Geosynthetics, J. Kuwano & J. Koseki (eds)

Numerical analysis of transport of landfill leachate through layered system underlain by an unsaturated soil stratum considering nonlinear sorption and degradation

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Keywords: unsaturated soil, volumetric water content, saturation, pollutant, landfill, CCL, nonlinear sorption, bio-chemical degradation.

ABSTRACT: The landfill is assumed to be underlain by a three-layer system composed of a compacted clay liner (CCL) and unsaturated soil as well as a layer of aquifer. Assuming that the moisture distribution is steady-state in both CCL and unsaturated soil, one-dimensional equation for controlling the transport of pollutants through such three-layer strata is presented in this paper. In the analyses, both effects of nonlinear sorption behavior and bio-chemical degradation are taken into account for CCL and unsaturated soil. The boundary-value issue for a given landfill profile is numerically solved. Through numerical comparative computations, the effects of various factors on the pollutant migration are systematically examined. On one hand, the degradation of CCL only has an appreciable influence on the transport of pollutants in CCL while its effect is a minor on other layers. On the other hand, the degradation of the unsaturated soil layer only has a considerable effect on the transport of pollutants in unsaturated soil layer and aquifer while it has a negligible influence that in CCL. When the degradation is considered, the concentration of pollutants in the aquifer will approach a lower steady value after a certain time. The effect of higher degradations in CCL and unsaturated soil layer on retardation of pollutant transport will more noticeable than the effect of sorption-induced retardation.

1 INTRODUCTION

In most studies of landfill leachate transport, it is assumed that the underlain deposit of landfill is of fully saturated state. However, in common conditions, groundwater level is below ground surface and the soil layer between barrier layer and underlain aquifer is in unsaturated state. It has been shown that fluid flow in underlying vadose zone of landfill will attain a steady state after about 6 to 8 years. Kool and *et al*. (1994) idealized the landfill by two layers composed of vadose and saturated zones. It is further assumed that in vadose zone, volume water-content keeps constant and moisture transport is idealized by one-dimensional steady state while three-dimensional steady-state seepage and transport of pollutant is considered in saturated zone. Concentration of pollutant source of landfill is assumed to be constant. Then a composite model for leachate transport of landfill is established. Under the condition that the soil beneath landfill is a natural clay layer or is a composite barrier layer, the finite layer theory is utilized by Fityus and *et al*. (1999) to analyze pollutant transport in unsaturated soil layer of finite depth with no consideration nonlinear sorption properties of soil. The effect of bio-chemical degradation of refuse has been investigated by Zhao and *et al*. (2000, 2002), EL-Fadel and *et al*. (2002), Reitzel and *et al*. (1992), Zhang and *et al*. (2002). In this paper, the compacted clay liner (CCL) is used as seepage-prevention lining. The underlying deposit of landfill is idealized by a three-layer system which is composed of CCL and unsaturated soil layer and aquifer. Both effects of bio-chemical degradation of refuse and of non-linear sorption and first-order degradation of pollutants on the transport in CCL and unsaturated soil layer are considered. The controlling equation of pollutant transport is established and numerically solved. Numerical analyses are made to examine influence on underlain aquifer caused by landfill pollutant passing through CCL and unsaturated soil.

2 MOISTURE MOVEMENT IN UNSATURATED SOIL

The leachate is filtrated in a low rate from CCL with a low permeability into unsaturated soil layer. The contact surface between CCL and unsaturated soil layer may be considered as a boundary of low permeability. The effect of filtration of rainfall is also not taken into account. The following Richards equation expressed by θ suggested by Fityus and *et al.* (1999) is employed used to describe moisture transport in unsaturated soil

$$D_m(\vartheta)\frac{\partial^2\theta}{\partial z^2} - \alpha D_m(\vartheta)\frac{\partial\theta}{\partial z} = \frac{\partial\theta}{\partial t} \quad (1)$$

Where z is vertical coordinates downwards from the ground surface, ϑ is volumetric water content, $D_m(\vartheta)$ is a function of diffusivity of moisture. In the following formulations, θ and α are introduced. In fact, θ can be obtained from ϑ through Kirchhoff transformation while α is a parameter to represent the relative importance of effect of gravity and capillarity on water content of soil. Solving Eq. (1) leads to the spatial distribution of volumetric water content with time.

