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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.

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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):

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

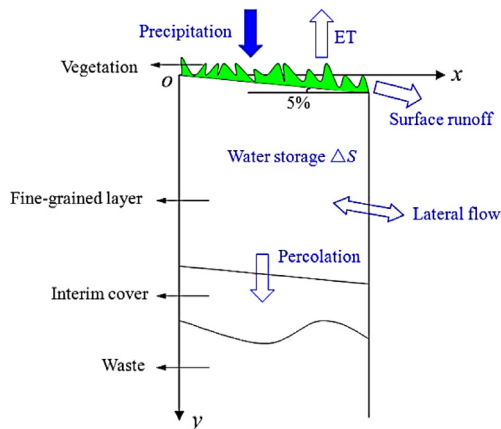


Fig. 1. Moisture balance of a monolithic ET cover.

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

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

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:

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

where $\cos(\mathbf{n}, \mathbf{x})$ and $\cos(\mathbf{n}, \mathbf{y})$ 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:

$$\left. \left(k_\psi \frac{\partial \psi}{\partial y} + k_\psi \right) \right|_{\Gamma_2} = k_\psi \quad (8)$$

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

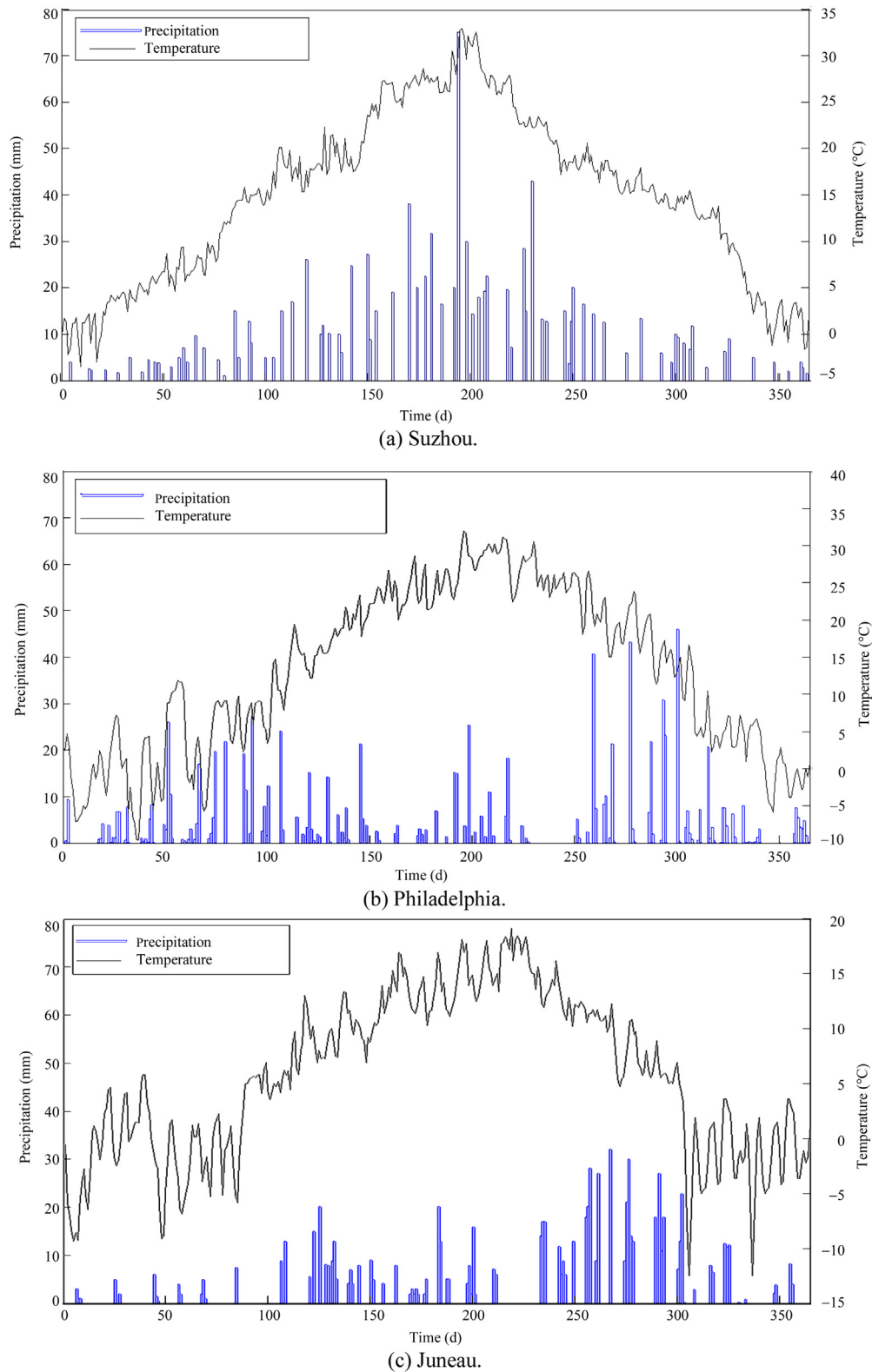


Fig. 2. Daily precipitation and temperature of the three cities.

on the 341st day. In Juneau, it started from the 112th day and ended on the 303rd day. The LAI is assumed to be 2.0 in Suzhou and 1.0 in the other two cities. Root depth is assumed to be 50 cm at the three sites.

