INFILTRATION OF LEACHATE FROM AN ASH POND THROUGH A LINER

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ABSTRACT

A composite liner and leachate collection system are placed in an ash pond in order to prevent the leachate from joining the water table. Saturated hydraulic conductivity of a liner is less than that of the underlying soil, the leachate would percolate from the liner in isolated jets and all the soil pores do not get filled with leachate. Green and Ampt infiltration theory is applied in two layered system, when the upper layer has more saturated hydraulic conductivity than lower layer. In this paper, the unsaturated flow of leachate through a soil layer having more permeable than the liner is analyzed using Green and Ampt infiltration theory by introducing a postulation. Using this postulation, infiltration rate of leachate from an ash pond having 0.3 m thick brick lining and the time to reach the water table which lies at a depth of 10 m below the ash pond has been quantified.

Keywords: *Green and Ampt infiltration theory; leachate; liner; unsaturated flow.*

I. INTRODUCTION

Environmental assessment for a new thermal power plant of 50 MW units or larger in respect of ambient air, water, and land is a prerequisite in order to establish emission requirements and other measures on a site-specific basis. Guidelines in respect of liquid effluent levels to be achieved daily without dilution have been given in Thermal–Power-Guidelines for New Plants [1] . Fly ash handling systems may be generally categorised as dry or wet, even though the dry handling system involves wetting the ash to 10-20 % moisture content to improve handling and to mitigate the dust generated during disposal. In wet systems, the ash is mixed with water to produce a liquid slurry with 5-20 % solids by weight. This is discharged to settling ponds often with bottom ash and Flue Gas Desulfurization (FGD) sludges as well. These ponds may be used as final disposal site, or the settled solids may be dredged and removed for final disposal in a landfill. Where ever feasible, decanted water from ash disposal ponds should be recycled to formulate ash slurry. Where there are heavy metals present in ash residues or in FGD sludges, care must be taken to monitor and treat the leachate and to its disposal to avoid contamination of water bodies. A composite liner and a leachate collection system are placed in the ash pond in order to prevent the leachate from joining the water table. As the saturated hydraulic conductivity of a liner is less than that of the underlying soil, the leachate would percolate from the liner in isolated jets and all the soil pores would not get filled. In this paper, the unsaturated flow of leachate through the soil layer underlying a geo-synthetic liner is analyzed using Green and Ampt infiltration theory.

II. METHODOLOGY

2.1 Infiltration from Ash Pond

In general, as fly ash slurry contains about 80% water, infiltration would occur once the slurry is discharged into an ash-pond. For environmental protection a composite liner and a leachate collection system are placed in the ash pond as shown in Fig.1 [2].

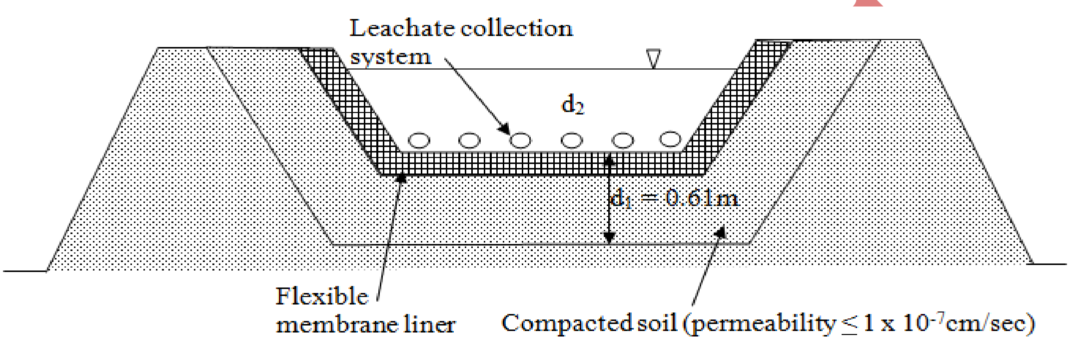

Fig. 1- Composite Liner And Leach ate Collection System (Not To Scale)

Prior to the disposal of slurry into the ash-pond, the zone beneath the ash-pond up to the under lying water table would be in an unsaturated state. If the difference between the values of seepage coefficients (hydraulic conductivities) of the liner and underlying soil is significant, then the leachate would percolate from the saturated liner to the underlying soil in isolated jets [3] and would not fill all the soil pores. The bottom boundary of the liner behaves like a constant pressure head boundary. The flow through the unsaturated zone is analyzed using principle of Green and Ampt infiltration theory. The flow of leachate from the ash pond is assumed to be one-dimensional and in vertical direction. The depth of slurry water is assumed to be equal to d_2 .

