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A discussion on the design criteria of capillary barrier

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ABSTRACT: Many scholars have suggested adopting capillary barrier as the top cover layer of landfill. Capillary barrier has better anti-seepage ability than traditional compacted clay blanket, and has a longer service life and wider application area. The design criterion of capillary barrier is proposed in this study. In raining season, the time of the water percolation through capillary barrier is named as the breakthrough time. There is a theoretical relation between the breakthrough time and the water holding capacity of the capillary barrier. Such relation was verified by laboratory soil column tests upon rainfall infiltration. In dry season, the evaporation should be larger than the amount of water infiltrated into the barrier in raining season. Based on this rule, the design parameters of capillary barriers in arid areas (Yinchuan), semi-arid areas (Lanzhou), semi-humid areas (Xi'an) and humid areas (Hangzhou) are determined.

1 INTRODUCTION

Through indoor tests, field seepage tests and numerical simulations, it was verified that capillary barriers can reduce landfill leachate (eg. Miyazaki 1988; Parent and Cabral 2005; Stormont and Anderson 1999; Tami et al. 2004; Ng et al. 2015). Most scholars are exploring and improving the traditional capillary barriers, mainly from the two aspects of the soil materials and the barrier structure (including the slope of the cover, the thickness of the upper, lower and drainage layer). In this paper, based on soil column experimental data, a model for the breakthrough time of capillary barriers is proposed. Further, the design criterion of capillary barrier is proposed and applied to the design of capillary barrier in specific area.

2 WATER HOLDING CAPACITY OF FINE-GRAINED SOIL LAYER IN CAPILLARY BARRIER

2.1 Soil column system

A soil column test device for simulating rainfall infiltration is shown in Figure 1, including the rainfall simulation device (including Marriott’ bottle, rainfall device), the soil column mold and the moisture sensor. The rainfall simulation device can simulate the rainfall with different intensities. The soil column mold with a diameter of 0.2 m can be used to hold the compacted soil sample. The moisture sensors (MP406B) are used to measure the volumetric water content of the soils.

Figure 1. Schematic setup of soil column test.

In this study, completely decomposed granite (CDG) and gravel soil（approximately 5 mm）are used as fine-grained and coarse-grained soil layer of the capillary barrier. The CDG used in this study is a widely graded soil, and has a specific gravity of 2.632, a fine content of 49.5%, a liquid limit of 43.3%, and a plasticity index of 16.8%. The dry density of CDG in the tests is controlled at 1.328 g/cm^3 with the saturated hydraulic conductivity of 7.6E-7 m/s. The dry density of gravel is controlled at 1.6 g/cm^3 with the saturated hydraulic conductivity of 4.5E-02 m/s.

Two groups of tests are used to study the effects of heights and initial water content of fine-grained soils on water holding capacity of capillary barrier, respectively. In the first group, the heights of CDG of the four tests are o.15 m, 0.30 m, 0.40 m, 0.55 m. In the second group, the height of CDG is 0.15 m, and the initial volumetric water content of CDG is 0, 8.9 %, 15.8 %, 23.6 %, respectively. The height of the underlying gravel layer is 0.10 m in all the tests and the gravel layer is initially dried. The rainfall density maintains at a same values in the tests. Water can outflow from the bottom of the soil columns. Moisture sensors are installed both in gravel and CDG layers.

In this study, the rainfall intensity is greater than the saturated permeability coefficient of soil. The infiltration process can be divided into three stages: rainfall intensity control infiltration, unsaturated soil control infiltration and saturated soil control infiltration (Figure 2).

In the first stage, there is no water on the surface of the soil column. That's to say, the infiltration is controlled by the flow boundary condition, i.e. the rainfall intensity. At this stage, the movement of water in soil is obviously affected by capillary force. Water is majorly adsorbed by soil matrix. In the second stage, ponding starts to happen at the top of soil column. The effect of rainfall intensity on the infiltration capacity decreases. The infiltration is controlled by the head boundary condition at the top surface of soil column. At this stage, water flows into the pores of soil under the action of both capillary force and gravity, and gradually fills the pores of the soil, when the top soil is under an unsaturated state. Moreover, because of the increase of water content, the gradient of the matrix suction decreases and the soil infiltration rate becomes weaken. At the third stage, the top soil is close to saturation and water flows under the action of gravity.