2.3.3. Soil type

Three types of soils were chosen as vegetative soils. Hydraulic properties of these soils were defined using Van Genuchten equation (Roesler et al., 2002) and are given in Table 2. Soils A, B and C

belong to fine-grained soil. Soil D belongs to sand and is used in a capillary barrier as coarse-grained soil. SWCCs of these soils are presented in Fig. 3. The volumetric water content corresponding to matric suction 33 kPa is considered to be the field capacity (θ_{fc}) of a soil, and the one corresponding to 1500 kPa was considered to be the wilting point (θ_{wp}) (Hillel, 1998). Thus $\theta_{fc} - \theta_{wp}$ is defined as the storage capacity, which represents the maximum amount of removable water under evapotranspiration. The storage capacities of soils A, B and C are 0.17, 0.23 and 0.36, respectively.

3. Parametric analyses

3.1. Thickness of vegetative layer

Soil B and weather data of Suzhou were used in this analysis. “Cover B” in this graph (and the subsequent graphs) represents an ET cover made up of soil B, and so do “Cover A” and “Cover C”. The initial volumetric water content was 0.18. In order to avoid the influence of an uncertainty in initial water content on the result, every simulation was performed for a 4-year period time and result of the 4th year was presented. The first thickness employed was 600 mm. The results show that there was rare surface runoff during the year except that a 10 mm surface runoff occurred on the 194th day corresponding to the intense rainfall period in summer. The calculated annual evapotranspiration was 985 mm. Daily evapotranspiration is shown in Fig. 4, which was mainly controlled by temperature. In addition, it was also influenced by antecedent precipitation, or the actual water content. For example, on the 168th day, the temperature was high whereas the amount of evapotranspiration was only 1.1 mm.

Daily percolation and water content of cover soils near the lower boundary are presented in Fig. 5. Percolation mainly happened in the rainfall-concentration period, i.e. from July to September. Accordingly, water content of the bottom soil was relatively high. The annual percolation amounted to 15 mm. It could be calculated from Eq. (1) that variation of water storage over the year was $\Delta S = 1000 - 10 - 985 - 15 = -10$ mm, where minus means loss of water.

Percolation, i.e. the amount of water expected to percolate through the soil cover, is the criterion to evaluate the performance of the landfill cover. The annual acceptable percolation of an ET cover in humid areas has not been specified by the regulatory community, but it can be controlled at no less than 1 mm in arid and semi-arid regions (Vaughn et al., 2006). For the study of the influence of cover thickness on the cover performance, thicknesses of 800 mm, 1000 mm, 1200 mm and 1400 mm for cover B were analyzed. The trend is shown in Fig. 6. It is illustrated that percolation decreased with an increasing cover thickness. The annual percolation of the 1400 mm thick vegetative cover was only 0.7 mm. The standard for percolation control in such climate condition can be satisfied.

3.2. Soil types

Using climatic data of Suzhou, the performances of covers A, B and C can be compared. When the cover thickness was 600 mm, the

annual percolations of covers A, B and C were 40 mm, 15 mm and 2 mm, respectively, suggesting that water storage capacity ($\theta_{fc} - \theta_{wp}$) has a major influence on the performance of an ET cover.

Calculations were carried out considering various cover thicknesses. It can be observed in Fig. 6 that the percolation became negligible when the thickness of cover C reached 800 mm. To cover A, the annual percolation firstly decreased evidently as thickness increased; however, the decreasing trend became slightly when the thickness exceeded 1600 mm. Even when the thickness reached 2000 mm, there still remained percolation of 8 mm. This illustrates that increasing cover thickness will not always be an effective way to minimize percolation of an ET cover. It is the difference in storage capacity ($\theta_{fc} - \theta_{wp}$) that resulted in the different performances of the three covers. Thus, soils with high storage capacities are recommended in humid regions in order to minimize final percolation.

3.3. Leaf area index (LAI)

A 600 mm and an 800 mm thick cover B were used to investigate the effect of LAI on annual percolation. Climatic data of Suzhou were used in this analysis. LAIs of the covers were assigned from 1 to 5, in which “5” means the highest vegetation level. The changes in annual percolation with different LAIs are presented in Fig. 7. The annual percolation decreased clearly as LAI increased when $LAI \leq 3$, but the trend became unclear when $LAI > 3$. Taking the 600 mm thick cover as an example, when $LAI = 3, 4$ and 5 , the calculated annual percolations were 9.1 mm, 8.8 mm and 8.0 mm, respectively, suggesting that enhancement of the presence of vegetation may not be an effective way to improve the performance of an ET cover. Furthermore, a value of $LAI = 5$ was almost impossible during the whole growing season, especially in dry period of time without irrigation.