3 INITIAL-BOUNDARY-VALUE EQUATIONS

The mechanism of pollutant transport in porous media contains advection, dispersion, geochemical reaction and first-order bio-chemical reaction. The layered system can be represented as one-dimensional model and basic equation of pollutant transport in CCL is given by

$$D_l\frac{\partial^2 c}{\partial z^2} - v_l\frac{\partial c}{\partial z} - \lambda_l c = n_l\frac{\partial c}{\partial t} + \rho_l\frac{\partial S_l}{\partial t} \quad (2)$$

Where c and S are concentrations of pollutant of liquid and solid phases respectively, v_l is seepage velocity, n_l is effective porosity, D_l is dispersion coefficient, λ_l is first-order degradation parameter and ρ_l is dry density of CCL.

For unsaturated soil layer, the following advection-dispersion equation is used to describe the transport process of pollutant

$$\vartheta\frac{\partial c}{\partial t} + \rho_u\frac{\partial S_u}{\partial t} + \vartheta\lambda_u c + \frac{\partial}{\partial z}\left(\vartheta v_u c - \vartheta D_u\frac{\partial c}{\partial z}\right) = 0 \quad (3)$$

The Langmuir's isotherms are adopted to express nonlinear equilibrium sorption behaviour of CCL and unsaturated soil layer respectively as below

$$S_l = \frac{S_{ml}b_l c}{1 + b_l c}, \quad S_u = \frac{S_{mu}b_u c}{1 + b_u c} \quad (4)$$

where S_{ml} and b_l are maximum sorption capacity and sorption intensity of CCL respectively while S_{mu} and b_u are maximum sorption capacity and sorption intensity of unsaturated soil layer respectively.

Substitution the second equation of Eq. (4) into Eq. (3) yields basic equation of pollutant transport in vadose zone with consideration of nonlinear sorption of soil

$$\left(\vartheta + \frac{\rho_u S_{mu} b_u}{(1 + b_u c)^2}\right)\frac{\partial c}{\partial t} = -\frac{\partial}{\partial z}\left(\vartheta v_u c - \vartheta D_u\frac{\partial c}{\partial z}\right) - \vartheta\lambda_u c \quad (5)$$

Where ρ_u and D_u are dry density and moisture diffusivity of unsaturated soil, λ_u is degradation parameter.

For a given problem, it is necessary through experiments to determine the relation of coefficient of moisture diffusivity dependent on volumetric water content ϑ beforehand, *e.g.*, the following linear function is approximately given

$$D_u(\vartheta) = \begin{cases}\Lambda + \Omega\vartheta, & \vartheta > \vartheta_1 \\ 0, & \vartheta \le \vartheta_1\end{cases} \quad (6)$$

Where Λ, Ω and ϑ_1 are the parameters. Although variation of ϑ with depth can be defined through numerical analysis, such a linear variation of ϑ with depth as $\vartheta(z) = A + B(z - h_1)$ is assumed for simplification, where A and B are fitting parameters.

Substituting Eq. (6) into Eq. (5) leads to governing equation of pollutant transport in unsaturated soils.

For aquifer, seepage velocity of ground water usually is relatively so large that advection plays a dominant role in pollutant transport and the effect of dispersion is negligible. It is shown by the authors that only when the coefficient of distribution, K_d, between solid and liquid phase of pollutants is large, sorption of aquifer will impose much more influence on pollutant transport. Therefore in common conditions the effect of sorption of aquifer may be overlooked. In fact, the aquifer may be taken as an independent physical layer while appropriate boundary conditions are imposed. Alternatively the bottom of the aquifer is directly regarded in this paper as an impervious boundary condition. Such an assumption will overestimate the influence of pollutant on aquifer.

Then the basic equations are numerically solved together with initial and boundary conditions. At initial instant, all three layers are assumed to be not polluted. At the landfill-CCL contact surface, bio-chemical degradation of a given pollutant component in the leachate is taken into account and is assumed to decay with time in such an exponential function as $c(0, t) = c_0 k^{mt}$, where c_0, k, m are degradation parameters of refuse determined by experiments. On the interface between the CCL and unsaturated soil, continuity of current and continuity mass flux of pollutant must be fulfilled. For one-dimensional steady state problem, D'arcy velocity of layers should satisfy continuity condition of current,

$$v_{a,l} = \theta_l v_l = v_{a,u} = \theta_u v_u \quad (7a)$$

$$\left(v_a - \theta D\frac{\partial c}{\partial z}\right)_{c\,|\,x = h_1} = \left(v_a - \theta D\frac{\partial c}{\partial z}\right)_{u\,|\,z = h_{1i}} \quad (7b)$$

