	0.1	0.3 (0.4)	5 (3)	–	–	–	–
	0.2	1 (1)	8 (11)	–	–	–	–
	0.3	3 (4)	24 (23)	4 (4)	25 (23)	4 (4)	13 (23)
	0.4	9 (8)	31(33)	–	–	–	–
DL	0.6	50 (50)	223 (225)	53 (50)	227 (225)	52 (50)	92 (225)
BL	1.0	169 (158)	262 (266)	174 (158)	269 (266)	180 (158)	214 (266)

Note: t_s – time to saturation (days); t_d – time to deviation from initial condition (days); values in parenthesis are the results of numerical simulation performed using wetting hydraulic parameters (WHP)

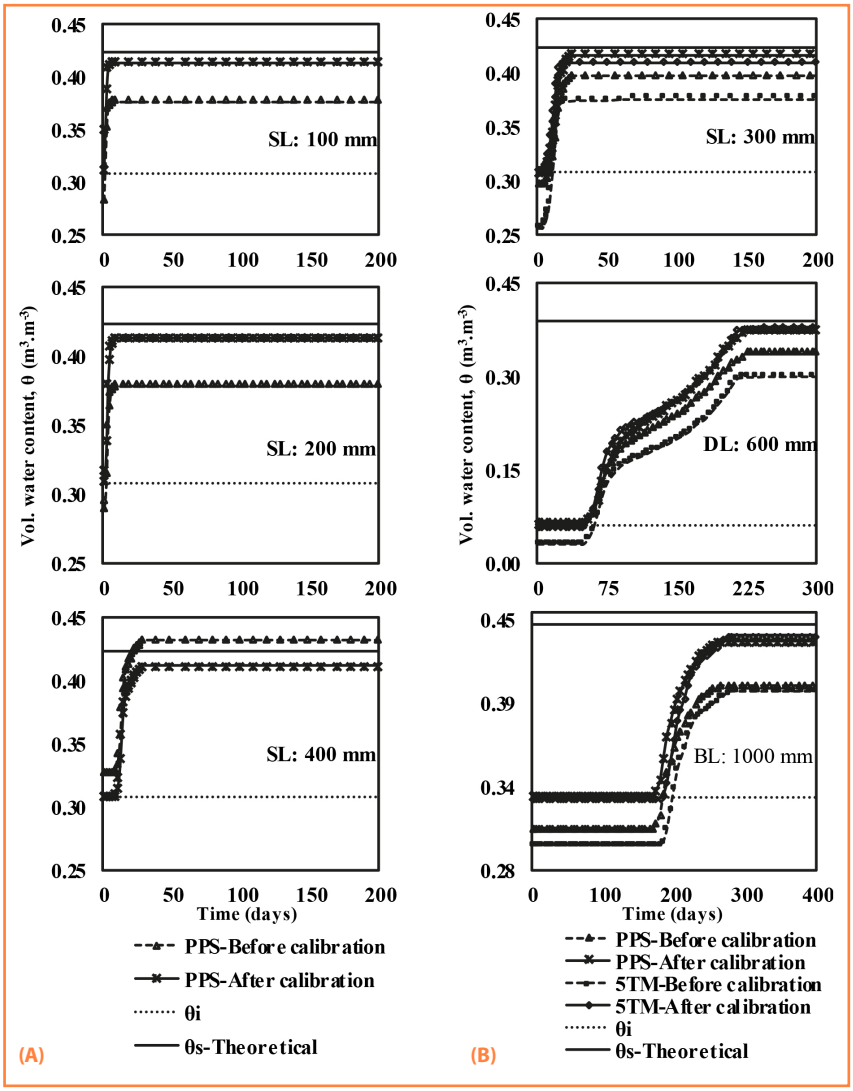


Figure 3 (A) Profile probe measurements in surface layer, (B) Comparison of profile probe with 5TM measurements before and after their calibration

where: G – specific gravity, ρ_d dry density reported in Table 1 and ρw is density of water

Once the sensor measurement reaches θ_s, it remains constant for the entire duration of the study. There is no expected variability in θ as the soil undergoes progressive wetting only under constant ponding head. The time to saturation (t_s), time to deviation from initial condition (t_d) is noted from Figs. 3A and 3B and listed in Table 4.

