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STUDY OF WATER FLOW AND RETENTION IN CLAY-SAND LINERS

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ABSTRACT: This research paper presents a simulation study to predict the percolation of water through soil liners using numerical modeling with HYDRUS-2D. The soil liners included compacted clay/sand mixtures of 0 to 25% clay at 5 to 30 cm thickness. The cumulative water flux or hydraulic barrier at drain layer at the end of simulation period reached a ratio of 0.81, 0.54, 0.29 and 0.09 of water flux at a top profile with no soil liner. The soil liners of 25 and 30 cm thickness with 20% and 15% clay had lesser percolation or water flux at drain layer by about 0.21 and 0.44 compared to water flux at top layer with no soil liner. Using a modeling approach efficient liner systems can be designed for use in water harvesting projects or landfill covers. The modeling and simulation are dependent on the hydraulic conductivity of the compacted soil liner, soil water characteristics curves as well as irrigation and rainfall rates.

Keywords: Clay sand mixture, HYDRUS-2D, Numerical modeling, Landfill cover, Soil liner

1. INTRODUCTION

1.1 Background

The barrier layer is used in landfill liners to restrict the migration of water and/or pollutants from the landfill into the environment. In addition, the layer is used to limit the ingress of water into landfill due to precipitation. However, in some cases, the cover may serve other equally important functions. The commonly used barrier layers include compacted natural inorganic clay or clayey soils. The low hydraulic conductivity of compacted clayey soils makes them suitable materials for use as liners and covers in landfills for environmental protection and has the longest history of the successful application as isolation barriers in landfills [1]. Many studies have investigated hydraulic barrier layer consisting of different mixtures or waste materials. Some of these substitutions are the soil-ash mix, waste sludge materials, paper sludge, construction sludge, petroleum contaminated soils, granite residual soil, and sand-bentonite mixtures. The sand-bentonite mixtures achieve good performance but with a relatively high cost. However, for waste containment systems, it is desirable to achieve its required purposes at minimum cost. Therefore careful consideration should be given to the choice of materials for the construction of the hydraulic barrier layer, which is considered the main component of landfill cover or soil liner. In order to effectively control seepage, the soil liners must have a relatively low permeability. Accurate control testing of the soil liner is of great importance for assessing the permeability of clay. Reference [2] stated that in order to achieve the soil liner quality, the following specification must accomplish:

- Soil must be classified into groups of (ML, CL, or MH) in the unified soil classification system.
- 50% by weight of soil must pass 0.075 mm sieve.
- The clay content shall not be less than 25% (material less than or equal to 0.005mm sieve).
- The plasticity index of the soil must greater than or equal to 10.
- The hydraulic conductivity of soil must not exceed $1x10^{-7}$ cm/s
- Soil compaction is required to reach 98% of the maximum dry density in a standard Proctor test. The moisture content must keep at optimum moisture content or within 2% above optimum.

Reference [3] suggested that compacted clay liners should be of low permeability and low swelling with an adequate resistance to shearing and must be of low shrinkage. Typically, the hydraulic conductivity of compacted clay should be less than $1x10^{-7}$ cm/s for soil liners and covers [4], [5]. The required liner thickness for domestic and light industrial waste types as suggested by [5] is to be 0.6 m for compacted clay liners. However, the natural non-clay soil cannot perform satisfactorily as a barrier because of its uncontrolled hydraulic conductivity. An innovative way to improve the hydraulic properties of natural non-clay soils by the addition of bentonite becomes popular in the field of environmental geotechnics. Bentonite has considered as a buffer material because of its low hydraulic conductivity, high sorption capability, and self-sealing characteristics. Usually compacted clayey soils used as liners. When suitable clayey soils are not locally available, compacted bentonite enhanced soils (amended soil) are economic alternatives for use in liner design systems. Reference [6] investigated the physical and hydraulic characteristics of bentonite-amended soil and found that addition of 6.5% bentonite to the sandy soil reduced the hydraulic conductivity by more than two orders of magnitude. According to [7] suggested that clay barrier cover to be less than 45 cm in thickness for non-hazardous waste landfills with a hydraulic conductivity ≤ $1x10^{-5}$ cm s^{-1} and must not exceed the hydraulic conductivity of the baseline. This requirement will prevent leachate building up within the landfill. The practice of using a saturated hydraulic conductivity of ≤ 10^{-7} cm s^{-1} is based on the criterion noted earlier. This requirement was adopted in this study. High compaction at high water content is generally associated with severe drying cracks. The clay barrier assumed to be protected by a 15 cm minimum erosion or vegetated soil layer. Reference [8] suggested the protection layers act as a gas collection or drainage media.

