

Hydraulic Performance Evaluation of Multi-layered Cover System for Near Surface Disposal Facility

Synopsis of the thesis

submitted in the partial fulfilment of the requirement for the degree of

DOCTOR OF PHILOSOPHY

by

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Introduction

The ever increasing hazardous wastes due to rapid urbanization and industrialisation have resulted in the need for multi-layered cover system (MLCS) for the final closure of the near surface disposal facility or landfills (EEA 2013). Previous literature (Landreth et al. 1991) clearly indicate the importance of MLCS to reduce water percolation into the underlying waste for preventing leachate induced groundwater contamination. Besides, these wastes need to be isolated from surrounding environment for sufficiently long period (more than 100 years) in order to minimize the risk of contamination to the ecosystem (Koerner and Daniel 1997). Hence, a well-designed cover system is required to be constructed after the landfill reaches full capacity (Guerrero et al. 2013; Laner et al. 2012).

The literature shows that economic design of MLCS is a challenging task (USEPA 1989) taking into account the climate of the site. Studies on MLCS were undertaken by the previous researchers based on site-specific conditions and materials (Albright et al. 2006; Ng et al. 2016). The critical field assessment of water movement into the unsaturated MLCS has not been conducted previously for extremely humid weather (typical to North-eastern India, with mean annual rainfall above 2000mm). In addition, climate change impact on the MLCS performance was rarely investigated. An in-depth understanding about numerous governing factors which play significant role in the hydraulic performance of the MLCS is required. The necessity of investigation on such factors motivated this study.

Objective and scopes

Primary objective of the present study is to evaluate the hydraulic performance of multi-layered cover system for near surface disposal facility to contain hazardous waste.

Accordingly, the scopes of the study are outlined as follows:

- (i) Performance evaluation of water content sensors for each soils used in the MLCS.
- (ii) Laboratory investigation on MLCS columns under constant water ponding.
- (iii) Field investigation on sloped MLCS under natural weather condition.
- (iv) Numerical analyses of hydraulic performance efficacy of the MLCS considering climate change effects.

Outline of the thesis

The thesis is organized in nine chapters. **Chapter 1** gives a general overview of the thesis, motivation behind this research work and its importance. **Chapter 2** reviews the literature comprehensively on the background research and identifies the gap areas. The objective and scope of the study are also listed in the chapter based on the research gap addressed. **Chapter 3** deals with the theoretical concepts and the details of the methodologies, which adopted in this study to meet the research objectives. **Chapter 4** presents the experimental investigations and basic characterization

of soil materials. **Chapter 5** describes the performance evaluation of the water content sensors (profile probe and 5TM), and summarizes the soil specific calibration parameters which were used for further measurements. **Chapter 6** discuss the controlled laboratory evaluation of four different configurations of MLCS columns under constant water ponding. In the chapter, these test results were also compared with simulated results from the numerical analyses by considering three different sets of soil hydraulic parameters. **Chapter 7** discusses the results of the field test of a trial MLCS constructed in the field and exposed to natural weather condition for 800 days spanning from May 2016 to July 2018. Based on five different sets of time variable boundary conditions and three different sets of hydraulic properties, numerical simulations were carried out in the chapter for comparing with the field observations. **Chapter 8** explains the climate change impact assessment of water percolation characteristics of MLCS. The futuristic climate parameters of 87 years forecasted by statistical down scaling model (SDSM) technique, were utilized in the chapter for assigning time variable boundary condition in numerical analyses. Finally, **chapter 9** summarizes the major findings and conclusions of the study. Future work of this study is presented as the final section of chapter 9.

Materials and measurement methods

Five soils and their five different mixes with its details and designations are listed in Table 1. The soils RF and BF are used as surface layer and are mixtures of 50% fly ash (FA) with 50% of red soil (RS) and black soil (BS), respectively. RB, BB and BF are the mixtures of 30% bentonite (BN) with 70% of red soil, black soil and fly ash respectively. Table 1 also list the name, designation, make and use of the sensors employed in the study.

Soil characterization

Basic physical, geotechnical and chemical properties of all soil materials used in the study were investigated using standard laboratory procedures and results are summarized in Table 2. Investigation were carried out by following the guidelines from either Indian or ASTM standards.

Table 1 List of soil materials and equipment used in the current study

Soil Material			Equipment		
Name (Designation)	Source	Used for	Name (Designation)	Make	Used to measure
Medium sand (MS)	Locally available river sand	DL	Profile probe (PP)	Delta-T devices	θ
Fly ash (FA)	Farakka, West Bengal	SL and BL	5TM sensor (5TM)	Meter group	θ
Red soil (RS)	Locally available silty clay	SL and BL	TEROS21 sensor (TEROS21)	Meter group	ψ
Black soil (BS)	Mumbai, Maharashtra	SL and BL	WP4 potentiometer (WP4)	Meter group	ψ
Bentonite (BN)	Barmer, Rajasthan	BL	Data logger (DL)	Delta/Meter group	θ and ψ