Fig. 3B checks the parity in θ measured by PPS and 5TM sensor at the same location of three layers. The figure shows that θ measurements in all three layers were underestimated by both the sensors before soil specific calibration. Especially, the deviation was more pronounced in the case of 5TM. It can also be clearly observed from the figure that there is considerable difference between θ measured by PPS and 5TM sensors before calibration. However, after adopting corrective calibration the θ measured by both the sensors gave comparable results. The study brings out the importance of soil specific calibration for individual soil layers of MLCS especially when multiple types of sensors are deployed in the field. Absence of corrective procedure can lead to error in data interpretation and deriving conclusions. Hence, the corrected measurements of 5TM and PPS readings were considered for further comparative analysis with simulated numerical results.

In this study, three sets of input parameters: wetting hydraulic parameter (WHP), drying hydraulic parameter (DHP) and predicted hydraulic parameter (PHP) were considered for numerical simulation of θ and ψ with depth and time. The aim was to understand the suitability of these input parameters for performing numerical analysis of the real-life MLCS. Even though it is explicit that the seepage is a wetting phenomenon, it is tedious, time consuming and sometimes difficult to obtain WHP as compared to DHP (Gallage, Kodikara & Uchimura, 2013; Gapak & Bharat, 2018). As a result, DHP is generally considered for seepage analysis assuming the hysteresis to be negligible (Abbasi et al., 2012; Ng & Leung, 2012). In the absence of measurements, researchers also adopted PHP based on the known basic soil properties. It is therefore important to appraise the variability in the numerical simulation results attributed to the chosen input parameters. The θ measured by PPS at 0.1 m, 0.2 m and 0.4 m depths in SL were compared with simulated θ as shown in Fig. 4A. The observation indicates that the numerical simulation performed using WHP was marginally closer than DHP as compared to measured results. It is also noted that the simulation using WHP is slightly less and those performed using DHP is slightly higher than the measured results. This means that from designer's perspective, it is safe to consider DHP (predicts higher θ) as a reliable input for numerical simulation of MLCS in the absence of WHP. However, in all the cases PHP based numerical results were not in good agreement and lower than the measured results. Hence, PHP