A section of flow domain is shown in Fig. 2.

Referring to Fig. 2, the *z* axis being positive down wards, the hydraulic head, *h*, is defined as:

$$h = \frac{p_w}{\gamma_w} - z \qquad (1)$$

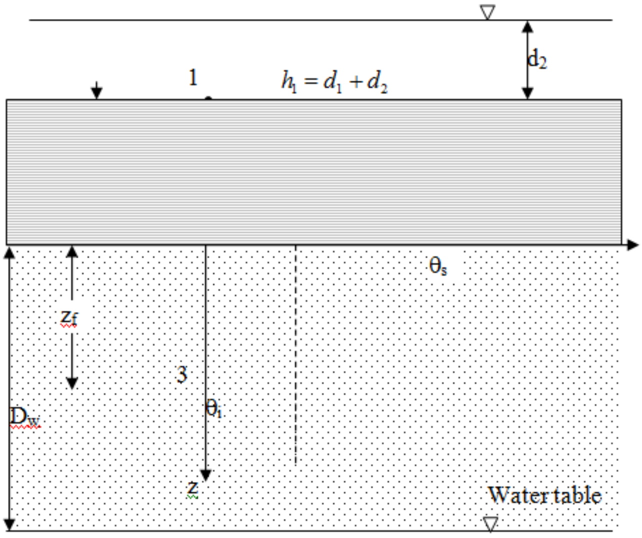

Fig. 2- Unsaturated Flow through a Liner

Accordingly, the hydraulic heads at points 1, 2, and 3 are: $h_1 = d_1 + d_2$; $h_2 = -h_{c2}(t)$; $h_3 = -H_f - z_f$ in which d_1 = thickness of the liner; d_2 = the maximum depth of leachate maintained in the ash pond, H_f = average suction head acting at the moving front; z_f =position of the moving front at time *t*; $h_{c2}(t)$= unknown suction head at the bottom of the liner in the ash-pond bed. The discharge from ash-pond bed through the liner at any time is the infiltration rate. Applying Green –Ampt theory:

$$-\tilde{k}_1 \frac{\left[-h_{c2}(t) - d_1 - d_2\right]}{d_1} = -k_2(\hat{\theta}) \frac{(-H_f - z_f) + h_{c2}(t)}{z_f}$$

(2)

$\tilde{k}_1$= hydraulic conductivity of the liner; $k_2(\hat{\theta})$= hydraulic conductivity of the unsaturated soil beneath ash-pond. $\hat{\theta}$= moisture content of the unsaturated soil behind the moving front, which is to be ascertained. Based on Horton's infiltration theory, that rate of infiltration decreases with time under a constant ponding depth, it has been postulated that in case of infiltration through a two layered soil system under a constant depth of ponding, where the upper layer has less hydraulic conductivity than that of the lower layer, the soil behind the moving front in the lower layer remains in an unsaturated state. The degree of saturation of the lower layer is such that the unsaturated hydraulic conductivity $k_2(\hat{\theta})$of the lower layer is equal to the saturated hydraulic conductivity $\tilde{k}_1$of the upper layer. With this postulation Horton's theory is not violated. Applying this condition in (2)

$$\frac{\left[d_1 + d_2 + h_{c2}(t)\right]}{d_1} = \frac{-h_{c2}(t) + H_f + z_f}{z_f}$$

(3)

Solving for the unknown $h_{c2}(t)$ from (3)

$$h_{c2}(t) = \frac{H_f - z_f d_2 / d_1}{1 + z_f / d_1}$$

(4)

Let the time be measured since the slurry water is discharged to the ash pond. Let w_0 be the depth of water required to fill the void space in the liner. Let t_0 be the time required to fill the void space. As w_0 is a very small quantity t_0 is presumed to be very small. Defining

$$w = w_0 + z_f\left(\hat{\theta} - \theta_i\right)$$

(5)

The infiltration rate I at time $t > t_0$ is given by:

$$I = \frac{dw}{dt} = \tilde{k}_1 \frac{d_1 + d_2 + \dfrac{H_f - z_f d_2 / d_1}{1 + z_f / d_1}}{d_1} = \left(\hat{\theta} - \theta_i\right) \frac{dz_f}{dt}$$