Notes: DL = drainage layer, SL = surface layer, BL = barrier layer, θ = volumetric water content, ψ = soil suction

Table 2. Properties of soil materials used in the study

Properties	MS	FA	RS	BS	BN	RF	BF	FB	RB	BB
Specific gravity (G)	2.69	2.17	2.68	2.61	2.88	2.41	2.38	2.51	2.72	2.69
Hygroscopic water content (%)	2.54	2.63	5.45	9.17	11.67	3.95	5.73	6.85	7.31	9.92
% of Gravel (> 4.75 mm)	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
% of Coarse sand (2.00 – 4.75 mm)	13.5	0	17.1 6	14.3	0.00	8.34	7.23	0.00	12.01	10.21
% of Medium sand (0.425 – 2.00) mm)	69.6	0	15.5	15.5	0.00	7.73	8.15	0.00	10.91	10.70
% of Fine sand (0.075 – 0.425 mm)	15.4	24	16.0	8.20	4.90	20.3	17.3	14.6	12.70	9.17
% of Silt (0.002 – 0.075 mm)	1.32	74	18.7	22.2	31.2	46.5	47.8	52.4	22.49	23.73
% of Clay (< 0.002mm)	0.00	2	32.4	39.8	63.8	17.0	19.4	32.9	41.89	46.12
Liquid limit (%)	-	-	42	60	295	33	37	93	117	130
Plastic limit (%)	-	-	22	33	42	17	19	20	28	35
Shrinkage limit (%)	-	-	21	22	11	16	18	17	18	19
Plasticity Index (%)	-	-	20	27	253	16	18	73	89	95
Specific surface area (m ² /gm)	-	67	55	89	348	31	48	109	143	167
Optimum moisture content (%)	-	19	20	29	33	19	24	22	23	32
Maximum dry density (g/cm ³)	-	1.38	1.68	1.40	1.34	1.63	1.36	1.49	1.57	1.36
Saturated hydraulic conductivity (m/s)	4E-5	2E-7	3E-7	5E-7	2E-12	2E-8	4E-8	3E-9	2E-10	4E-10
Linear shrinkage (%)	-	-	1.83	1.95	3.22	0.56	1.35	1.32	2.25	3.70
Free swell index (%)	-	-	10	12	686	4	5	75	213	214
Soil pH value (at 28.5 ^o C)	-	8.23	6.85	6.01	9.15	7.31	7.24	8.47	7.54	6.95
Organic content (%)	-	-	0.48	1.95	0.22	0.21	0.96	0.06	0.40	1.43
Cation exchange capacity (meq/100gm)	-	1.85	8	10	27	3	6	8.32	13.7	15.1

Calibration of PP and 5TM sensors

A simple laboratory set up is developed in this study to conduct the soil specific evaluation of 5TM and six PP sensors (Shaikh et al. 2018) before deploying them for θ measurement. The Table 3 summarizes the new calibration parameters found in the corrective procedure. For brevity, parameters of only one PP sensor are listed in the table.

Table 3 Details of soil specific calibration parameters for 5TM and PP sensor

Soil	5TM sensor				PP sensor			
	A	B	C	D	A	B	C	D
MS	0.00001	0.0009	0.0378	0.0487	-0.72	-1.68	-0.57	-0.07
FA	0.00002	0.0013	0.0407	0.0577	4.44	8.31	5.72	1.22
RS	0.00001	0.001	0.0376	0.0450	2.95	4.30	2.42	0.42
BS	0.000005	0.0006	0.0315	0.0279	4.45	9.07	6.70	1.53
BN	0.000006	0.0007	0.0318	0.0186	8.32	16.11	10.54	2.19
RF	0.00001	0.0008	0.0324	0.0180	2.37	2.87	1.59	0.35
BF	0.000007	0.0006	0.0275	0.0071	0.94	0.55	0.26	0.02
FB	0.000009	0.0007	0.0291	0.0076	0.14	0.72	0.37	0.08
RB	0.000005	0.0005	0.0270	0.0027	1.73	3.10	2.55	0.60
BB	0.000007	0.0008	0.0330	0.0159	2.13	3.10	1.97	0.37

Notes: $\theta = Ax^3 - Bx^2 + Cx - D$, where A, B, C, and D = soil specific calibration parameters, x = dielectric constant for 5TM sensor or voltage for PP sensor

Column study

In this study, four different configurations of MLCS columns of 30 cm diameter and 115 cm height (as shown in Fig. 1), were tested under a constant water ponding depth of 150 cm. The volumetric water content (θ) and soil matric suction (ψ) were observed as a function of depth and time. The study attempts to understand the saturation rate of different layers of MLCS and hence evaluate the adequacy of different configuration. Numerical analyses of the MLCS columns were also performed by assigning three different sets of hydraulic properties obtained from drying, wetting and predicted soil water characteristic curve. Based on test results presented in Fig. 2, the time to saturation at 100 cm in hydraulic barrier layer of four soil columns in ascending order (days) was found to be C4 (128) < C3 (258) < C1 (262) < C2 (506). The corresponding numerical simulation based on wetting hydraulic parameters was noted to be in fair agreement with observed results, C4 (144) < C3 (236) < C1 (273) < C2 (543). The study thus reveals the hydraulic barrier efficiency of soil column C2 by incorporating a low permeable geo-synthetic clay liner (GCL) above the hydraulic barrier layer. Table 4 presents the analyses on material cost of bentonite and GCL, which indicates the economic benefit of using GCL in comparison to bentonite based hydraulic barrier to achieve the same performance efficiency of landfill cover system.