In the present paper, a numerical simulation model of water flow through a sand/clay mixture was studied as a hydraulic barrier layer ([9] and [1]). The HYDRUS-2D numerical model ([10], [11], [12]) was used in this research paper. The numerical modeling methodology presented here is an attempt to predict the impact of barrier layers and estimate their role and influence in the overall percolation rates.

1.2 Application of HYDRUS-2D for soil liner

HYDRUS-2D and its parent code, SWMS_2D [13] was extensively used by researchers in different applications. The works of [14], [15] and [16] were practical examples for extracting soil hydraulic parameters for different conditions. Reference [17} studied contaminated sites and remedial measures using SWMS_2D coupled with MODFLOW and MT3D. The works of [18] utilized SWMS_2D to handle the performance evaluation and risk assessment of a site in Switzerland. Reference [19] studied a Nevada waste disposal site using HYBelDRUS-2D.They simulated a 100 year, 6-hour storm event for different cover designs. They determined the soil water characteristic curves as well as saturated hydraulic conductivity for different soil fractions compacted to densities of 83% and 90% of the maximum dry density. This data was used in HYDRUS-2D to establish the appropriate cover thickness needed to limit the infiltration in a single storm event. The HYDRUS-2D was said to be verified by the developers as compared to simulations carried out using other techniques and codes; UNSAT2 (Neuman, 1973) and SWATRE [21] codes. Reference [22] claimed that analytical solution of a two-dimensional steady-state flow problem is in agreement with the HYDRUS-2D output. The comparison with UNSAT2 was made for a one-dimensional infiltration experiment [23]. The verification of HYDRUS-2D using SWATRE [24] was carried out for a one-dimensional field profile. The general purpose partial differential equation solver, PDE2D, was claimed to have consistent results with data obtained by the parent code SWMS-2D [25].

Reference [26] coupled SWMS-2D with an overland flow model to simulate a recharge problem and found that simulated and measured water content is in close agreement and good validation test for HYDRUS-2D. Reference [27] also used HYDRUS-2D in the simulation of the capillary barrier system involved in a landfill cover. Reference [28] stated that HYDRUS model is the most suitable and most recommended for research scientists. Recently, [1] predict the impact of cover and barrier layers (sand/FADR mixture hydraulic barrier layer) and estimate their potential effect on the percolation rates through the landfill system using HYDRUS-2D numerical model. The results indicate that the Sand-FADR mixture is acceptable as a hydraulic barrier layer. The barrier was shown not causing an increase in the initial volumetric water content (0.2 cm^3 cm^{-3}) below a depth of about 40 cm. Therefore, the objective of the present study is to test the numerical simulation model of water flow through soil liner (clay/sand mixture) as a hydraulic barrier layer [9] and [1] numerical model is used in this paper [10], [11], [12]. The simulation and modeling methodology used here is an attempt to predict the impact of soil liner and barrier layers and estimate the potential effect on the percolation rates through the soil profile.