(6)

Simplifying, (6) reduces to

$$\tilde{k}_1 \frac{d_1 + d_2 + z_f + H_f}{d_1 + z_f} = \left(\hat{\theta} - \theta_i\right) \frac{dz_f}{dt}$$

(7)

or

$$\tilde{k}_1 \frac{\left(\hat{\theta} - \theta_i\right)\left(d_1 + d_2 + H_f\right) + z_f \left(\hat{\theta} - \theta_i\right)}{\left(\hat{\theta} - \theta_i\right) d_1 + z_f \left(\hat{\theta} - \theta_i\right)} = \left(\hat{\theta} - \theta_i\right) \frac{dz_f}{dt}$$

(8)

Incorporating $z_f \left(\hat{\theta} - \theta_i\right) = w - w_0$ and $\left(\hat{\theta} - \theta_i\right) \dfrac{dz_f}{dt} = \dfrac{dw}{dt}$ in (8)

$$\tilde{k}_1 \frac{\left(\hat{\theta} - \theta_i\right)\left(d_1 + d_2 + H_f\right) + w - w_0}{\left(\hat{\theta} - \theta_i\right) d_1 + w - w_0} = \frac{dw}{dt}$$

(9)

Rearranging

$$\tilde{k}_1 dt = \frac{\left(\hat{\theta} - \theta_i\right) d_1 + w - w_0 + \left(\hat{\theta} - \theta_i\right) d_2 - \left(\hat{\theta} - \theta_i\right) d_2 + H_f \left(\hat{\theta} - \theta_i\right) - H_f \left(\hat{\theta} - \theta_i\right)}{\left(\hat{\theta} - \theta_i\right)\left(d_1 + d_2 + H_f\right) + w - w_0} dw$$

(10)

Integrating

$$\tilde{k}_1 t = w - (H_f + d_2)\left(\hat{\theta} - \theta_i\right) \ln\left\{ \left(\hat{\theta} - \theta_i\right)\left(d_1 + d_2 + H_f\right) + w - w_0 \right\} + A$$

(11)

At $t = t_0$ $w = w_0$. Applying this condition in (11),

$$A = \tilde{k}_1 t_0 - w_0 + (H_f + d_2)\left(\hat{\theta} - \theta_i\right) \ln\left\{\left(\hat{\theta} - \theta_i\right)\left(d_1 + d_2 + H_f\right)\right\}$$

(12)

Incorporating A in (11)

$$\tilde{k}_1 (t - t_0) = w - w_0 - (H_f + d_2)\left(\hat{\theta} - \theta_i\right) \ln\left\{ \left(\hat{\theta} - \theta_i\right)\left(d_1 + d_2 + H_f\right) + w - w_0 \right\} + (H_f + d_2)\left(\hat{\theta} - \theta_i\right) \ln\left\{\left(\hat{\theta} - \theta_i\right)\left(d_1 + d_2 + H_f\right)\right\}$$

(13)

Simplifying

$$\tilde{k}_1(t-t_0)=w-w_0-(H_f+d_2)(\hat{\theta}-\theta_i)\ln\left\{1+\frac{w-w_0}{(\hat{\theta}-\theta_i)(d_1+d_2+H_f)}\right\}$$

(14)

Since t_0 and w_0 are likely to be very small quantities, the relation between cumulative infiltrated quantity and time is approximated as:

$$t=\frac{w}{\tilde{k}_1}-\frac{(\hat{\theta}-\theta_i)(H_f+d_2)}{\tilde{k}_1}\ln\left\{1+\frac{w}{(\hat{\theta}-\theta_i)(d_1+d_2+H_f)}\right\}$$

(15)

θ_i =initial moisture content of the soil in the unsaturated zone. $\hat{\theta}$ = moisture content behind the moving front in the soil layer which can be determined from the following relationship of $k_2(\theta)$ versus θ:

According to Van Genuchtan (1980), the relationship between soil moisture content, θ and hydraulic conductivity, $k_2(\theta)$ is given by:

$$k_2(\theta)=\tilde{k}_2\left(\frac{\theta-\theta_i}{\theta_s-\theta_i}\right)^l\left\{1-\left[1-\left(\frac{\theta-\theta_i}{\theta_s-\theta_i}\right)^{\frac{1}{m}}\right]^m\right\}^2$$