3.4. Distribution of precipitation

Cover C with a thickness of 1400 mm was taken as an example. The simulation was carried out using climatic data of Suzhou, Philadelphia and Juneau. The calculated cumulative evapotranspiration, volumetric water content of bottom soils and cumulative percolations over a year are shown in Fig. 8.

In Fig. 8a, the cumulative evapotranspiration in Philadelphia from the 102nd day to the 232nd day was a little higher than that of the other two cities, due to the abundant antecedent precipitation. There were many rainfalls in the middle of the year in Suzhou and the temperature was high during that time, therefore a peak evapotranspiration period happened, and the cumulative evapotranspiration in Suzhou became the largest after the 232nd day. The cumulative evapotranspiration in Juneau was the lowest, because the temperature there was relatively low and intensive precipitation happened in low temperature season.

In Suzhou, most precipitation was sent back to atmosphere by evapotranspiration as the rainy season coincided with the hot period, so the bottom soils remained dry throughout the year, as shown in Fig. 8b. However, in Philadelphia and Juneau, a majority of precipitations could not be evaporated or transpired from the soil, especially when temperature was low. In Juneau, there was a huge precipitation in winter, so water content significantly increased during that time and became saturated.

When water content exceeds the field capacity of cover soil, obvious percolation occurs. As a result, there is a strong percolation in the beginning and end of the year in Juneau, whereas in Suzhou almost has no percolation (Fig. 8c). The annual percolations in Suzhou, Philadelphia and Juneau are 0 mm, 12 mm and 51 mm, respectively.

Table 2
Hydraulic parameters of cover soils (Roesler et al., 2002).

Cover soil	θ_r	θ_s	α (kPa ⁻¹)	n	k_s (cm/s)	θ_0
A	0	0.37	0.005	1.33	1.1×10^{-4}	0.17
B	0	0.46	0.0176	1.29	1.9×10^{-5}	0.18
C	0	0.48	0.015	1.61	6.1×10^{-6}	0.2
D	0.013	0.41	0.35	7.22	2.0×10^{-2}	0.05

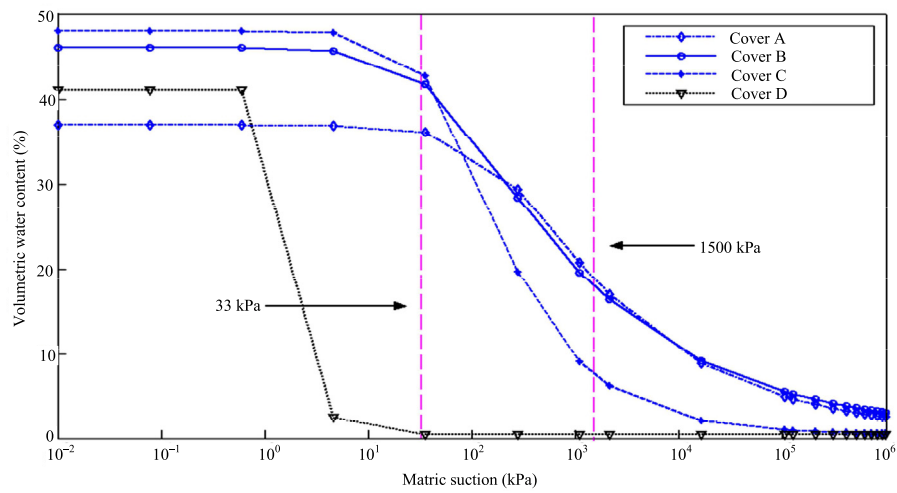


Fig. 3. SWCCs of cover soils (Roesler et al., 2002).

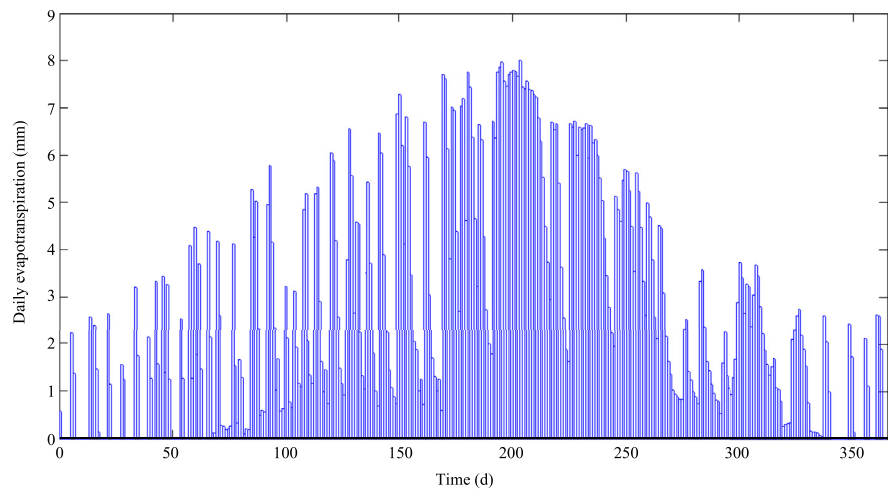


Fig. 4. Daily evapotranspiration of the 600 mm thick cover B.