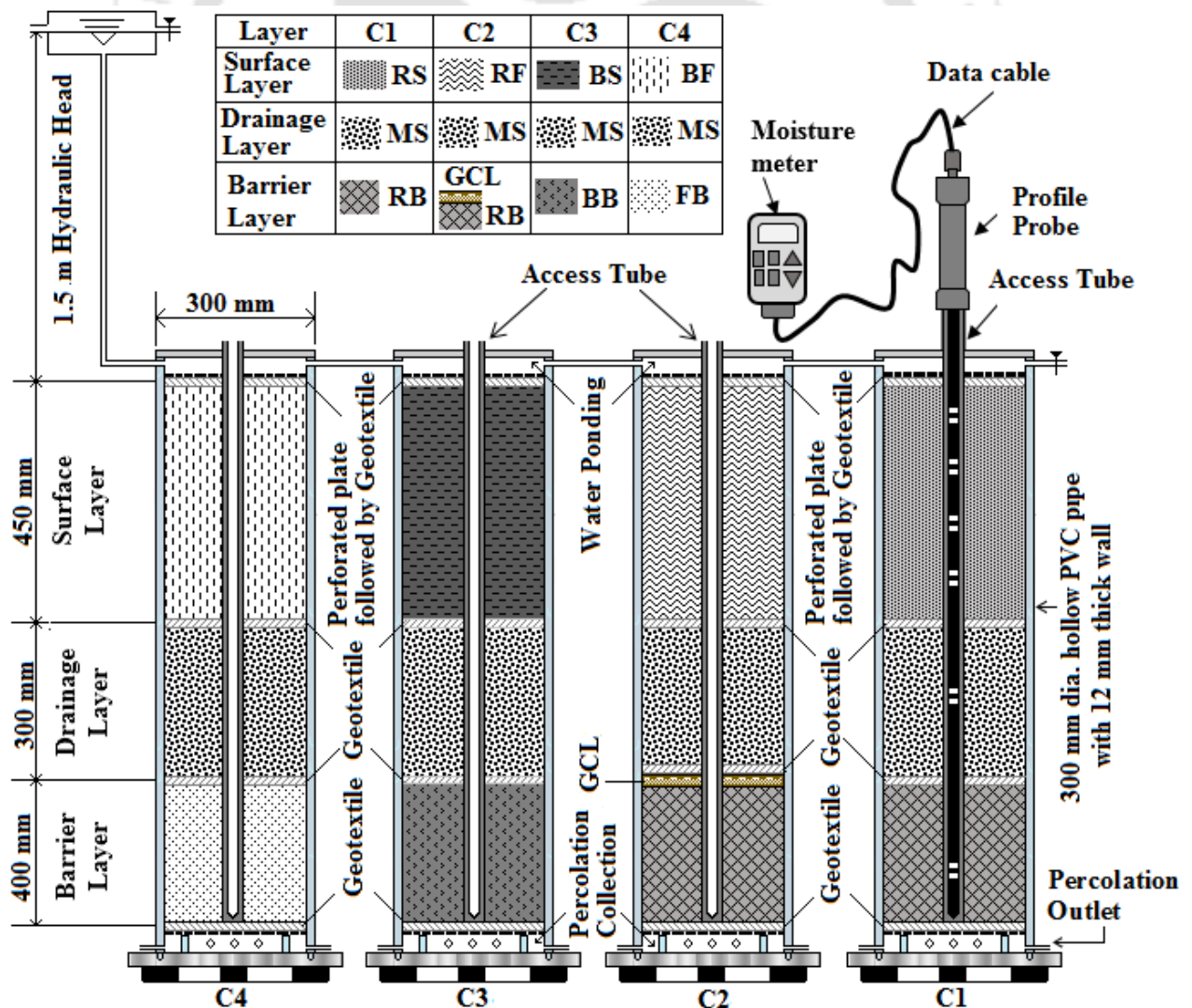


Fig. 1 Schematic diagram of experimental laboratory MLCS

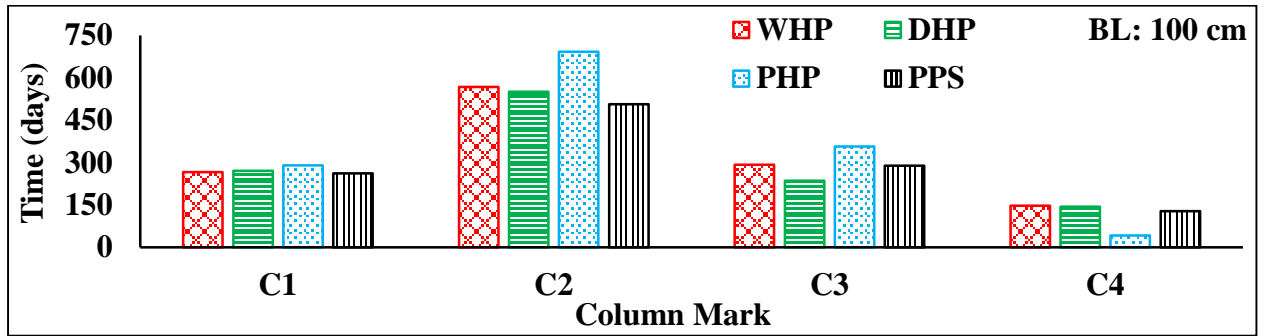


Fig. 2 Number of days to reach saturation for various column layers based on experimental (PPS) and numerical results (WHP, DHP and PHP)

Field study

In this study, an instrumented three-layer MLCS shown in Fig. 3 were constructed in the field and exposed to natural weather conditions of north-east India for 800 days spanning from 10th May 2016 to 18th July 2018. The θ and ψ were monitored as a function of time and depth to assess the hydraulic performance of MLCS. Numerical analysis of the pilot MLCS were performed using HYDRUS 2D (Šimůnek et al. 1998) with the measured soil-atmosphere boundary condition, 5 different evapotranspiration models and three sets of hydraulic parameters. The results indicate significant impacts of weather changes in the surface layer; marginal and no effects in drainage and barrier layer, respectively. The numerical simulations performed by considering drying hydraulic parameters (DHP) and evapotranspiration estimated either by Penman-Montieth (Zotarelli et al. 2015) or Hargreaves-Samani (Hargreaves and Samani 1985) model, matched well with the field observations (refer Fig. 4). Figure 5 illustrates the θ profile along mid-section of the cover system during prolonged periods of extreme drought and heavy rainfalls. θ profile at 210th and 560th day is considered to represent the extreme drought condition, while the 400th and 500th day represents the extreme rainfall condition. Based on measured and simulated θ profiles shown in Fig. 5, even during the days of prolonged heavy rainfall, no percolation was observed in barrier as well as drainage layer.

Climate change impact

