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Parametric analyses of evapotranspiration landfill covers in humid regions

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ABSTRACT

Natural soils are more durable than almost all man-made materials. Evapotranspiration (ET) covers use vegetated soil layers to store water until it is either evaporated from the soil surface or transpired through vegetation. ET covers rely on the water storage capacity of soil layer, rather than low permeability materials, to minimize percolation. While the use of ET covers in landfills increased over the last decade, they were mainly used in arid or semi-arid regions. At present, the use of ET covers has not been thoroughly investigated in humid areas. The purpose of this paper is to investigate the use of ET covers in humid areas where there is an annual precipitation of more than 800 mm. Numerical analyses were carried out to investigate the influences of cover thickness, soil type, vegetation level and distribution of precipitation on performance of ET covers. Performance and applicability of capillary barriers and a new-type cover were analyzed. The results show that percolation decreases with an increasing cover thickness and an increasing vegetation level, but the increasing trend becomes unclear when certain thickness or LAI (leaf area index) is reached. Cover soil with a large capability of water storage is recommended to minimize percolation. ET covers are significantly influenced by distribution of precipitation and are more effective in areas where rainy season coincides with hot season. Capillary barriers are more efficient than monolithic covers. The new cover is better than the monolithic cover in performance and the final percolation is only 0.5% of the annual precipitation.

1. Introduction

Alternative final covers such as evapotranspiration (ET) covers are increasingly being considered for use at landfills when equivalent performance to conventional final covers can be demonstrated. Unlike conventional cover designs that use materials with low hydraulic permeability (barrier layers) to minimize the downward migration of water from the cover to the waste (percolation), ET covers use water balance components to minimize percolation. These cover systems rely on the properties of soil to store water until it is either transpired through vegetation or evaporated from the soil surface. An ET cover typically consists of a thick layer of fine-grained soil, such as silts or clayey silts, which are capable of supporting vegetation (EPA, 2003). Basically, an ET cover does not act as a barrier, but as a reservoir that retains water during rainfall and later returns it to the atmosphere by evapotranspiration.

As ET covers are expected to be less costly in construction and maintenance, the use of ET covers is becoming increasingly popular, however, performance data and design guidance for these covers are limited (Benson et al., 2001). Lysimeter tests have been carried out by many researchers to evaluate the performance of ET covers (e.g. Roesler et al., 2002; Dwyer, 2003). But lysimeter test is expensive and time-consuming. Furthermore, lysimeter conditions may not be representative of actual field conditions, because geomembrane in the bottom of lysimeter can cut off the moisture and heat flux from waste below. Thus, using lysimeter as a tool for ET cover evaluation was questionable (Kavazanjian et al., 2006). Performance of ET covers was evaluated by Zornberg et al. (2003) and Albright et al. (2004) using water balance methods. The factors that affect the accuracy of water balance analyses were described by Gross (2005).

However, most of the above-mentioned researches were focused on ET covers in arid and semi-arid regions. The performance of ET covers in humid regions still needs to be investigated. Parametric analyses were carried out in this paper. Accordingly, influences of cover thickness, soil type, vegetation level and distribution of precipitation on performance of ET covers were

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investigated. Performance and applicability of capillary barriers and a new-type cover in humid areas were also analyzed.

2. Numerical model

2.1. Moisture balance of an ET cover

The moisture balance of an ET cover can be illustrated in Fig. 1. As the slope of the cover is only 5%, lateral flow can be neglected (Bohnhoff et al., 2009), and hence moisture balance of the cover can be expressed as

$$\Delta S = P - R - E - T - P_r \quad (1)$$

where ΔS is the variation of water storage in the cover, P is the precipitation, R is the surface runoff, E is the evaporation of water from soil surface, T is the evapotranspiration by vegetation, and P_r is the percolation. The sum of E and T makes evapotranspiration, ET, i.e. $E + T = ET$.

Evapotranspiration is significantly influenced by climatic condition, such as solar radiation, wind speed, relative air humidity and temperature, quality of vegetation, grow stage, root depth, and actual water content of cover soils. Surface runoff is influenced by precipitation, unsaturated hydraulic conductivity and actual water content of cover soils.