2. EXPERIMENTAL WORKS

2.1 Materials and Methods

The sand used in this study was local sand obtained from within Riyadh city, Saudi Arabia. The index properties of sand are given in [29]. The expansive clay used was obtained from the city of Al-Qatif (eastern province of Saudi Arabia). Al-

Qatif clay was characterized as highly expansive soil due to high montmorillonite mineral content [30]. Samples of Al-Qatif expansive clay were air-dried, pulverized and sieved using sieve No.40. The sand and clay were mixed thoroughly at rates of 0, 5, 10, 15, 20 and 25 % clay by dry weight, and then optimum water content corresponding to each mix was added and stored in plastic bags for 24 hours. Compacted samples of sand/Al-Qatif clay mixture were prepared for the determination of soil water retention curve and permeability tests. For each mixture, the optimum water content and maximum dry unit weight were determined using standard Proctor compaction method ASTM D698-method A (ASTM, 2003). The saturated hydraulic conductivity of sand/Al-Qatif clay mixtures were tested using flexible wall constant head permeameter, ASTM D5084 -method A(ASTM, 2003), as described in [29].

2.2 Soil liner layout

The input data for HYDRUS-2D modeling is taken from the experimental work on Sand-Clay Mixture ([30] and [29]) such as permeability and retention curve data, the climatic data for 90 days (winter period) was taken as a case for Al-Hassa, Saudi Arabia obtained from the Presidency of Metrology and Environment, Saudi Arabia, (Fig. 1). In this paper, unit horizontal area (1.0 m X 1.0 m) of the soil profile is considered for a model by HYDRUS-2D. The section has varying depths due to the thickness of the soil liner used. The section of the studied profile is composed of (Fig. 2):

- 15 cm vegetated cover layer (Loamy soil)
- 20 cm sand filter layer
- 5, 10, 15, 20, 25 and 30 cm soil liner thickness (clay/sand mixture with 0, 5, 10, 15, 20 and 25% clay)
- 10 cm drainage layer (sandy soil)

2.2 Unsaturated soil hydraulic properties

The HYDRUS-2D code uses the unsaturated hydraulic properties θ(h) and K(h) defined by van Genuchten, [31] who introduced an equation to the unsaturated hydraulic conductivity function by using [32] statistical pore-size distribution model. The van Genuchten main equations for the soil water retention, θ(h), and hydraulic conductivity, K(h), are defined as:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{(1+(\alpha h)^n)^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \qquad (1)$$

and

$$K(h) = \begin{cases} K_s K_r(h) & h < 0 \\ K_s & h \geq 0 \end{cases} \qquad (2)$$

$$K_r = S_e^{\tau}\left[1-\left(1-S_e^{\frac{1}{m}}\right)^m\right]^2 \qquad (3)$$

and θ is soil water content (cm^3/cm^3), θr and θs are the residual and saturated water contents (cm^3 /cm^{-3}), respectively, h is the soil pressure head (cm), and α (cm^{-1}), n, and m are constants which define the shape of the curve, and τ is an empirical constant assumed equal to 0.5 [31]. Furthermore, m =1-1/n and the degree of saturation is defined as Se = (θ-θr)/(θs-θr). A modified form of Equation (1) also provided in the HYDRUS-2D code and adds additional flexibility in the description of the hydraulic properties near saturation ([10]. The values of (, m and n are obtained by fitting Equation (1) to the soil water retention data using RETC model [33]. (van Genuchten *et al.*, 1991), Table 1.

Parameter values for θr; θs; α; n; and Ks representative for each of the sand/clay mixtures are obtained by fitting Equation (1) to the soil water retention data using RETC model [33] then given in Table 2. All values were taken from the literature review. Fig. 3 shows the soil water characteristic curves in terms of the water content and also presents the corresponding unsaturated hydraulic conductivity functions computed using Equations (2 and 3). Due to the major differences in the shape of the soil hydraulic functions, a representative for porous media varying from very coarse to very fine materials, the hydraulic behavior of the different soil types is very different**.**

2.3 HYDRUS-2D model

Hydrus-2D [10] simulates the flow using Darcy equation for saturated and unsaturated soil conditions in a 2D plane. The model considers the losses due to evapotranspiration but neglecting the effect of the air phase on the liquid flow. The Hydrus-2D model solves Richards' equation (4), by utilizing Galerkin-type linear Finite Element Method [10] for the flow of different saturation. The model can handle isotropic and anisotropic soil formation.