The appropriate input hydraulic parameter and evapotranspiration model identified from the previous section was used to study the climate change impact of MLCS. Numerical analyses were performed for 87 years by considering the climate input of two separate humid locations i.e. Guwahati and Mumbai city in north-east and western India, respectively. Based on water percolation through the cover layers, the hydraulic efficiency of the cover system was studied. The study reveals that saturation time for MLCS was improved by two times when GCL was incorporated in the cover system. When no degradation was considered, Fig. 6 showed that the time of saturation for 100 cm depth of cover system was 18 and 20 years without GCL; 42 and 44 years with GCL for Guwahati and Mumbai, respectively. Comparable saturation time was 13 and 14 years without GCL; 25 and 28 years with GCL for Guwahati and Mumbai, respectively when 30% increase, 20% decrease and 15% increase in permeability of SL, DL and BL was assumed as the effects of material degradation.

Table 4. Cost analysis of geo-synthetic clay liner (GCL) and bentonite used in hydraulic barrier layer

Column /layer	Soil mix used	Use of GCL	C/S area (m ²)	Density (kg/m ³)	Thickness (m)	Volume (m ³)	Bentonite mass (kg)	Bentonite cost (USD)	GCL cost (USD)	Total cost (USD)	Benefit of using GCL
[1]	[2]	[3]	[4]	[5]	[6]	{[4]×[6]}	{0.3×[5]×[7]}	{0.1×[8]}	{5×[4]}	{[9]+[10]}	[12]
C1/BL	70% red soil	without GCL	0.0707	1570	0.40	0.0283	13.32	1.33	0	1.33	–
	+ 30% bentonite	with GCL	0.0707	1570	0.15	0.0106	5.0	0.50	0.35	0.85	36%
C2/BL	70% red soil	without GCL	0.0707	1570	0.40	0.0283	13.32	1.33	0.0	1.33	–
	+ 30% bentonite	with GCL	0.0707	1570	0.00	0.00	0.0	0.5	0.35	0.35	74%
C3/BL	70% black soil	without GCL	0.0707	1360	0.40	0.0283	11.54	1.15	0	1.15	–
	+ 30% bentonite	with GCL	0.0707	1360	0.12	0.0085	3.5	0.35	0.35	0.70	39%
C4/BL	70% fly ash	without GCL	0.0707	1490	0.40	0.0283	12.64	1.26	0	1.26	–
	+ 30% bentonite	with GCL	0.0707	1490	0.05	0.0035	1.58	0.16	0.35	0.51	60%

Notes: Cost of bentonite and GCL was assumed to be 0.1USD/kg and 5USD/m² respectively. Installation and transportation cost were not considered.