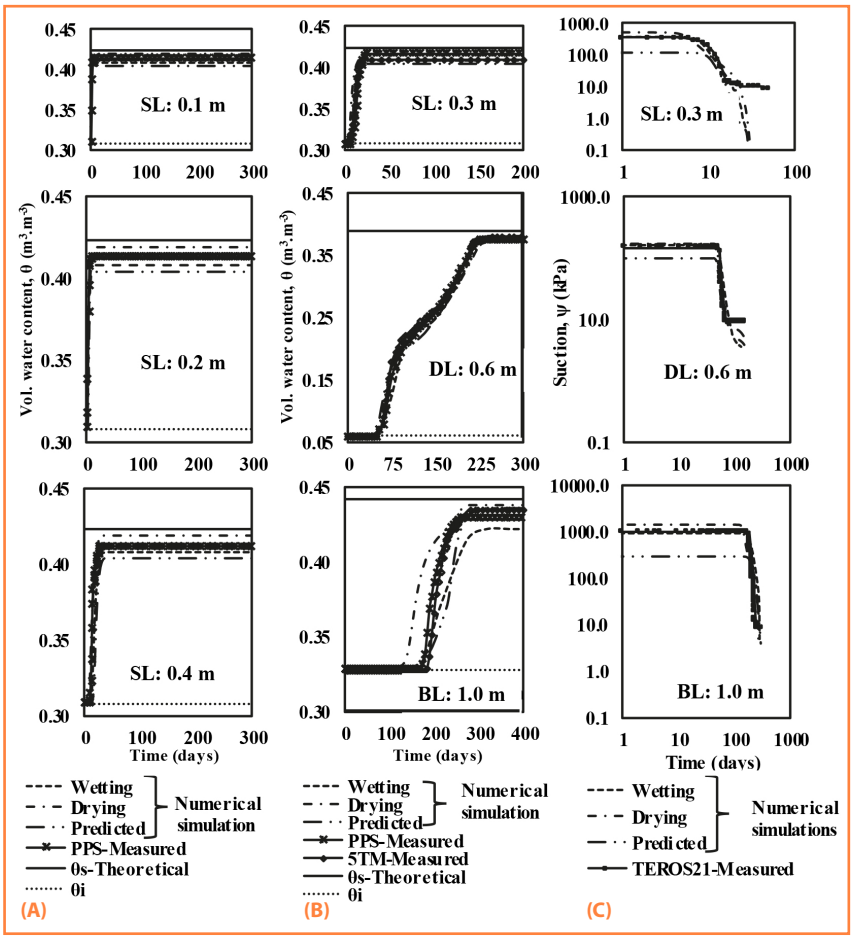


Figure 4 Comparison of simulated results with (A) profile probe measurements, (B) both profile probe and 5TM measurements, (C) TEROS21 measurements

based input is not recommended for numerical simulation of environmentally sensitive projects like MLCS.

Fig. 4B compares θ measured by both PPS and 5TM at 0.3 m in SL, 0.6 m in DL and 1.0 m in BL along with the numerical results. The figure shows that the θ measured at all the depths by both the sensors are in good agreement. For 0.3 m depth there is minimal variation after achieving saturation (after reaching θ_s) where in the PPS results are close to DHP and 5TM results matches exactly with the WHP. The PHP based simulation is less than both PPS and 5TM measurements. For drainage layer, all the results matched well. This is mainly due to the minimal uncertainties and variabilities related to the hydraulic characterization of sands as compared to silts and clays (Yang et al., 2004). The variation of θ measured at 1.0 m in BL matched relatively better with the numerical simulations performed based on WHP. The differences are more for the transition of θ from initial to saturated condition. It is further noted that the measurements from PHP and 5TM are close to each other in the transition zone. The numerical simulation matched well with the measurements in the saturation state where θ approaches θ_s. The differences in the transition zone may be attributed to the combined influence of hidden uncertainties related to the SWCC characterization and the calibration procedure for barrier layer (not shown in this study explicitly), which could not be explored in the present study.

Fig. 4C compares the TEROS 21 measurements with its respective numerical simulations to understand the performance of the MLCS in terms of soil suction. It need to be mentioned here that the accuracy of TEROS 21 could not be ascertained for higher range of suction which is obvious for materials (highly plastic clays) used in the barrier layer (Fredlund, Sheng & Zhao, 2011). The figure shows that the ψ measured by TEROS 21 sensor beyond 9 kPa, matched well with ψ simulated with WHP for both SL and DL materials considered in this study. Based on the Fig. 4C and Table 4, it can be seen that ψ measured by TEROS 21 sensor at 0.3, 0.6 and 1.0 m, remained unchanged for 4, 52, 180 days, respectively. Thereafter, ψ began to vary from initial condition and approached its minimum measured suction of 9 kPa for near saturation. The rate of ψ variation at 0.3 m in SL and 0.6 m in DL was very fast whereas it was gradual at 1.0 m in BL. Considering minimum measured suction of 9 kPa as the reference, t_s was found to be 13, 92 and 214 days at 0.3, 0.6 and 1.0 m respectively. WHP based numerical analyses gave t_s at 0.3, 0.6 and 1.0 m as 16, 85 and 279 days, respectively. This indicates that TEROS 21 measurements in SL and DL were in good agreement with the simulations whereas a considerable deviation was noticed in the case of BL. This may be attributed to the inability of TEROS 21 to measure suction less than 9 kPa (Tripathy et al., 2016). Thereby, θ measurements can be considered more reliable than ψ measurements for entire range of wetting and drying.