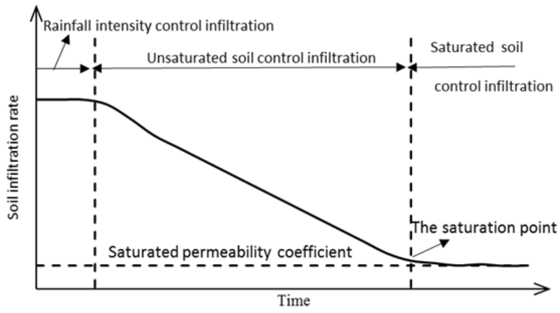

Figure 2. Three conditions of rainfall infiltration in unsaturated soil column.

2.2 Test results

When the monitored soil water contents in soil content become stable, the soil column is regarded to under a quasi-steady state. In the experiments, water is accumulated on the surface of the four groups of soil columns. The rainfall is converted into water accumulation, the storage and drainage of the fine-grained soil and coarse-grained soil. Under different soil column heights, total rainfall and water storage at the time of quasi-steady state are very different, as shown in Figure 3. With the increase of the thickness of CDG, the water storage of CDG increases.

In the second group of tests, in order to compare the total water discharge and storage before the quasi-steady states are achieved, the analysis time period of four tests is selected with the same total rainfall flux, Q_{in}. When the cumulative rainfall Q_{in} is about 4000 ml, the water content of CDG has been stable. The water quantity analysis of the four tests is shown in Figure 4 with a histogram. Within these time periods, the water content of the whole soil column with the initial volumetric water content of 8.96 %, 15.8 % and 23.6 % has reached equilibrium, while the water content of gravel in the initial dry soil column is still changing, and has not reached equilibrium. This phenomenon demonstrates that: Firstly, the fine-grained soil with low water content slows down the water infiltration rate greatly. Secondly, the water storage ability of fine-grained soil decreases with the increase of the initial water content of the fine-grained soil. Thirdly, no water accumulates on the surface of the soil column when the initial water content is 22.8 %. That's to say, the amount of water accumulation decreases with the increase of initial water content of the fine-grained soil.

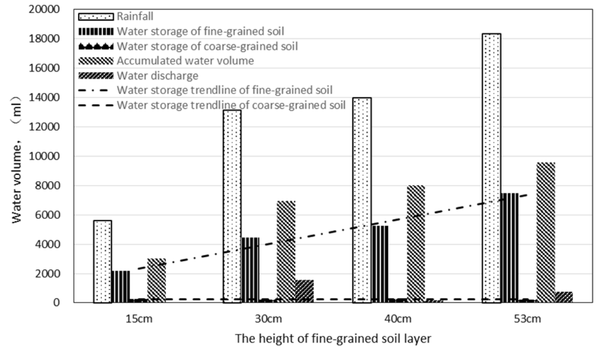

Figure 3. Analysis of water content under quasi-steady state for the soil columns with different heights.

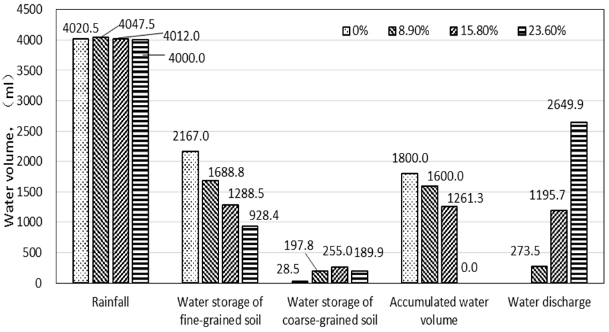

Figure 4. Analysis of water content for soil columns with different initial water contents but identical rainfall intensity.

In a word, when the initial moisture content of fine-grained soil of soil column is relatively low, it can slow down the speed of water flow, increase water storage capacity and prolong the effective time of the cover.