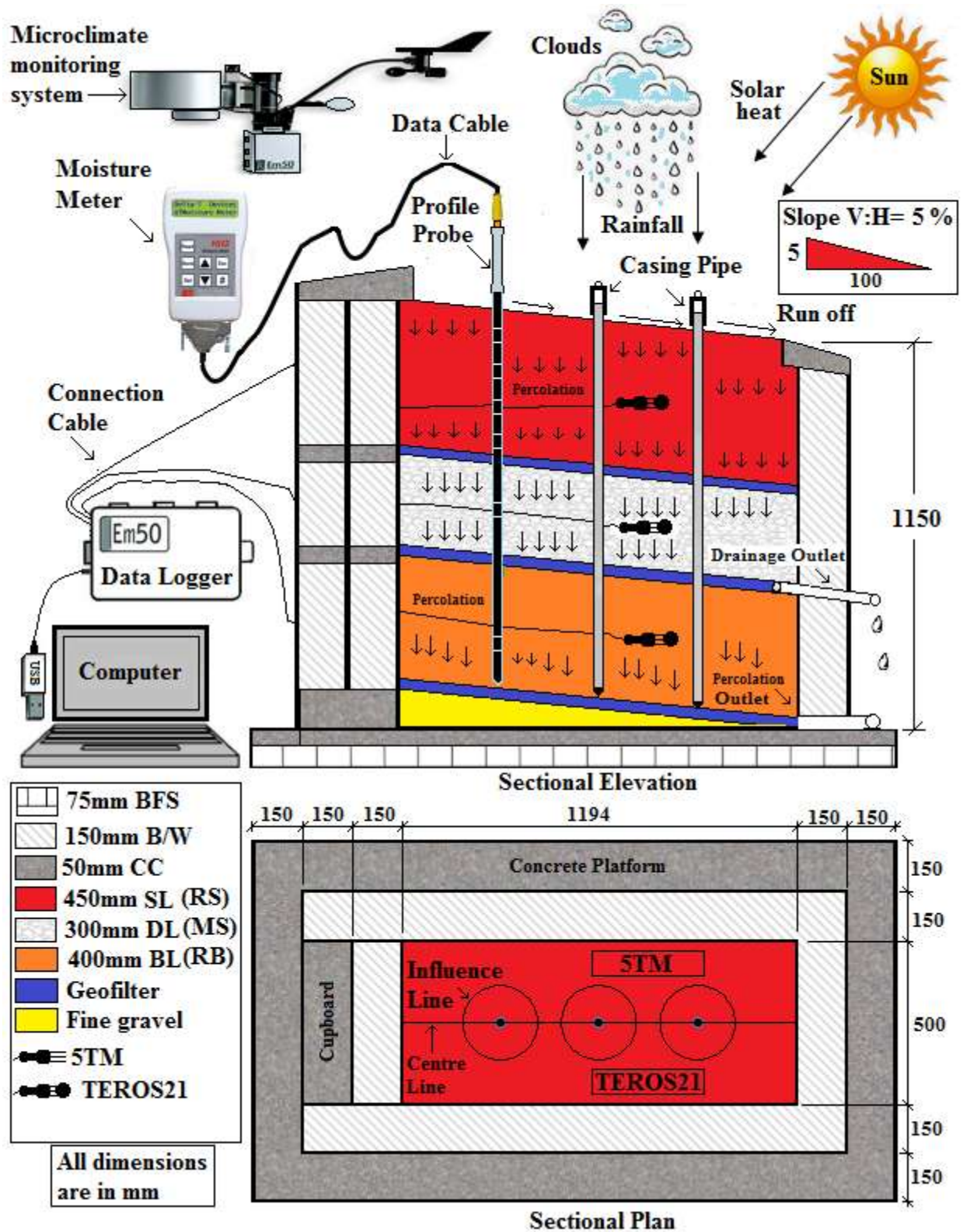


Fig. 3 Schematic diagram of experimental field MLCS

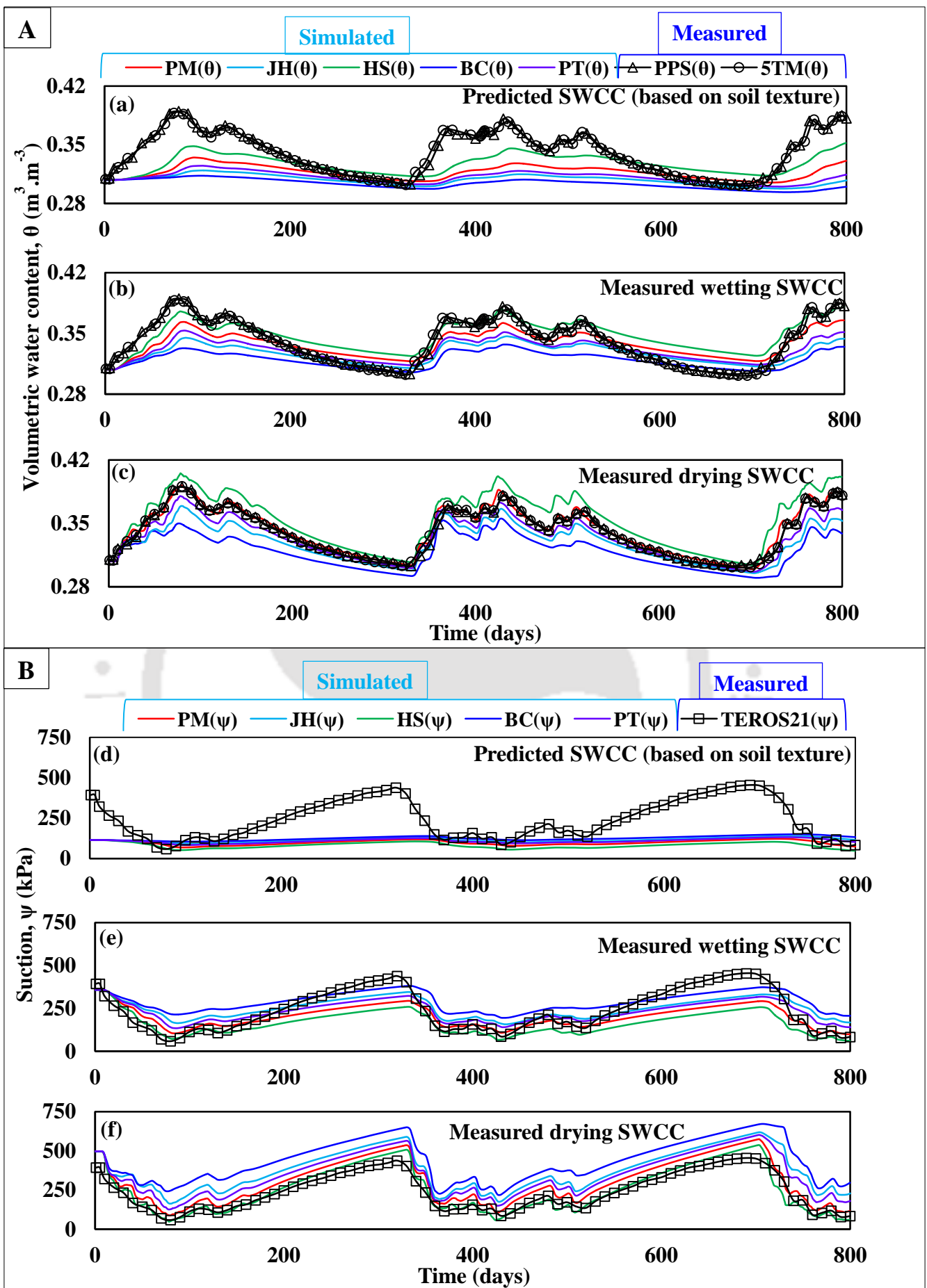


Fig. 4 Comparison of field measurements and simulated results (for 30 cm depth in surface layer)