(16)

where θ = volumetric soil moisture content, θ_s = volumetric saturated soil moisture content, θ_i = volumetric residual soil moisture content, α = empirical parameter cm^{-1} depends on soil type, $n\,and\,m$ are the empirical parameters depend on soil type, $m=1-1/n$, l = pore connectivity parameter $\cong 0.5$, $\tilde{k}_2$ = saturated hydraulic conductivity of the soil underlying the liner. As per the postulation at $\theta=\hat{\theta}$, the hydraulic conductivity of the unsaturated soil behind the moving front is equal to the hydraulic conductivity of the liner. Hence,

$$k_2(\hat{\theta})=\tilde{k}_2\left(\frac{\hat{\theta}-\theta_i}{\theta_s-\theta_i}\right)^l\left\{1-\left[1-\left(\frac{\hat{\theta}-\theta_i}{\theta_s-\theta_i}\right)^{\frac{1}{m}}\right]^m\right\}^2=\tilde{k}_1$$

(17)

As $\hat{k}_1$ and $\hat{k}_2$ are known, $\hat{\theta}$ is obtained from (17) following an iteration procedure.

At the time the moving front reaches the water table, the cumulative infiltrated quantity is given by: $w=(\hat{\theta}-\theta_i)D_w$, where D_w =depth to water table below the liner. Thus arrival time of the leachate at the water-table position is obtained from (15) as:

$$t_a = \frac{(\hat{\theta}-\theta_i)D_w}{\tilde{k}_1} - \frac{(\hat{\theta}-\theta_i)(H_f + d_2)}{\tilde{k}_1}\ln\left\{1+\frac{D_w}{d_1 + d_2 + H_f}\right\}$$

(18)

If there is no lining material $d_1 = 0$ and, $\hat{\theta} = \theta_s$ and the relation between cumulative infiltrated quantity and time reduces to

$$t = \frac{w}{\tilde{k}_2} - \frac{(\theta_s - \theta_i)(H_f + d_2)}{\tilde{k}_2}\ln\left\{1+\frac{w}{(\theta_s - \theta_i)(H_f + d_2)}\right\}$$

(19)

The time at which the saturation front touches the water table is given by

$$t_a = \frac{(\theta_s - \theta_i)D_w}{\tilde{k}_2} - \frac{(\theta_s - \theta_i)(H_f + d_2)}{\tilde{k}_2}\ln\left\{1+\frac{D_w}{H_f + d_2}\right\}$$

(20)

Prior to the moving front reaching the water table, the wetting front soil suction head prevails and it ceases to act as soon as the moving front reaches the water table. Infiltration rate from the pond without lining just prior to the saturation moving front joining the water table is given by:

$$I(t_a) = \tilde{k}_2 \frac{H_f + d_2 + D_w}{D_w}$$

(21)

With lining the infiltration rate just prior to the unsaturated moving front joining the water table is:

$$I(t_a) = \tilde{k}_1 \frac{H_f + d_1 + d_2 + D_w}{d_1 + D_w}$$

(22)

Assuming that rise in water level height is nominal, the dimensionless recharge rate from unit area of the ash pond without lining is:

$$s/\tilde{k}_2 = \frac{d_2 + D_w}{D_w}$$

(23)

With lining the dimensionless recharge rate is

$$s/\tilde{k}_1 = \frac{d_1 + d_2 + D_w}{d_1 + D_w}$$

(24)

III. RESULTS AND DISCUSSION

The time of arrival of leachate wetting front at ground water table, which lies at a finite depth below the ash pond, due to ponding of the leachate in a lined ash pond has been calculated for three soil classes namely: Sandy loam, Clay loam and Silty-clay. The porosity, effective porosity, the residual soil moisture content after gravity flow ceases, saturated hydraulic conductivity, and wetting front soil suction head for each soil class are taken from [4]. The parameters l, m appearing in the relation between $k_2(\theta)$ and θ for each soil class have been taken from [5]. The parameter *n* for Sandy loam, Clay loam and Silty clay is 1.61, 1.31, 1.09 respectively. The parameter l has been taken as 0.5. The thickness of the liner is assumed to be 0.3 m. Results have been given for depth of ponding equal to 0.5 m. Water table is assumed to be lying at a depth of 5 m below the ash pond bed. The infiltration rate when the wetting front reaches the water table has been quantified. After the front reaches the water table the suction head ceases to act. Assuming that the rise in water table height is nominal consequent to recharge from the ash pond, the steady seepage rate of leachate has been quantified. The leachate volume can be quantified multiplying the infiltration rate per unit area with ash pond leachate spread area.