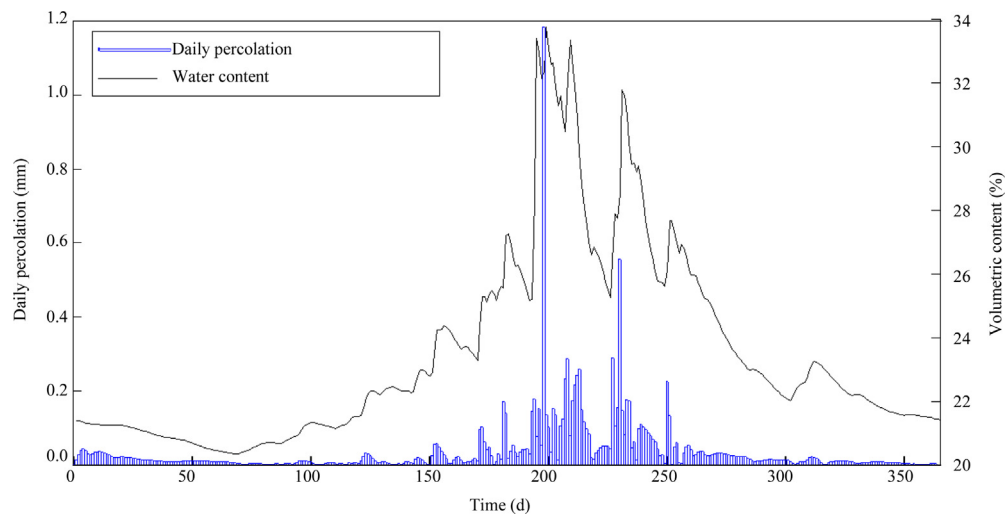


Fig. 5. Daily percolation and water content of bottom soils of the 600 mm thick cover B.

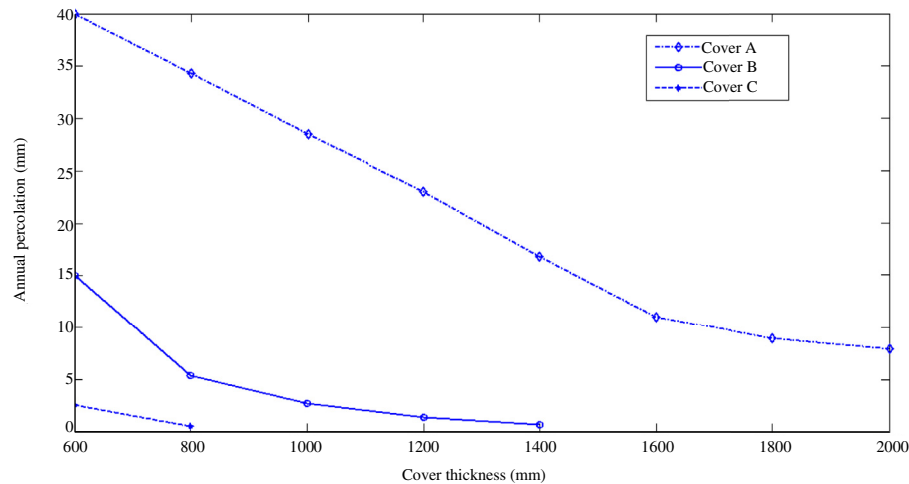


Fig. 6. Annual percolation of covers A, B and C with various thicknesses.

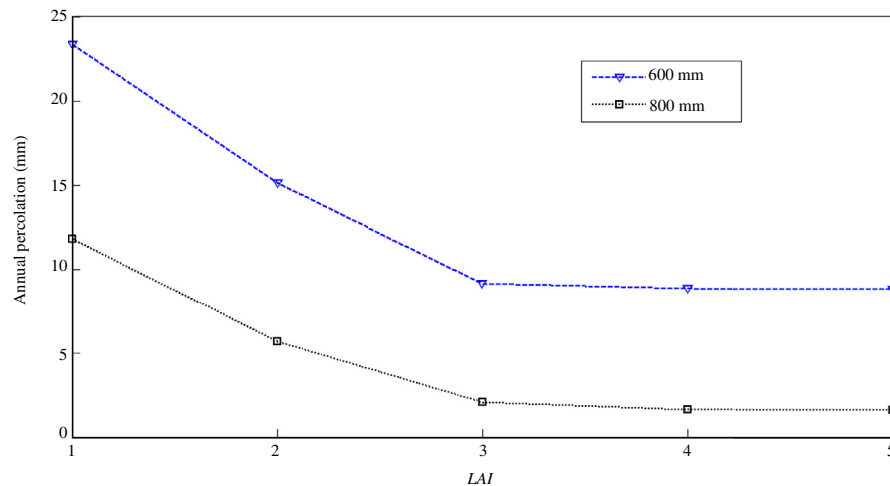


Fig. 7. Annual percolations of cover B with various LAIs.

