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# Factors Affecting the Maximum Leachate Head in the Landfill Drainage Layer under Clogging Conditions

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**Abstract:** Clogging of the landfill drainage layer leads to a high leachate head developing over the bottom liner, which increases the risk of leachate leakage. Estimation of the maximum leachate head in the landfill drainage layer is of great significance to the pollution control of bottom liners. In this study, a simplified model considering the development of clogging is established through assuming the spatial and temporal distributions of clogging in a drainage layer of landfill. The calculation results are compared with a previous study to verify the proposed model. Through parameter analysis, it is discovered that the larger the initial hydraulic conductivity, the less the influence of clogging on the leachate head at the beginning, but it will increase over time. Meanwhile, a longer drainage distance, a larger inflow rate, or a higher ion concentration will lead to a greater influence of clogging on the leachate head. The completion time of clogging is more sensitive to the variation of inflow rate and ion concentration. In order to effectively control the maximum leachate head, it is suggested that the drainage material with large hydraulic conductivity such as pebbles or gravel should be used, the drainage slope should be greater than 4%, the drainage distance should be controlled at 20 m, and calcium products should be removed from leachate through adsorption, precipitation, or waste reuse.

**Keywords:** landfill; leachate drainage layer; maximum leachate head; hydraulic conductivity; clogging



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## 1. Introduction

Municipal solid waste (MSW) is mainly disposed of in landfills worldwide. Degradation of landfilled MSW will produce a large amount of highly polluting leachate. The development of high leachate levels would bring groundwater pollution, reduce landfill gas recovery efficiency, and give rise to landslide disasters [1–4]. Sustainable landfilling, which requires eliminating the potential hazard and risk of leachate to the environment, is a fundamental goal in waste management worldwide. A drainage layer and a liner layer are set at the bottom of the modern landfill to prevent leakage of leachate and the pollution of underground water and soil. The breakthrough time of pollution of the bottom liner is directly affected by the maximum leachate head in the drainage layer. Estimation of the maximum leachate head in the landfill drainage layer is of great significance to the pollution control of bottom liners, which contributes to the sustainable development of the environment and ecology around landfills.

In the regulations of many countries, it is strictly required that the maximum leachate head in the landfill drainage layer should be less than 30 cm [5,6]. Scholars have made a number of studies to calculate the maximum leachate head in a landfill drainage system [7–12]. Among the steady-state calculation methods of the maximum leachate head, the method described by McEnroe [11] was regarded as a relatively accurate method. In the meantime, another method for calculating the maximum liquid depth in layered media as well as composite landfill drainage systems was proposed by Ke et al. [13]. In order to offset the defect of the steady-state model which cannot be used to simulate the varying leachate head over time, nor quantize the efficacy of the leachate collection system, Demetracopoulos et al. [14] established the QSS (quasi-steady state) model based on the model proposed by Wong [15]. In their model, it is assumed that the leachate flows horizontally in the drainage layer and leaks from the bottom of the saturated liner. The TS (transient) model, which can be used to calculate the leachate head, leachate discharge, and leakage at any moment, was proposed by Korfiatis and Demetracopoulos [16] based on water equilibrium equation. The TS model is of relatively accurate simulation but accompanied by complex solution process for the governing equation. On the other hand, the QSS model is of simple calculation process but relatively unsatisfactory simulation results. Another transient method for leachate head calculation in drainage systems was proposed by Ke et al. [17], based on the extended Dupuit assumption, and the results were compared and verified with those of other methods.

Due to the effects of physical, chemical, and biological factors in the running process of the landfill, varying degrees of clogging will occur in the drainage layer. This will lead to the decrease in the hydraulic conductivity of drainage system [18–21]. Therefore, the leachate head of the drainage layer in the landfilling process is often inconsistent with the estimation in the initial design. The leachate head is usually beyond the requirement because of the failure of the leachate drainage system. It is of great significance for the design and operation of landfills to reasonably estimate the maximum leachate head of drainage system under clogging conditions. Through studying the maximum leachate head of drainage layer under clogging conditions and analyzing the influence factors, the quantitative relations between the factors and the maximum leachate head can be determined. After that, reasonable management and operation of landfill can be realized so that the leachate head can be controlled within the required range before the closure of landfill. However, due to the complex clogging mechanism and long duration, it is difficult to build an accurate model. At present, there has been little research regarding the maximum leachate head of drainage layer under clogging conditions.

Based on lots of field excavation and laboratory tests, a numerical "Bioclog" model concerning landfill clogging was proposed by Cooke et al. [22] and Rowe and Yu [23]. Moreover, the changes in leachate head of landfills under 1-D and 2-D situations were simulated under clogging conditions [24–28]. In the Bioclog model, comprehensive factors are considered. However, since many factors are to be determined, it is difficult to accurately obtain all parameters for different projects, and the methods are relatively complex for engineers. Therefore, it has yet to be widely applied in actual engineering.