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x_i}\left[\left(K_{ij}^A \frac{\partial h}{\partial x_j} + K_{ij}^A\right)\right] - S \qquad (4)$$

θ is the volumetric water content (cm3 cm-3), h is the pressure head (cm), S is a sink term for water uptake by plants (day-1), xi (i=1,2) are the spatial coordinates (cm), t is time(days), K_{ij}^{A} are components of a dimensionless anisotropy tensor KA, and K is the unsaturated hydraulic conductivity function (cm day^{-1}) given by:

$$K(h,x,z) = K_r(h,x,z)K_s(x,z) \quad (5)$$

Where: Kr is the relative hydraulic conductivity and Ks is the saturated hydraulic conductivity (cm day^{-1}). The two dimensions considered in a 2D flow are the vertical and horizontal. (x1=x is the horizontal coordinate and x2=z is the vertical coordinate). For this study S term was not considered as the net rainfall allows for evapotranspiration. The parameters used in this study in order to simulate the flow through the liner layer system are presented in Tables (2 and 3). Extensive trials were used to optimize parameters needed for the liner layer system. The mesh size, time step, tolerances were varied as practical to achieve the least errors. The boundary conditions were established as per the liner layer system arrangement. The boundaries were taken as a no-flux boundary, seepage face or as free drainage boundary as indicated in Table (2).

3. RESULTS AND DISCUSSION

The role of a properly designed and constructed soil liner is to limit the percolation of water to the groundwater. At the design stage, the success of the cover may be gauged through the computed water flux through the successive cover layers. Table (4) illustrates the top and bottom flux of water through the soil profile. The results indicated that the ratio of water flux at drain layer compared to water flux at top surface decreased as a percentage of clay addition increased and as the thickness of soil linear increased. Fig. 4 and Fig.5 show the water flux at drain layer soil liner. It is noted from the figures that the clay/sand mixture is excellent as a hydraulic barrier layer because the water flux was decreased. Fig. 6, Fig. 7 and Fig.8 show the soil water content distribution in the soil profile depth with and without soil liner layer. It is noted from the figures that the clay/sand mixtures can form an excellent hydraulic barrier. It can be noted that for the soil liner layer, the water content differed according to soil liner thickness. The role of properly designed and constructed soil liner is to limit the percolation of surface water applied through irrigation and rainfall and down to the bottom of the hydraulic barrier. The success of the soil liner may be evaluated through the comparison of water flux through the different soil liner as illustrated in Table (5). The data in Table (5) indicates that effective soil liners with 25% clay at 5, 10, 15 and 20 cm thickness, when compared to 5 cm thickness of soil liner at 0% clay (sandy soil only), can reduce the water flux at drain layer to 0.81, 0.54, 0.29 and 0.09 of water flux at top surface. Increasing thickness of soil liner to 25 and 30 cm decreased the water flux at drain layer to 0.21 and 0.44 of water flux at the top layer, respectively. With view construction cost of soil liner, it can be recommended to use soil liners with 20 cm thickness at 25% clay/sand mixture. This case can be able to decrease water flux at drain layer to 0.09 of water flux at the top surface. Further studies need to be conducted for evaluating multiple layer barriers and the sensitivity of the cover design to the change in the rainfall rate, for longer periods. These factors can improve and help in selecting appropriate soil liner. The study performed in this research represents clays from eastern parts of Saudi Arabia. Other clays may have different chemistry [34] and other concerns with regard to performance and risks [35], [36] may be available.