Further calculation showed that there were still 6.4 mm (in Philadelphia) and 7.6 mm percolations (in Juneau) even if the cover thickness reached 2000 mm. A monolithic ET cover could not minimize the percolation to less than 1 mm in Philadelphia and Juneau. Analysis shows that the climatic condition, especially seasonal distribution of precipitation, has a major influence on performance of an ET cover.

3.5. Capillary barrier ET cover

Another common ET cover design is capillary barrier. A capillary barrier cover consists of a coarser-grained soil overlaid by a finer-grained vegetative layer. In this analysis, the cover was made up of a 1400 mm thick soil C overlying 300 mm thick soil D. The analysis was conducted using the climatic data of Philadelphia and Juneau.

Water content of soils near the soil C–D interface is given in Fig. 9. Sometimes water content of soils above the interface exceeded the field capacity of soil C in Philadelphia, e.g. from the 70th day to the 120th day. However, water content of soil D

remained almost unchanged throughout the year (Fig. 9a). The reason lays in the contrast in unsaturated hydraulic conductivities between soil C and soil D, which formed a capillary break that limited downward water movement. The calculated annual percolation of the capillary barrier cover in Philadelphia was only 0.16 mm. In contrast, the annual percolation of the 1400 mm thick monolithic cover in Fig. 8c was 12 mm. It can be concluded that performance of a capillary barrier cover is much better than that of a monolithic cover in this climate condition.

In Juneau, water content of soil C above the interface often exceeded field capacity and even approached saturation in spring and winter, as shown in Fig. 9b. The capillary barrier effect disappeared and a lot of water moved downward into soil D, and thus water content of soil D increased apparently. This correspondingly caused an annual percolation of 24 mm. There was still 7.4 mm percolation when calculating soil C with a thickness of 1700 mm. Increasing the thickness of the finer textured layer postponed the saturation of the interface, but could not avoid saturation, and hence percolation. Too much precipitation in low-temperature season makes such a cover that cannot be used in this location.