$$c_l(z = h_1) = c_u(z = h_1) \quad (7c)$$

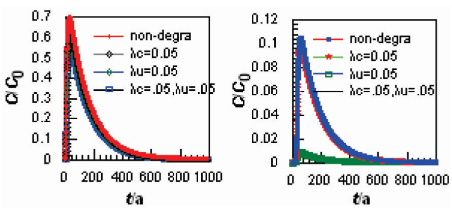
4 NUMERICAL RESULTS AND DISCUSSIONS

An idealized landfill underlain by three layers is numerically analyzed by proposed procedure. The related basic parameters are chosen as following. (1) Length of landfill is 200 m. (2) Degradation parameters of refuse are $c_0 = 1.34288697$, $k = 0.99986$, $m = 25$ (Zhao and *et al*. 2000, 2002). (3) For CCL, $h_l = 2$ m, $\rho_l = 1.2$ g/cm^3, $v_l = 0.1$ m/a, $S_{ml} = 0.5$ $b_l = 0.1$, $\lambda_l = 0.05$, $n_l = 0.45$. (4) For unsaturated soil layer, $h_u = 8$ m, $\rho_u = 1.6$ g/cm^3, $S_{mu} = 0.5$ $b_u = 0.1$, $\lambda_u = 0.05$, $A = 0.25$, $B = 0.038$, $\Lambda = -0.0044$, $\Omega = 0.029$ and water contents in top and bottom of the layer are $\vartheta_T = 0.25$ and $\vartheta_B = 0.554$. (5) For aquifer, $h_a = 1$ m, $n_a = 0.3$, $v_a = 10$ m/a.

4.1 *Effects of degradation*

The sorption of the CCL is assumed to stronger while sorption of unsaturated soil layer is weaker, The following four cases are investigated: (1) No degradation in both CCL and unsaturated soil layer, (2) degradation in the CCL with $\lambda_l = 0.05$ and no degradation in unsaturated soil layer, (3) No degradations in the CCL and degradation in unsaturated soil layer with $\lambda_u = 0.05$, (4) degradation in both CCL and unsaturated soil with $\lambda_l = \lambda_u = 0.05$.

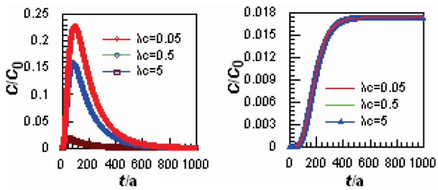
As shown in Figure 1, it can be seen that bio-chemical degradation of either CCL or the unsaturated soil on pollutant transport in the CCL is negligible while the effect on pollutant transport of the unsaturated soil layer is considerable. In fact, the CCL with thickness of 2 m is relatively thick compared with unsaturated soil layer with thickness of 8 m. The time required for pollutant to pass through the layer is so shorter that the effect of degradation on pollutant transport in the CCL is noticeable. In addition, the degradation of the unsaturated soil layer plays a more significant role than that of CCL. Therefore when unsaturated soil layer of definite thickness exists between CCL and aquifer, bio-chemical effect of unsaturated soil layer on pollutant transport especially in the unsaturated soil layer will play a positive role in control pollution of leachate on underlain aquifer.



(a) Compacted clay liner (b) Unsaturated soil

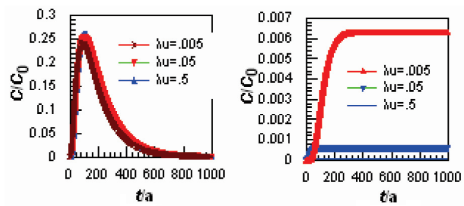
Figure 1. Effect of degradation on pollutant transport.

For the case in which $D_l = 0.01$m^2/a, $\vartheta_T = 0.15$ and $\lambda_u = 0$, numerical analyses are conducted for $\lambda_l = 5, 0.5, 0.05$ respectively. The computed results are given in Figure 2. Alternatively, when the bio-chemical degradation effect of the CCL is overlooked, comparative analysis on the effect of the degradation parameter of the unsaturated soil layer with $\lambda_u = 0.005, 0.05, 0.5$ are performed under the condition with the same parameters as used for Figure 2. The computational results are presented in Figure 3. It is indicated that for a different value of λ_l, the pollutant transport in CCL is strongly affected and the concentration of pollutant in unsaturated soil layer may reach a large stable amount after a certain period. It is manifested that the effect of the bio-chemical degradation parameter λ_u in unsaturated soil layer on pollutant transport in CCL is negligible while its effect on pollutant transport in the unsaturated soil layer is appreciable.