4. CONCLUSION

The numerical modeling with HYDRUS-2D is used in this study to simulate and predict the percolation through soil liner (clay/sand mixture, 0 to 25% clay) at 5 to 30 cm thickness with 15 cm vegetative cover layer. For the studied period (90 days), the clay/sand mixture layer was able to restrict the water percolation through the soil profile, therefore, the cumulative percolation at the bottom boundary (drain layer) was less for a soil liner 20 cm thickness with 25% clay. The cumulative water flux under soil liner or hydraulic barrier at drain layer at the end of simulation period reached a ratio of 0.81, 0.54, 0.29 and 0.09 of the profile with no soil liner. The soil liners of 25 and 30 cm thickness with 20 and 15% clay had less percolation or water flux at drain layer by about 0.21 and 0.44 compared to no soil liner. The water balance error did not exceed 10% in all cases. Further studies should be conducted for evaluation of multiple layer barriers and the sensitivity of soil liner design to the change in irrigation and rainfall rates for periods longer than what is studied in this research. Investigation of these factors can improve and help in selecting appropriate barrier design.

5. ACKNOWLEDGEMENTS

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Table 1. Hydraulic parameters used in modeling of water flow through soil liner

Ref.	Sand	Clay /sand mixtures				
		5%	10%	15%	20%	25%
θr, cm3 cm-3	0.017	0.021	0.025	0.028	0.031	0.035
θs, cm3 cm-3	0.276	0.285	0.299	0.310	0.340	0.380
α , cm-1	0.023	0.047	0.051	0.044	0.050	0.056
n	1.430	1.274	1.256	1.249	1.241	1.234
Ks, cm day-1	0.017	27.8	23.2	15.3	6.5	3.5

Table 2. Numerical model characteristics

	Parameters	Value
Time	Initial	0 day
	Final	90 days
	Initial time step	0.1 day
	Minimum time step	0.0001 day
	Maximum time step	1.0 days
	Number of print time	90
Iteration	Maximum number of	20
	Water content	0.001 cm^3 cm^{-3}
	Pressure head tolerance	1.0 cm
Rectang	Horizontal rectangular	100 cm
	Vertical rectangular	Variable
	Number of vertical	101
	Number of horizontal	Variable
Boundar	Top	Atmosphere
	Bottom	Drain
	Right side	No flux
	Left side	No flux
	Initial condition in	0.2 cm^3 cm^{-3}
Vegetati	Type	Grass
	Root depth	15 cm
	Root distribution factor	1
Root water uptake model	Feddes *et al.* (1978)	Grass (Wesseling, 1991)

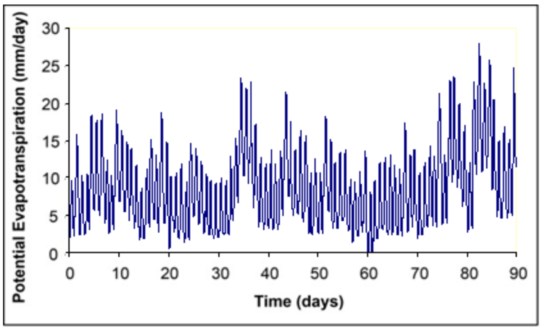

Fig. 1. Potential evapotranspiration.

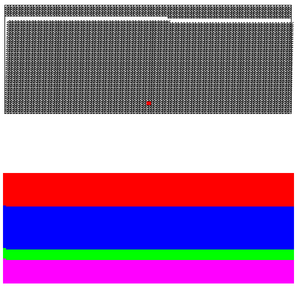

Fig. 2. Studied section of soil liner (vegetative cover=red, sand filter=blue, soil liner=green and drainage layer=purple) and subsurface drain (upper)

Table 3. Root water uptake parameters (Feddes *et al.*, 1978)

Parameters	Definition	Value
P0(cm)	Value of the pressure head below which roots start to extract water from the soil	-10
POpt(cm)	Value of the pressure head below which roots extract water at the maximum possible rate	-25
P2H(cm)	Value of the limiting pressure head, below which roots cannot longer extract water at the maximum rate (assuming a potential transpiration rate of r2H)	-300
P2L(cm)	As above, but for a potential transpiration rate of r2L	-1000
P3(cm)	Value of the pressure head, below which root water uptake ceases (usually taken at the wilting point)	-8000
r2H(cm/day)	Potential transpiration rate [LT-1] (currently set at 0.5 cm/day)	0.5
r2L(cm/day)	Potential transpiration rate [LT-1] (currently set at 0.1 cm/day).	0.1