For better understanding, Table 4 and Fig. 5A presents the results of time to deviation from initial condition (t_d in days) and time to saturation (ts in days) for different depth of measurements. For completeness, t_d and t_s from numerical simulation are

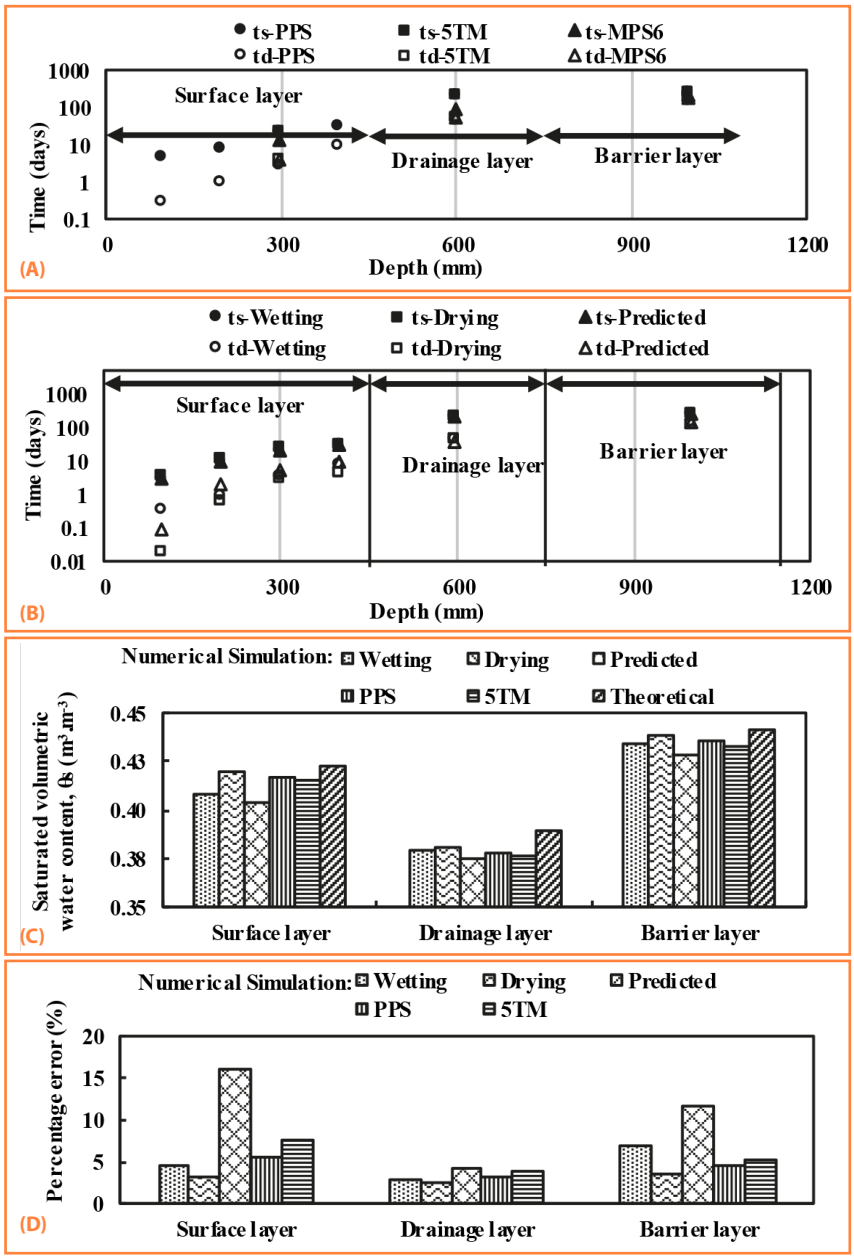


Figure 5 Time to deviation from initial condition and time to saturation based on (A) experimental measurements and (B) numerical simulations, (C) Saturated volumetric water content and (D) Percentage errors in evaluation of change in soil water storage of each column layer based on numerical and experimental results