The moisture content $\hat{\theta}$ behind the moving front, the arrival time t_a of the leachate at the water table, the infiltration rate $I(t_a)$ and the steady seepage rate s are presented in Table 1. Results have been given for hydraulic conductivity of lining, $\tilde{k}_1$ ranging from 3.6×10^{-4} to 3.6×10^{-2} cm/hour besides for brick lining whose hydraulic conductivity is 2.9×10^{-2} cm/hour [6]. As seen from the table for sandy loam and clay loam $\hat{\theta}<\theta_s$, indicating that behind the wetting front, the soil is in an unsaturated state. For silty clay, for hydraulic conductivity of lining, $\tilde{k}_1 \le 3.6\times10^{-2}$ cm/hour, as $\hat{\theta} \cong \theta_s$, the soil behind the moving front can be assumed to be very nearly saturated. In this case the arrival time t_a is computed directly from equation (18) replacing $\hat{\theta}$ by θ_s.

Table 1. Leachate arrival time at ground water table after the first filling of the ash pond and dimensionless infiltration rate prior to the front joining the water table for different soil groups, and dimension less recharge rate for different soil groups corresponding to $d_2 = 0.5m, D_w = 5.0m$

Soil Class	θ_s	θ_r	H_f (cm)	$\tilde{k}_2$ (cm/h)	n	$\tilde{k}_1$ (cm/h)	$\hat{\theta}$	d_1 (m)	t_a (day)	$I(t_a)/\tilde{k}_1$	$s/\tilde{k}_1$	$I(t_a)/\tilde{k}_2$	$s/\tilde{k}_2$
						-	-	0.0	5.74	-	-	1.122	1.1
						3.6×10^{-4}	0.145	0.3	6387.7	1.115	1.09	-	-
						3.6×10^{-3}	0.251	0.3	939.4	1.115	1.09	-	-

Sandy loam	0.453	0.041	11.01	1.09	1.89	3.6×10^{-2}	0.343	0.3	134.6	1.115	1.09	-	-
						2.9×10^{-2}	0.333	0.3	162.9	1.115	1.09	-	-
Clay Loam	0.464	0.155	20.8	0.1	1.31	-	-	0.0	45.3	-	-	1.142	1.1
						3.6×10^{-4}	0.377	0.3	9602	1.134	1.09	-	-
						3.6×10^{-3}	0.429	0.3	1184	1.134	1.09	-	-
						3.6×10^{-2}	0.462	0.3	133	1.134	1.09	-	-
						2.9×10^{-2}	0.461	0.3	165	1.134	1.09	-	-
silty Clay	0.479	0.056	29.22	0.05	1.09	-	-	0.0	121	-	-	1.158	1.1
						3.6×10^{-4}	0.4648	0.3	17215	1.149	1.09	-	-
						3.6×10^{-3}	0.4782	0.3	1778	1.149	1.09	-	-
						3.6×10^{-2}	$\cong 0.479$	0.3	178	1.149	1.09	-	-
						2.9×10^{-2}	$\cong 0.479$	0.3	223	1.149	1.09	-	-

3.1 An Example

An ash pond is underlain by sandy loam soil. The ponded leachate depth $d_2 = 0.5\,m$. The water table lies at a depth $D_w = 5\,m$. The ash pond is lined with brick and the thickness of lining $d_1 = 0.3m$. The hydraulic conductivity of brick lining is $0.0288\,cm/hour$. The leachate would join the water table 162.9 days after ponding. If the ash pond area is $159\,hectares$, $12027\,m^3/day$ of leachate will join the water table. With a less permeable liner having hydraulic conductivity equal to $3.6\times10^{-4}\ cm/hour$, the leachate volume is $150\,m^3/day$.

IV. CONCLUSIONS

Based on Green and Ampt theory and a postulation for satisfying Horton's infiltration theory, an analytical expression is derived for computing infiltration rate from a lined ash pond. Provision of liner is essential. The brick lining is inadequate for restricting leachate infiltration. A liner having conductivity of the order of $3.6\times10^{-4}\ cm/hour$ is preferable to brick lining.

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