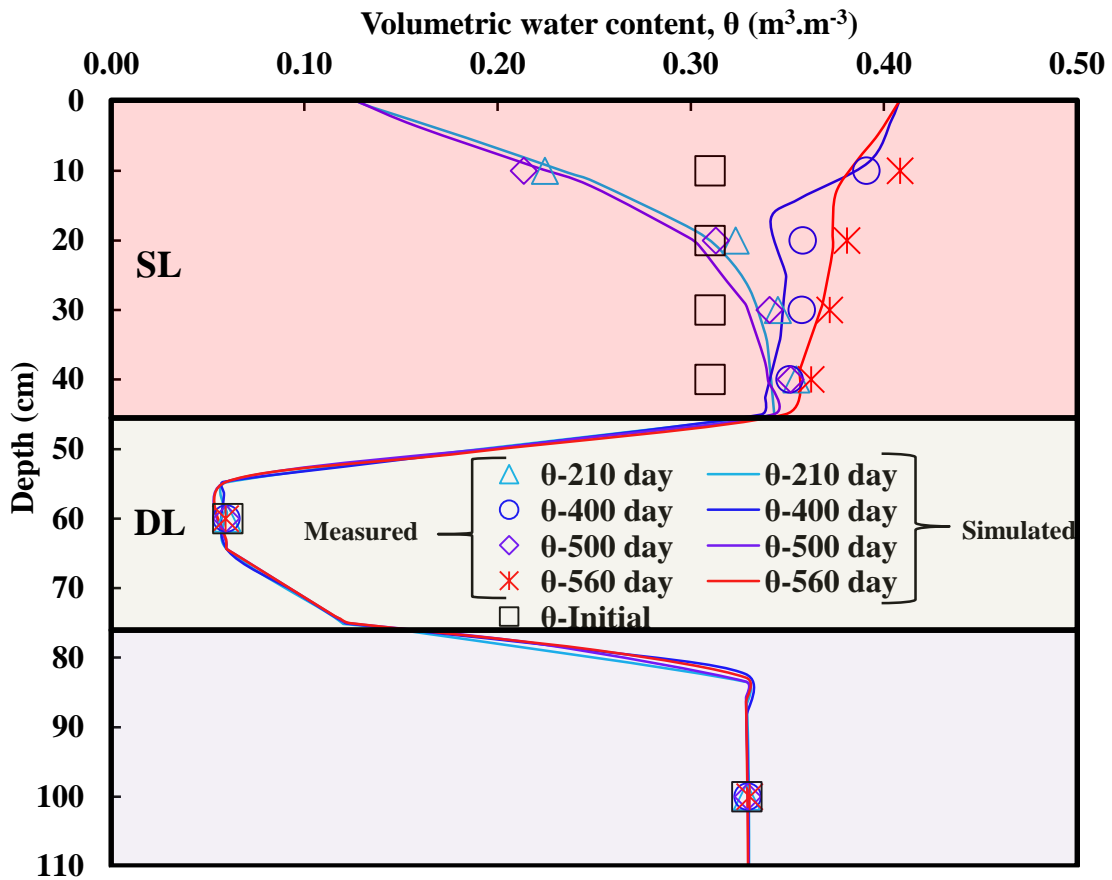


Fig. 5 Measured and simulated water content profile (based on PM model and DHP) for extreme dry period (210th day and 560th day) and extreme rainfall period (400th day and 500th day)

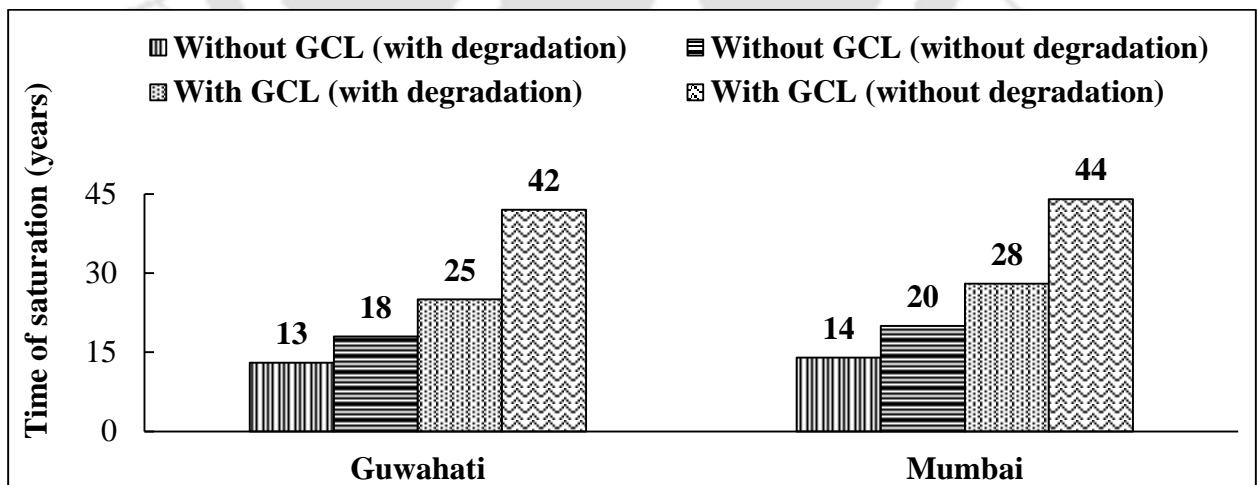


Fig. 6 Time of saturation up to 100 cm depth of the proposed MLCS

Major findings

From calibration study

- ❖ Measurement accuracy improved from $\pm 6\%$ to $\pm 1\%$ for PP sensors and from $\pm 8\%$ to $\pm 1\%$ for 5TM sensor by a corrective method adopted for the current study. In addition, the disparity in readings of six PP sensors was removed with the improved accuracy.

From column study

- ❖ The observations from column test were in good agreement with the numerical simulation performed with wetting hydraulic parameters.
- ❖ Among four test columns, Column 2 performs most efficiently, likely due to the presence of geosynthetic clay liner (GCL) as additional barrier material. Performance of Column 4 was observed to be the worst and can be attributed to the addition of fly ash in the surface and barrier layer and also due to the absence of GCL.
- ❖ Inclusion of GCL in the landfill cover system can save at least 36% cost of bentonite to achieve the same performance efficiency where GCLs are not considered.

From field study

- ❖ The measurements from the field test of cover system agreed well with the numerical simulation when evapotranspiration computed by Penman-Montieth model and drying hydraulic parameters were considered.
- ❖ For entire monitoring period, the field test indicates significant impacts of weather changes in the surface layer; marginal effects in drainage layer and no effects in barrier layer. Even during the days of prolonged rainfall, no percolation was observed in barrier as well as a drainage layer.