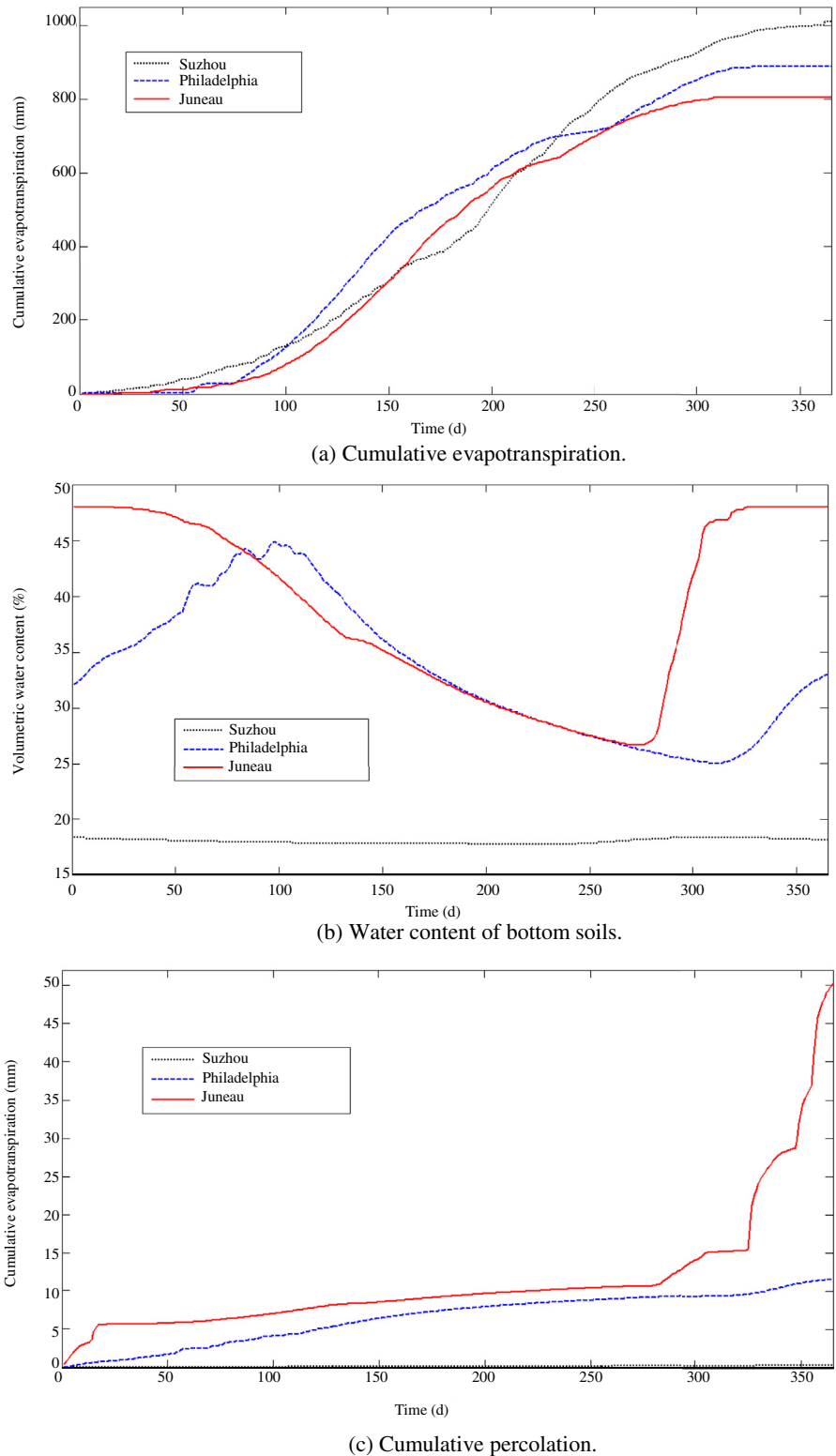
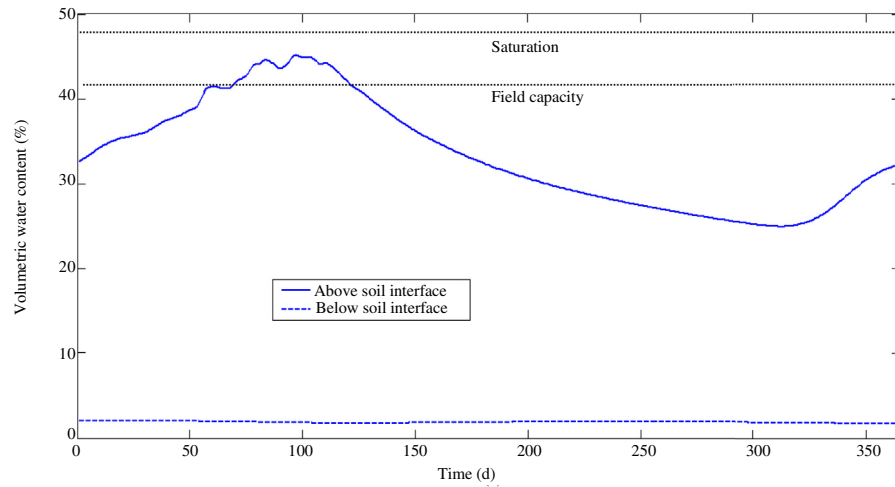


Fig. 8. Cumulative evapotranspirations, water content of bottom soils and cumulative percolations for the 1400 mm cover C in the three sites.

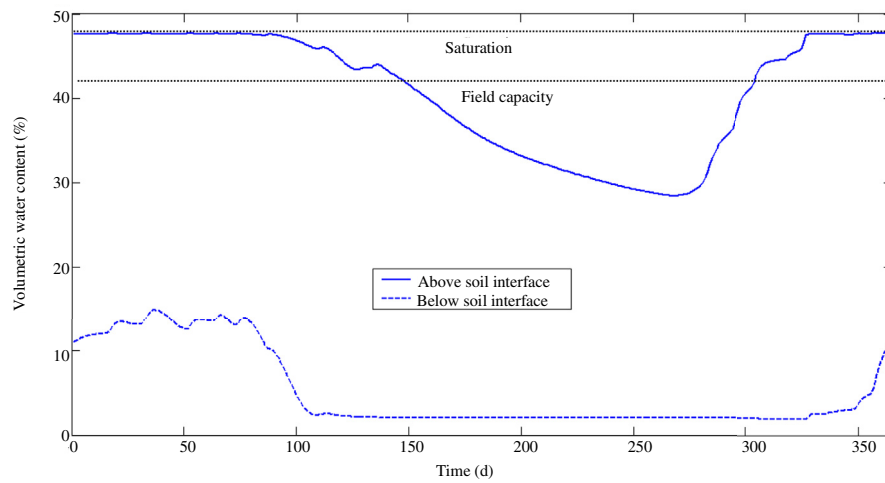
3.6. A new-type cover and the performance

The new-type cover consists of a geosynthetic clay liner (GCL) overlaid by a fine-grained vegetative layer (called GCL-ET cover hereafter). This cover can hold more water for subsequent evapotranspiration because of the low penetrability of GCL. A