Table 4. Water flux as affected by soil liner thickness and % of clay addition

Soil liner thickness (cm)	Rate of clay (%)	Top flux (cm/day)	Bottom flux (cm/day)	Bot./Top the ratio	Ratio (Bot./Top)
5	0	1.74E-01	1.10E-03	6.30E-03	1.00
	5	1.74E-01	1.08E-03	6.21E-03	0.99
	10	1.81E-01	1.05E-03	5.81E-03	0.92
	15	1.87E-01	1.16E-03	6.20E-03	0.98
	20	1.70E-01	9.75E-04	5.75E-03	0.91
	25	1.63E-01	8.29E-04	5.07E-03	0.81
10	0	1.80E-01	1.18E-03	6.53E-03	1.00
	5	1.88E-01	1.19E-03	6.34E-03	0.97
	10	1.82E-01	1.14E-03	6.27E-03	0.96
	15	1.88E-01	1.12E-03	5.96E-03	0.91
	20	1.79E-01	8.69E-04	4.85E-03	0.74
	25	1.69E-01	5.73E-04	3.39E-03	0.52
15	0	1.89E-01	1.24E-03	6.56E-03	1.00
	5	1.85E-01	1.16E-03	6.30E-03	0.96
	10	1.83E-01	1.08E-03	5.88E-03	0.90
	15	1.76E-01	1.06E-03	6.03E-03	0.92
	20	1.77E-01	6.59E-04	3.72E-03	0.57
	25	1.62E-01	2.94E-04	1.81E-03	0.28
20	0	1.91E-01	1.26E-03	6.58E-03	1.00
	5	1.84E-01	1.09E-03	5.90E-03	0.90
	10	1.81E-01	9.71E-04	5.37E-03	0.82
	15	1.77E-01	9.43E-04	5.34E-03	0.81
	20	1.63E-01	4.44E-04	2.73E-03	0.41
	25	1.56E-01	8.36E-05	5.36E-04	0.08
25	0	1.88E-01	1.19E-03	6.35E-03	1.00
	5	1.78E-01	9.43E-04	5.30E-03	0.83
	10	1.73E-01	7.77E-04	4.48E-03	0.71
	15	1.68E-01	7.52E-04	4.47E-03	0.70
	20	1.55E-01	2.03E-04	1.30E-03	0.21
	25	1.51E-01	-1.1E-02	-7.0E-02	-11
30	0	1.85E-01	1.14E-03	6.14E-03	1.00
	5	1.73E-01	6.80E-04	3.92E-03	0.64
	10	1.66E-01	4.77E-04	2.87E-03	0.47
	15	1.62E-01	4.47E-04	2.75E-03	0.45
	20	1.55E-01	-7.5E-03	-4.8E-02	-7.8
	25	1.53E-01	-3 E-02	-2.0E-01	-33

Table 5. Water flux as affected by soil liner thickness and % of clay addition
(most effective cases)

liner thickness (cm)	Rate (%)	Top flux (cm/day)	Bottom flux (cm/day)	Bot./Top ratio	Ratio as of control
5	25	1.7E-01	1.10E-03	6.30E-03	0.81
10	25	1.63E-01	8.29E-04	5.07E-03	0.54
15	25	1.69E-01	5.73E-04	3.39E-03	0.29
20	25	1.62E-01	2.94E-04	1.81E-03	0.09
25	20	1.5E-01	8.36E-05	5.36E-04	0.21
30	15	1.55E-01	2.03E-04	1.30E-03	0.44