From numerical study

- ❖ Numerical analyses considering forecasted climate of 87 years reveals that the pilot cover system will forbid water percolation into the underlying waste by at least 18 years without using GCL and 42 years with using GCL when material degradation is not considered.
- ❖ The hydraulic performance of the cover system worsened when material degradation is considered. If 30% increase, 20% decrease and 15% increase in permeability of SL, DL and BL is assumed as the effects of material degradation, the cover system will restrict water percolation into the waste by at least 13 years without GCL and 25 years with GCL.
- ❖ The cover system constructed in northeast India, saturates slightly faster than that in western India.

Major contributions

- ❖ The study strongly recommends conducting soil specific calibration of the water content sensors (PP and 5TM) before employing them for real-time field monitoring programs associated with important projects like cover system.
- ❖ In the absence of soil-specific calibration, the new set of calibration parameters proposed in this study can be used for types of the generic soils used in cover system.
- ❖ Identified the hydraulic parameter, which is best suited for simulating water percolation through MLCS layers under controlled laboratory condition. This study compared four different configurations of MLCS using laboratory column. The study identified the role of GCLs in reducing the cost of constructing MLCS.
- ❖ This study investigated the hydraulic performance of MLCS under natural weather condition. It was noted that the measured results matched well with the numerical simulation when evapotranspiration was computed by Penman-Montieth model, and soil hydraulic parameters were obtained from drying SWCC.
- ❖ Top surface layer needs to be well-designed to resist the soil-atmosphere interactions for improving hydraulic performance and prolonging the design life of MLCS.
- ❖ This study demonstrated the impact of climate change on MLCS, which is not reported in the literature. The deterioration in the performance of material with time was considered by percentage change in permeability and not based on measured results.

Limitations

- ❖ Effect of erosion of top surface layer of field MLCS was ignored in the numerical analyses.
- ❖ It is very difficult to properly model the actual material degradation due to numerous field uncertainties. In this study, its effects were assumed and considered to be constant throughout entire time duration chosen for the analyses.

Future scopes

- ❖ Further studies need to be conducted to properly investigate the effects of erosion, cyclic wetting drying on the hydraulic performance of the MLCS.
- ❖ Effects of material deterioration were incorporated in numerical analysis through a constant degradation model, which necessitates further studies to evolve a systematic deterioration model.
- ❖ The MLCS field studies need to be extended for different configurations and to be studied under varying climatic scenario.
- ❖ To obtain more reliable results from numerical study of the MLCS, it needs to be carried out using other codes like UNSAT-H, HELP, SEEP/W, VADOSE/W, SoilCover, etc. in addition to HYDRUS 2D.

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List of publications

Conference paper

- ❖ Rout, A., **Shaikh, J.**, and Sreedeeep, S. (2015). “Performance evaluation of three volumetric water content sensors” 50th Indian Geotechnical Conference, 2015, Pune, India. (Best paper award)

Journal paper

- ❖ **Shaikh, J.**, Yamsani, S.K., Sekharan, S., and Rakesh, R.R., (2018). “Performance Evaluation of Profile Probe for Continuous Monitoring of Volumetric Water Content in Multilayered Cover System” Journal of Environmental Engineering, ASCE, 144(9), 040180781, 1-14, (Published)
- ❖ **Shaikh, J.**, Yamsani, S.K., Sreedeeep, S., and Rakesh, R.R. (2019). “Performance evaluation of 5TM sensor for real time monitoring of volumetric water content in multi-layered cover system” J. Advances in Civil Engineering Material, ASTM. (Accepted)
- ❖ **Shaikh, J.**, Yamsani, S.K., Sekharan, S., and Rakesh, R.R., (2019). “Hydraulic performance assessment of a multi-layered landfill cover system under constant water ponding” Waste Management, ELSEVIER. (Under review)
- ❖ **Shaikh, J.**, Bordoloi, S., Yamsani, S.K., Sekharan, S., and Rakesh, R.R., (2019). “Field monitoring and climate change impact assessment of water percolation in landfill cover system under humid Indian conditions” Journal of Hazardous Material, ELSEVIER. (Under review)
- ❖ **Shaikh, J.**, Bordoloi, S., Yamsani, S.K., Sekharan, S., and Rakesh, R.R., (2019). “Field hydraulic assessment of an instrumented three-layer landfill cover for a high humid region” Journal Geotechnical Geoenvironmental Engineering, ASCE. (Under review)
- ❖ **Shaikh, J.**, Bordoloi, S., Yamsani, S.K., Sekharan, S., and Rakesh, R.R., (2019). “Percolation performance of four different three-layered cover system incorporating fly ash for flood ridden conditions” Canadian Geotechnical Journal, NRC (will be communicated)
- ❖ **Shaikh, J.**, Bordoloi, S., Yamsani, S.K., Sekharan, S., and Rakesh, R.R., (2019). “Effects of long-term degradation on the hydraulic performance of multilayered landfill cover system” Environmental Geotechnics, ICE. (Under preparation)
- ❖ **Shaikh, J.**, Bordoloi, S., Yamsani, S.K., Sekharan, S., and Rakesh, R.R., (2019). “A critical review on hydraulic performance assessment of landfill cover system considering climate change aspects” Critical Reviews in Environmental Science and Technology, Taylor & Francis. (Under preparation)