3 DESIGN CRITERIA OF CAPILLARY BARRIER

3.1 Calculation model of water holding capacity

For the capillary barriers, the water holding capacity of the fine-grained soil is essential. According to the maximum theoretical water holding capacity calculation model proposed by Stormont et al. (1999), at breakthrough time, the matrix suction increases linearly with the height of fine soil layer. Thus, the corresponding water content decreases and has a power function curve relationship with height. In the actual tests, the distribution of water content is complex and is affected by various factors. For the soil column tested in this study, water content profiles under the quasi-steady states are shown in Figure 5.

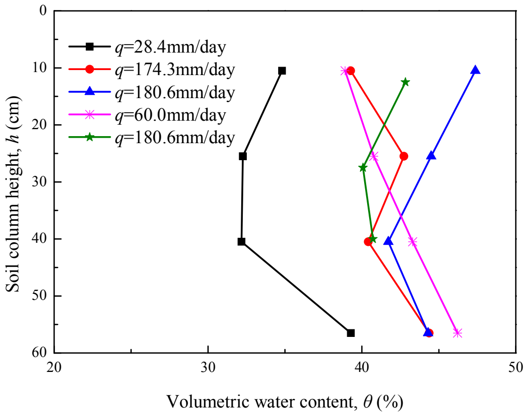

Figure 5. Water content profiles under quasi-steady state of different soil columns.

In tests, the distributions of water content are affected by and contain errors from soil initial compaction, rainfall intensity, soil column height and other factors. The concept of averaging can be used to estimate the moisture content of fine-grained soil when the interface fails.

Based on this, a simplified calculation model for water holding capacity (C) of fine-grained soil is proposed which is suitable for the capillary barriers.

$$C=\left(\theta_f-\theta_0\right)AH \tag{1}$$

where θ_f = the average volumetric water content of fine-grained soil layer at the breakthrough time; θ_0 = the initial volumetric water content of fine soil layer (%); A = the area of the cover (cm^2); H = the thickness of fine-grained soil layer (cm). The model can be used to estimate the maximum water holding capacity of the fine-grained soil when the interface fails. The water holding capacity of fine-grained soil can provide a simple basis for material selection and structure design of the capillary barrier.

The hydraulic characteristics of the tested soil are shown in Figure 6. The air-entry value of gravel soil is around 1.8 kPa. The intersection of permeability coefficient function curves of the two kinds of soil is about 0.45 kPa. At the interface, when the suction value reaches 1.8 kPa to 0.45 kPa, the water flux infiltrated into the gravel layer will become remarkable.

The measured values of water storage in tests are in good agreement with the calculated water holding capacity by the simplified model (Figure 7) when choosing the volumetric water content corresponding to air-entry value as θ_f.

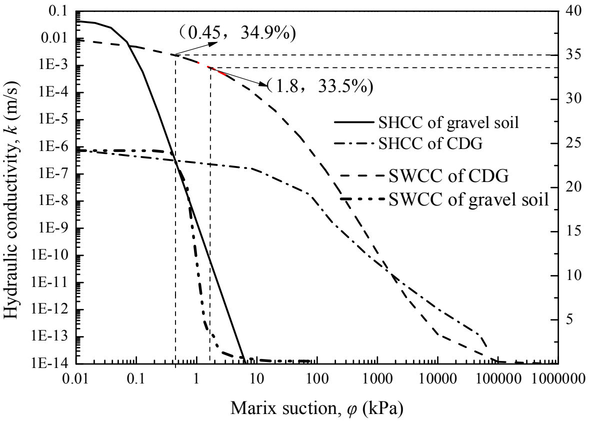

Figure 6. Hydraulic characteristics of CDG and gravel soil.