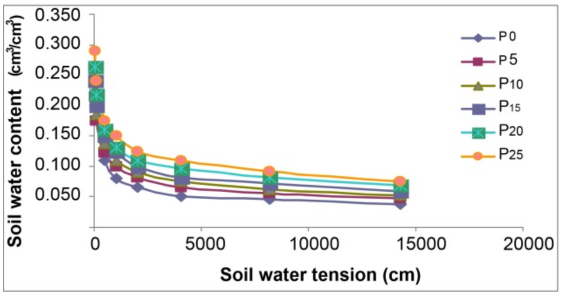

Fig. 3. Soil water retention curve of clay/sand mixtures

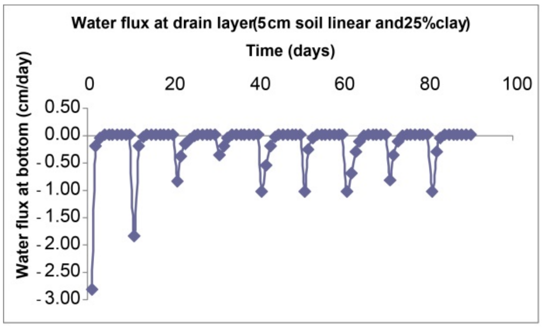

Fig. 4. Water flux at drain layer for 5 cm soil linear thickness and 25% clay

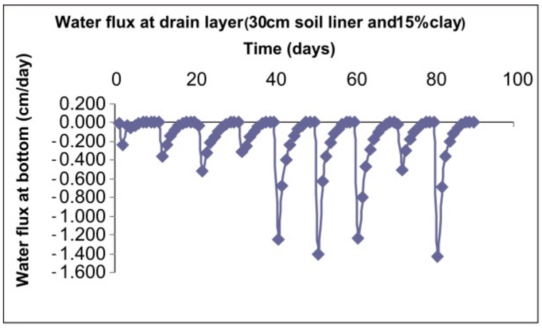

Fig. 5. Water flux at drain layer for 30 cm soil linear thickness and 15% clay

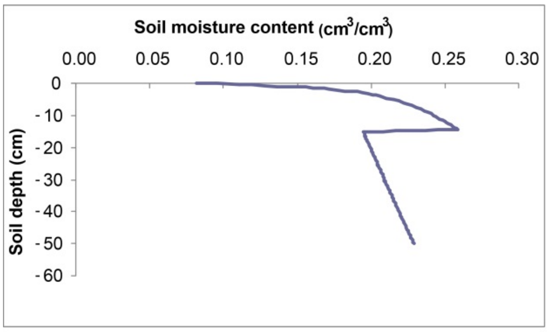

Fig. 6. Soil water content distribution in soil profile at 5 cm soil liner thickness with 0% clay/sand mixture

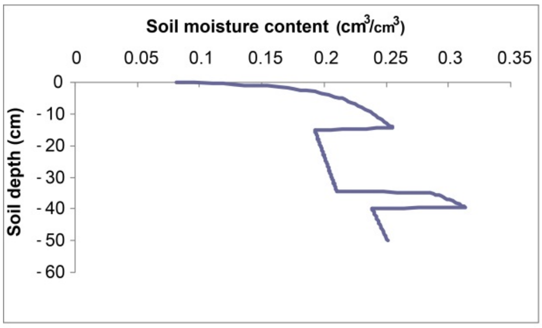

Fig. 7. Soil water content distribution in soil profile at 5 cm soil liner thickness with 25% clay/sand mixture

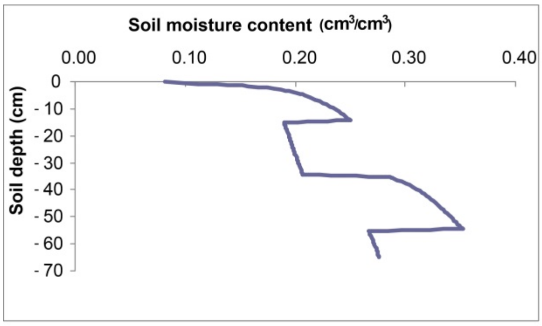

Fig. 8. Soil water content distribution in soil profile at 20 cm soil liner thickness with 25% clay/sand mixture

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