(a) Compacted clay liner (b) Unsaturated soil

Figure 2. Effect of λ_l r on pollutant transport.



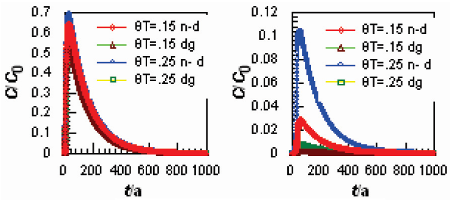
(a) Compacted clay liner (b) Unsaturated soil

Figure 3. Effect of parameters λ_u on pollutant transport.

4.2 *Coupling effects of saturation and degradation*

In order to examine coupling effect of saturation degree and degradation, four cases as below are considered in analyses. (1) $\vartheta_T = 0.15$ with no bio-chemical degradation in CCL and unsaturated soil layer, (2) $\vartheta_T = 0.15$ with bio-chemical degradation in both CCL and unsaturated soil layer, (3) $\vartheta_T = 0.25$ with no bio-chemical degradation in both CCL and unsaturated soil layer, (4) $\vartheta_T = 0.25$ with bio-chemical degradation in both layers.

From the computed results as illustrated Figure 4, it is observed that degree of saturation of unsaturated soil layer and degradation does not impose much effect on pollutant transport in CCL while their effects



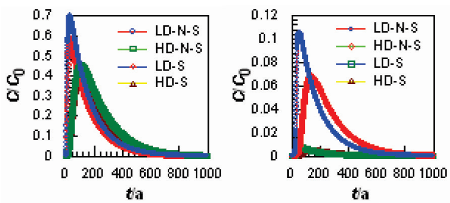
(a) Compacted clay liner (b) Unsaturated soil

Figure 4. Effect of degree of saturation and degradation.

on unsaturated soil layer are considerable. As the degree of saturation of unsaturated soil layer increases, passing-through capability of pollutant will increase, and the distribution of concentration of pollutant seems to be associated with the degree of saturation. Compared with the effect induced by saturation degree, bio-chemical degradation has minor effect. However, bio-chemical degradation in saturated soil layer is more obvious. When degree of saturation of unsaturated soil layer is low, passing-through capability of pollutant is relatively lower and pollutant seems to be consumed by bio-chemical degradation. Therefore concentration of pollutant is kept at a lower level because a large amount of pollutant is adsorbed by degradation in unsaturated soil layer. In fact, such effects are coupled with the influence of nonlinear sorption characteristics.

4.3 *Coupling effect of sorption and degradation*

In order to examine the coupling effects of sorption and degradation, following four cases are considered in analyses for the unsaturated soil layer with a relatively high water content, *e.g.*, $\vartheta_T = 0.25$. (1) Low degradation and sorption (LD-S), (2) High degradation and sorption (HD-S), (3) Low degradation and no sorption (LD-N-S) and (4) High degradation and no sorption (HD-N-S). The computed results are indicated in Figure 5.



(a) Compacted clay liner (b) Unsaturated soil

Figure 5. Effect of sorption and degradation.

It can be seen that when degradation of both CCL and unsaturated soil layer with high level is taken into consideration, concentration of pollutant in CCL obviously descends along with presence of retardation effect. Degradation consumes pollutant to a lower concentration. As a result, the breakthrough curve moves towards the right side and present retardation effect. When both bio-chemical degradation and sorption are taken into account in both of CCL and unsaturated soil layer, concentration of pollutant in CCL further descends due to sorption of soil particles on pollutant and consume of pollutant by degradation. The retardation effect due to bio-chemical degradation is more remarkable than that due to sorption. Compared with the effect of nonlinear sorption, the bio-chemical degradation imposes more obvious effect on pollutant transport in CCL. The pollutant transport in unsaturated soil layer is affected by sorption and bio-chemical degradation in a similar way as that in CCL. However, sorption has more remarkable effect on pollutant transport.

5 CONCLUDING REMARKS

In this paper, transport of landfill leachate is analyzed for the sandwich layered system with CCL-type barrier layer at top and underlain by an unsaturated soil layer and an aquifer. Through comparative analysis, it can be concluded that lower steady concentration of pollutant in unsaturated soil layer may be achieved when the bio-chemical degradation feature of CCL and unsaturated soil layer is considered. The effect of degree of saturation on pollutant transport in unsaturated soil layer is more obvious than that of bio-chemical degradation. Retardation effect caused by bio-chemical degradation is more remarkable than that caused by sorption.

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