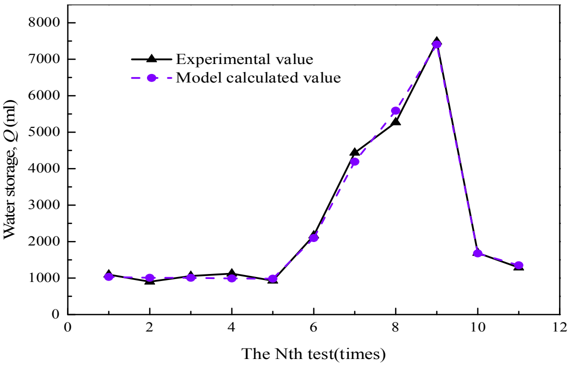

Figure 7. Comparison of water storage between experimental values and model calculated values.

3.2 Comparison of the model prediction of breakthrough time and the test results

Generally speaking, the breakthrough time is related to many parameters, such as hydraulic characteristics of coarse-grained soil and fine-grained soil, the initial water content, thickness, dry density, saturated water content of fine-grained soil and rainfall intensity.

As a simplified estimation, based on the test results, the breakthrough time can be estimated by the water holding capacity (Equation 1) and flux balance, as follows:

$$T=\frac{C}{Ak_i} \tag{2}$$

where k_i = infiltration rate of water in a soil column (m/s), as:

$$k_i = \begin{cases} q, q < k_s \\ \lambda k_s, q > k_s \end{cases}$$

When the rainfall intensity q is less than the soil's saturated hydraulic conductivity k_s or the initial water content of soil is high without ponding, $k_i = q$; When $q > k_s$, water will be ponding on the surface of the soil column and water majorly infiltrates under the action of gravity. λ is the average hydraulic gradient for such conditions. Through back analysis, the values of λ in the test are shown in Figure 8. Because of the variation of test conditions and test errors, the values of λ fluctuate. λ is supposed to be related to the depth of accumulated water in the soil column. The recommended range for λ is 1~1.5.

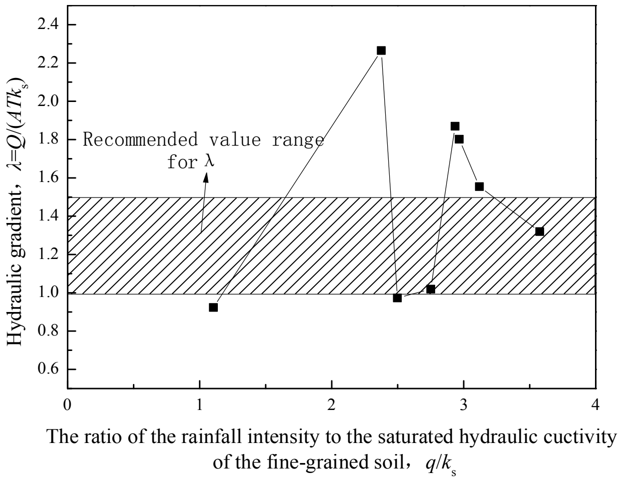

Figure 8. Range of the hydraulic gradient λ.

If λ is taken as 1.1, the breakthrough times calculated by Equation 2 are in good agreement with the experimental data (Figure 9).

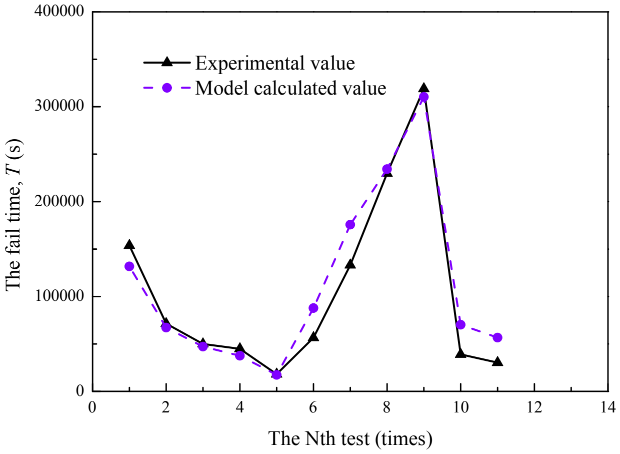

Figure 9. Comparison of failure time between experimental values and model calculated values.

In summary, the proposed model can be used to predict the water holding capacity and breakthrough time for capillary barrier. However, this model is relatively simple and does not consider the influence of the complex infiltration process and many other factors such as dry density, the shape of SWCC etc.