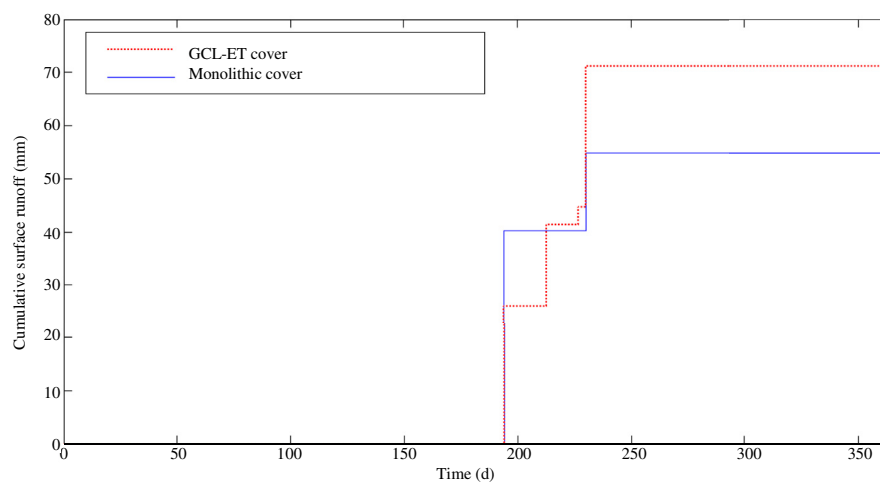
1200 mm thick soil B was used as the vegetative layer in the numerical model. Thickness of the GCL was 5 mm and the saturated hydraulic conductivity was 1.0×10^{-8} cm/s (Roesler et al., 2002). Performance of the new cover was compared with a 1200 mm thick monolithic cover B (short as monolithic cover hereafter).



(a) Philadelphia.



(b) Juneau.

Fig. 9. Water content near soil C–D interface in capillary barriers.**Fig. 10.** Cumulative surface runoff of the two covers.

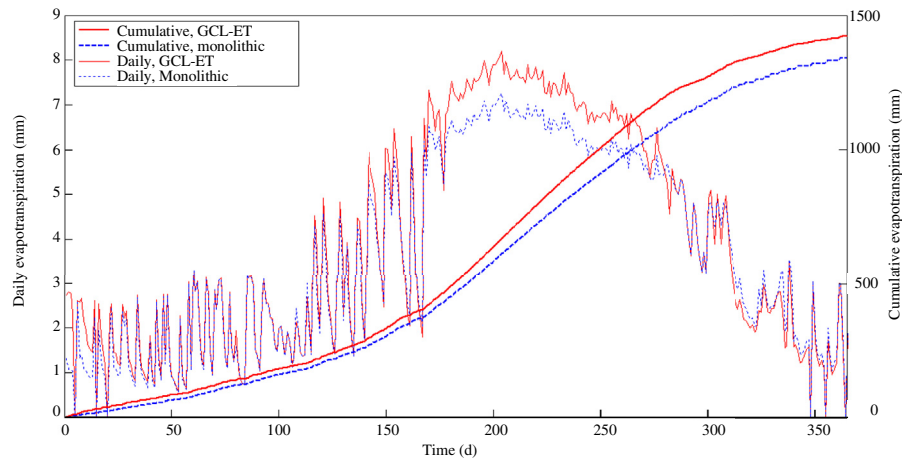


Fig. 11. The calculated evapotranspiration of the two covers.

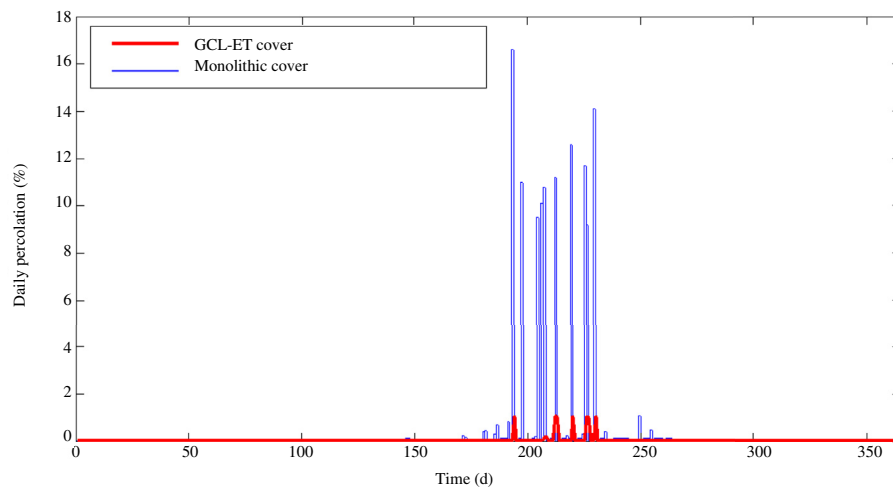


Fig. 12. Percolations through the two covers in a year.

In order to confirm the performance of the new cover, more humid weather data were used. Climatic data of Suzhou in 1987 were selected for the precipitation amounted to 1500 mm in that year. The rainy season coincided with the hot season in Suzhou, and there was 953.3 mm rainfall from June to September in 1987. The maximum 7-day precipitation was 390 mm and happened from the 192th to the 198th day. LAI was assumed to be 3 and other parameters were kept unchanged.