2.2. Governing equation and boundary conditions

To describe the moisture movement in cover soils, the following two-dimensional governing equation was used:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(k_\psi \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_\psi \frac{\partial h}{\partial y}\right) \quad (2)$$

where t is the time; θ is the volumetric water content; h is the total head; ψ is the matric suction; k_ψ is the hydraulic conductivity; x and y are the coordinates, as shown in Fig. 1.

Volumetric water content and hydraulic conductivity were both functions of matric suction, known as soil water characteristic curve (SWCC) and hydraulic conductivity function, respectively. They were defined using van Genuchten equation (Van Genuchten, 1980):

$$\theta = \theta_r + (\theta_s - \theta_r)\left[\frac{1}{1 + (\alpha|\psi|)^n}\right]^{1-1/n} \quad (3)$$

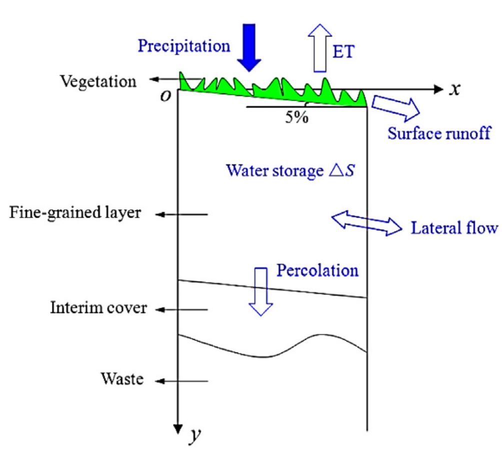

Fig. 1. Moisture balance of a monolithic ET cover.

Table 1
Weather data of Suzhou, Philadelphia and Juneau.

City	Annual precipitation (mm)	Average wind velocity (m/s)	Average relative humidity (%)
Suzhou	1000	2.5	76
Philadelphia	910	4.4	68
Juneau	810	3.2	78

$$k_\psi = k_s \Theta^{0.5}\left\{1 - \left[1 - \Theta^{n/(n-1)}\right]^{1-1/n}\right\}^2 \quad (4)$$

where k_s is the hydraulic conductivity parameter; θ_s is the saturated water content; θ_r is the residual water content; α and n are the curve fitting parameters; Θ is the dimensionless water content and is defined as

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (5)$$

The initial condition was defined as

$$\left.\begin{array}{l} \theta(x, y, t) = \theta_0 \\ t = 0 \end{array}\right\} \quad (6)$$

where θ_0 is the initial water content of soil in the cover.

The upper boundary corresponding to the surface of the ET cover was defined as a flux boundary:

$$\left[k_\psi \frac{\partial \psi}{\partial x}\cos(\boldsymbol{n}, \boldsymbol{x}) + k_\psi \frac{\partial(\psi + y)}{\partial y}\cos(\boldsymbol{n}, \boldsymbol{y})\right]\Big|_{\Gamma_1} = P(t) - R(t) - ET(t) \quad (t \geq 0) \quad (7)$$

where $\cos(\boldsymbol{n}, \boldsymbol{x})$ and $\cos(\boldsymbol{n}, \boldsymbol{y})$ are the cosine of angle between outward normal and coordinate axes. Value of the flux boundary can be positive or negative, indicating precipitation or evapotranspiration, respectively.

For the lower boundary corresponding to bottom of the cover, free drainage under gravity was assumed:

$$\left.\begin{array}{l} \left(k_\psi \frac{\partial \psi}{\partial y} + k_\psi\right)\Big|_{\Gamma_2} = k_\psi \\ t \geq 0 \end{array}\right\} \quad (8)$$

2.3. Parameters

2.3.1. Weather data

Weather data of three cities, i.e. Suzhou in China, Philadelphia and Juneau in USA, were used in the following analyses. The annual precipitation, average wind velocity and average relative humidity of the three cities are given in Table 1. It should be noted that Suzhou, Philadelphia and Juneau are in subtropical monsoon climate, temperate continental climate and temperate marine climate zone, respectively. The seasonal distributions of precipitation in the three sites were different. Daily precipitation and temperature are presented in Fig. 2.

2.3.2. Vegetation

The main factors that influence capability of vegetative evapotranspiration are vegetation level and root depth. Leaf area index (LAI) was used to characterize the quality of vegetation. LAI is a dimensionless ratio of the active leaf area to the nominal area of the land surface. According to the climate condition, growing season in Suzhou started from the 56th day and ended on the 335th day. In Philadelphia, it started from the 73rd day and ended