3.3 Design criteria of capillary barrier

For the over-year service of capillary barrier, the key point of the design of capillary barrier is that water holding capacity must be less than or equal to the evaporation Q_E of dry season. So it can make the fine soil drain effectively in dry season without remaining water in soil matrix. Otherwise, water will accumulated in the soil matrix.

Based on this idea, the following equation should be valid,

$$C = \left(\theta_f - \theta_0\right) H \le Q_E \frac{(T_a - T_{rs})}{T_a} \tag{3}$$

Where T_a = the total time in a year; T_{rs} = the duration of the rainy season.

Another key point in the design is to determine the saturated permeability coefficient of the fine-grained soil. In order to avoid a large amount of water entering the landfill after the interface fail, the breakthrough time of the capillary interface (T) should be longer than the time of rainfall (T_r). According to the time of rainfall (T_r), fine-grained soil layer thickness (H) and the simplified calculation model of breakthrough time (Equation 2), we have:

$$T = \frac{Q}{K_i} \ge T_r \tag{4}$$

In the calculation, we should calculate conservatively to guarantee the safety margin of capillary barrier. θ_f is taken as air entry value, which should be larger than the water content of fine-grained soil when water enters the coarse-grained soil layer (Figure 6). For convenience, θ_f can be approximated to 0.9 times the saturated water content of the fine-grained soil; θ_0 is the initial water content of the fine-grained soil layer when the dry season ends, and θ_0 can be generally used as a value little larger than the residual water content of the fine-grained soil. 1.5 times of the residual water content may be a proper value; λ is the average hydraulic gradient in the fine-grained soil layer under the condition of water accumulation during the raining season and its conservative estimation can be 2.0.

The capillary barriers should meet the upper two principles (Equations 3 and 4). Firstly, the evaporation capacity in dry season is greater than the holding capacity of fine fine-grained soil, as shown in Equations 5, otherwise, it will cause accumulated water for many years. Based on Equation 3, the following relation exists:

$$H \le Q_E \frac{(T_a - T_{rs})}{T_a} / \left(\theta_f - \theta_0\right) \tag{5}$$

Secondly, the water holding capacity should be greater than the amount of infiltration in the rainy season, otherwise the fine-grained soil layer will be penetrated. Based on Equations 2 and 4,

$$H \ge \min(q_r, \lambda K_s) T_{\mathrm{r}} / \left(\theta_f - \theta_0\right) \tag{6}$$

where q_r = the average infiltration density in raining season. And q_r can be taken as the difference between average rainfall intensity in the rainy season and average evaporation intensity as follows:

$$q_r = \frac{\eta Q_R - \dfrac{Q_E}{T_a}(T_{\mathrm{rs}} - T_r)}{T_{\mathrm{rs}}} \tag{7}$$

where Q_R = the total annual rainfall; η = the percentage of rainfall during the rainy season accounted for the annual rainfall; T_r = the number of raining days.

q_r can be used in the pilot calculation of the thickness of fine soil layer by Equation 6. In engineering practice, the smaller is H, the lower is the cost of the project. But when H is too small, the actual construction is inconvenient. Therefore, the value of H should generally be around 0.15m~0.5m. If the calculated H is in this range, it can be used directly in design.

If the required fine soil thickness is too large, we can reduce the saturated permeability coefficient of fine-grained soil to meet Equation 6. Therefore, when the calculated H is too big, saturated permeability coefficient required for the fine-grained soil layer is:

$$K_s \le \frac{\left(\theta_f - \theta_0\right) H}{\lambda T_r} \tag{8}$$

where H can be selected according to the convenience of construction, for example 0.5m. The permeability coefficient of simple compacted fine-grained soil is about 10^{-7} m/s. When the requirement of K_s is less than 10^{-7} m/s, soil may need special treatment, such as using higher compaction effort, increasing the content of clay, or adding cement or bentonites.