also presented in Fig. 4B. In general, t_d and t_s obtained from the numerical analyses are in close agreement with the measured results. The values listed in the parenthesis of Table 4 indicates the data corresponding to numerical analysis based on WHP. It can be noted from Figs. 5A and 5B that θ measured at 0.1 m, started to change abruptly from initial value (θ_i) in the very first day and took 5 days to reach saturation, which is expected for an exceptionally high ponding head considered in this study. As the depth increased in surface layer, the variation of θ was at a gradual rate resulting in higher t_d and t_s. As expected, there was no fluctuation in the measured results once it approached saturated condition as can be seen from Figs. 5A and 5B. This indirectly endorses the proper functioning of sensors used in this study. The t_d in the barrier layer (1.0 m) was found to be 169 and 174 days on the basis of PPS and 5TM readings, respectively. The corresponding t_s in the barrier layer was 262 and 269 days for PPS and 5TM readings, respectively. The values of t_d and t_s of barrier layer (at 1.0 m) from numerical simulation based on WHP was found to be 158 and 266 days, respectively. These values are close to the experimental results as stated above. The advantage of this study is that the t_s in the barrier layer could be assessed experimentally, which is otherwise missing in the literature. This is an important observation in terms of material characteristics even though the possibility of saturation of the hydraulic barrier is quite rare and not expected during its design life unless there is a serious malfunctioning of drainage layer leading to substantial build-up of head causing flow.

The measured θ_s in SL, DL and BL were compared with the results of numerical analyses as shown in Fig. 5C. Based on the experimental observations, Fig. 5C clearly shows that θ_s measured by PPS in SL, DL and BL was close to its expected theoretical value than that measured by 5TM sensor. The figure also depicts that theoretical θ_s of each layer was comparatively closer to the θ_s computed in numerical simulation based on DHP. θ_s measured by PPS were also very close to the θ_s computed in the numerical simulation performed using DHP. This advocates that the numerical simulation performed using DHP is not inferior to those based on WHP. In all cases, PHP was not yielding reliable prediction of θ_s. Percentage error (PE) in change of soil water storage (Δ*S*) estimated by Eq. 2, was computed by using Eq.3 and presented in Fig. 5D.

$$\Delta S = V_G \times (\theta_s - \theta_i) \qquad (2)$$

$$PE = \left(\frac{\Delta S_t - \Delta S_m}{\Delta S_t} \right) \% \quad (3)$$

where: V_G – geometric volume of column layer; ΔS_t – the estimated value based on theoretical value of θ_s; ΔS_m – determined from the measured or simulated value of θ_s

Based on both the measured and simulated results, the PE in ΔS followed the sequence PHP < WHP < DHP. The analysis of PE revealed that experimental measurements by PPS were marginally more accurate than the 5TM sensor.

4 Conclusions

In this study, a three-layered laboratory soil column of 1.15 m height was constructed to study the hydraulic performance of multi-layered cover system (MLCS) deployed over near surface waste disposal facility. The height of the layers of the MLCS was kept at par with the field requirements and subjected to a constant water ponding of 1.5 m depth for 400 days. The variation of volumetric water content and soil water potential was simultaneously monitored as a function of depth and time, till each layer approached saturation due to the percolation of water. Numerical analyses of the MLCS column were performed corresponding to three various sets of hydraulic properties acquired from drying, wetting and predicted soil water characteristic curve. It was noted that the measured observations matched well with the numerical simulations performed by considering wetting hydraulic properties. The study indicates the significance of soil specific calibration of water content sensors for enhancing the measurement accuracy. Layer specific saturated volumetric water content obtained from the study was noticed to be marginally lesser than its theoretical volumetric water content. This may be attributed to the entrapped micro air pockets in the soil mass during downward percolation of water. For a high water ponding condition, it was noted that time to saturation at 0.3 m (in top surface layer), 0.6 m (in middle drainage layer), and 1.0 m (in bottom hydraulic barrier layer) depths were 24, 223 and 262 days, respectively. The corresponding time to saturation predicted using numerical simulation was 25, 234 and 272 days in surface, drainage and hydraulic barrier layer, respectively. The root mean square error in the evaluation of soil water storage indicates that profile probe volumetric water content measurements was marginally superior to 5TM readings. The boundary condition adopted in this study is a worst possible hypothetical situation to understand the hydraulic performance and time to saturation of different layers in MLCS. However, MLCS with the same configuration need to be tested in the field under natural soil-atmosphere boundary condition, which is a more realistic condition the MLCS would be subjected to during its design life.

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