Surface runoff of the monolithic cover occurred on the 194th and 230th day, as illustrated in Fig. 10. The annual surface runoff was 54.8 mm. Surface runoff of the GCL-ET cover occurred on the 194th, 213th, 227th and 230th days, with a total amount of 71.1 mm. In rainy season, water could not flow downward immediately through the GCL, so the cover soil became saturated and could not hold more water. As a result, there came more surface runoff from the GCL-ET cover than from the monolithic cover.

The daily and cumulative evapotranspirations of the two covers are given in Fig. 11. The variation trends were much alike, but evapotranspiration of the GCL-ET cover was a little more than that of the monolithic cover. Evapotranspiration of the monolithic cover was 1340 mm, and evapotranspiration of the GCL-ET cover amounted to 1440 mm, i.e. 100 mm more than the former. The amount of evapotranspiration was decided not only by the energy,

but also by the available water in soils. Evidently, the GCL-ET cover could hold more water during rainfall event, and thus the subsequent evapotranspiration was larger.

Daily percolation of the two covers is shown in Fig. 12. There was little percolation before the intense rainfall period. After the 194th day, a relatively large amount of water flowed through the cover after the saturation of soils in the monolithic cover. The annual percolation of the monolithic cover was 134 mm. Low permeability of the GCL reduced the flow rate, and at the same time, made the GCL-ET cover hold more water, which was released by evapotranspiration subsequently. The annual percolation of the GCL-ET cover was only 7.6 mm, i.e. 0.5% of the annual precipitation. Performance of the GCL-ET cover was better than that of the monolithic cover. The GCL-ET cover can effectively reduce percolation and is suitable for the study area.

4. Conclusions

Parametric analyses on ET covers in humid areas were carried out in this paper. Main conclusions are drawn as follows.

- (1) Percolation usually decreases with an increasing cover thickness, except when an improper cover soil is used.

- (2) The bigger the storage capacity ($\theta_{fc} - \theta_{wp}$) of the cover soil is, the less the percolation will be.
- (3) Percolation usually decreases with an increasing LAI, but the trend becomes unclear when LAI exceeds 3.
- (4) Climate condition has a great influence on performance of ET covers. ET covers are more effective in areas where rainy season coincides with hot season.
- (5) A capillary barrier ET cover is more efficient than a monolithic cover, although it may be unsuitable for some area where lots of precipitation happens in low-temperature season.
- (6) A GCL-ET cover performs better than a monolithic cover. It can hold more water for subsequent evapotranspiration because of low GCL penetrability.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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References

- Albright WH, Benson CH, Gee GW, Roesler AC, Abichou T, Apiwantragoon P, et al. Field water balance of landfill final covers. *Journal of Environmental Quality* 2004;33:2317–32.
- Benson C, Abichou T, Albright W, Gee G, Roesler A. Field evaluation of alternative earthen final covers. *International Journal of Phytoremediation* 2001;3(1):105–27.
- Bohnhoff GL, Ogorzalek AS, Benson CH, Shackelford CD, Apiwantragoon P. Field data and water-balance predictions for a monolithic cover in a semiarid climate. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE 2009;135(3):333–48.
- Dwyer SF. Water balance measurements and computer simulations of landfill covers. New Mexico: University of New Mexico; 2003.
- Environmental Protection Agency (EPA), US. Evapotranspiration landfill cover systems fact sheet. US: Environmental Protection Agency (EPA); 2003. EPA 542-F-03–015, <http://clu.in.org/products/altcovers>.
- Gross BA. Water balance evaluations for monitored evapotranspirative cover systems at three sites in the semi-arid and arid Southwest U.S.. PhD Thesis. Austin: University of Texas at Austin; 2005.
- Hillel D. Environmental soil physics. New York: Academic Press; 1998.
- Kavazanjian EJ, Beth AG, Tarik HH. Unsaturated flow flux assessment for evapotranspiration cover compliance. In: The 4th International conference on unsaturated soils, ASCE. Reston, VA: American Society of Civil Engineers (ASCE); 2006. pp. 634–45.
- Roesler AC, Benson CH, Albright WH. Field hydrology and model predictions for final covers in the alternative cover assessment program-2002. Madison: University of Wisconsin-Madison; 2002. Geo Engineering Report No. 02-08.
- Van Genuchten MT. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* 1980;44(5):892–8.
- Waugh WJ, Mushovic PS, Kleinrath AW. Lysimeter tests for an ET cover design at Monticello, Utah. In: The 4th international conference on unsaturated soils, ASCE. Reston, VA: American Society of Civil Engineers (ASCE); 2006. pp. 801–12.
- Zornberg JG, Lafountain L, Caldwell JA. Analysis and design of evapotranspirative cover for hazardous waste landfill. *Journal of Geotechnical and Geoenvironmental Engineering* 2003;129(5):427–38.



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