4 PARAMETER DESIGN OF CAPILLARY BARRIERS IN DIFFERENT RAINFALL AREAS

In this paper, parameters of capillary barriers in four representative cities are calculated using the proposed model. The natural conditions in the four cities are listed in Table 1, including the rainfall, evaporation and other parameters. Only surface evaporation is considered and plant transpiration is not considered.

Table 1. Climate conditions in humid, semi-humid, semi-arid and arid areas.

City	Climate	Average annual rainfall (mm)	Average annual evaporation (mm)	T_r (d)	Distribution of rainfall season
Hang zhou	Humid	1273.9	958.6	100~160	March ~ September
Xi'an	Semi-humid	550	600~700	90	78 % of rainfall in May ~ October
Lan zhou	Semi-arid	314	600~800	70	50 % ~ 70 % of rainfall in June ~ August
Yinchuan	Arid	186.7	1100	40	June ~ August

Based on the local climatic conditions such as rainfall and evaporation, supposing θ_f =40 %, θ_0 =10 %, λ=1.5 and a default K_s of 10^{-7} m/s, the designed parameters of the fine-grained soil layer can be determined by Equations 5 ~ 9, as listed in Table 2. The Yinchuan area belongs to the arid area with large evaporation intensity and relatively small rainfall intensity. The calculation results show that this area has no special requirements for the hydraulic conductivity and thickness of the fine-grained soil layer. Xi'an and Lanzhou belong to semi-humid and semi-arid area respectively. The calculation results show that there are no special requirements for the saturated permeability coefficient of fine-grained soil in the two city, but requirements for fine soil thickness ranges are 0.54 ~ 1.26 m and 0.05 ~ 1.75 m respectively. Hangzhou belongs to humid areas and rainfall intensity and evaporation intensity are relatively large. The calculation demonstrates that only increase the thickness of fine grain soil is not work. The permeability of top fine layer in capillary barrier must be reduced.

Comprehensively considering construction, cost and the designing requirements of top fine layer (seepage control layer), we ultimately determined that the fine soil thickness in four cities of Hangzhou, Xi'an, Lanzhou and Yinchuan were 0.5 m, 0.54 m, 0.15 m and 0.15 m. At the same time, the saturated hydraulic conductivity of fine-grained soil in Hangzhou area should be taken as 6.4E−9 m/s in order to ensure the water stored in the anti-seepage layer being discharged timely and effective through evaporation.

Table 2. Design parameters of fine-grained soil layer in wet, semi-humid, semi-arid and arid areas.

City	Rainfall and evaporation calculation parameters	Evaporative design requirements (Equation 5)	Trial thickness (Equation 8)	Final design thickness (m)	Design requirements of Ks (Equation 9)
Hang zhou	T_{rs}=180 d, η=0.95	≤ 1.60 m	≥ 2.67 m	0.5	6.43×10^{-9} m/s
Xi'an	T_{rs} =150 d, η=0.78	≤ 1.26 m	≥ 0.54 m	0.54	No request
Lan zhou	T_{rs} =90 d, η=0.70	≤ 1.75 m	≥ 0.05 m	0.15	No request
Yin chuan	T_{rs} =90 d, η=0.95	≤ 2.75 m	No request	0.15	No request

*Fine-grained soil should meet the basic design requirements of the capillary barrier when there’s no request, that is, the intake value should be greater than 10 kPa and the saturated permeability coefficient should be less than 10E−6 m/s. Generally compacted silt or clay can meet this condition.

5 CONCLUSIONS

Soil column test is carried out to study the breakthrough time of capillary barrier, with the following findings:

(1) Under the action of continuous rainstorm, with the increase of the thickness of fine soil layer, the moisture migration slows down, the storage capacity of soil column increases, and the breakthrough time of capillary barrier increases.

(2) When the initial water content is lower, the water movement is slower and the water storage capacity is larger.

In dry season, the evaporation should be larger than the amount of water infiltrated into the barrier in raining season. Based on this rule, the design criterion of capillary barrier is proposed and applied to the determination of the design parameters of capillary barriers in arid areas (Yinchuan), semi-arid areas (Lanzhou), semi-humid areas (Xi'an) and humid areas (Hangzhou).

6 ACKNOWLEDGEMENTS

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