In this study, a simplified model and method is proposed to calculate the maximum leachate head of landfill under clogging conditions. The method can be used for analyzing the long-time running capability of the leachate drainage system of landfills. In the meantime, it also provides theoretical support for the management and operation of a landfill and the control of leachate head under clogging conditions.

## 2. Methodology

### 2.1. Simplified Model of Clogging

In this study, clogging rate is assumed to be related to deposition volume of clog material. Calcium is adopted to represent other substances (e.g., magnesium, iron, silicon) which can also cause clogging in the drainage layer. If the kinetics factors in the formation of clogging are ignored, it can be assumed that the calcium ions in the leachate precipitate instantaneously. According to the distribution of deposition after clogging (clogging is the most serious near the collection pipe, and linear distribution of clogging is assumed along the length of pipeline), the mass of deposited calcium can be calculated, and then the completion time of clogging can be obtained through dividing the mass of deposited calcium by the mass of calcium ions in the infiltration of leachate per unit time (inflow rate). Change of clogging volume of the drainage layer with distance is shown in Figure 1.

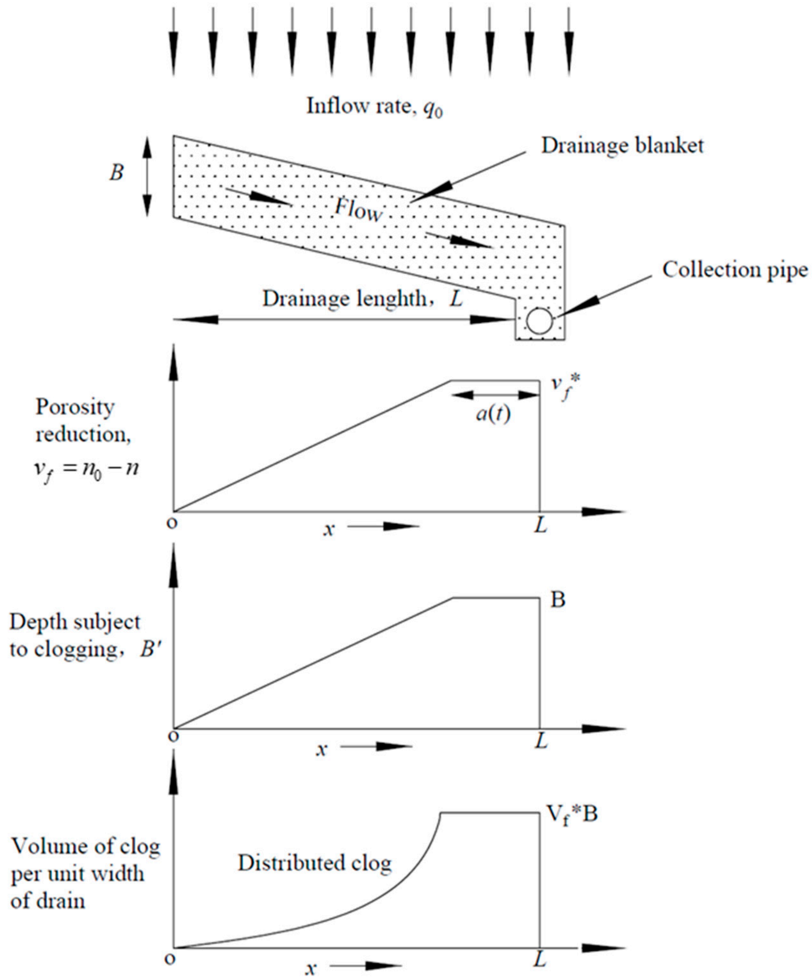


**Figure 1.** Change of clogging volume of drainage layer with distance.

To derive the completion time of maximum clogging volume, the following assumptions are adopted in this study:

(1) Clogging is the most serious near the collection pipe, and clog material is reduced with the increase of distance to the collection pipe. Both porosity reduction $v_f$ and the portion of depth subject to clogging $B'$ change linearly with distance before reaching maxima;

(2) At the nearest position from collection pipe, both porosity reduction $v_{fL}$ and depth subject to clogging $B_L{}'$ increase from zero and reach the maxima at time $t_1$;

(3) Clogging volume reaches the maximum at time $t_2$, in other words, $t_2$ is the completion time of clogging, both porosity reduction $v_f$ and clogged depth $B'$ within the distance to the collection pipe $a(t)$ reach the maxima;

(4) The depth of a drainage layer $B$ and the portion of depth subject to clogging $B'$ are calculated in vertical direction;

(5) Since the leachate contains solid component, its viscosity is set as 1.2 mPa·s according to the measurement, which is higher than that of water at 1.0 mPa·s.

According to the above assumptions, equations of porosity reduction, clogged depth, and hydraulic conductivity of drainage layer within the entire clogging development process are derived in Appendix A, which is the preparation for the derivation of leachate head under clogging conditions.

*2.2. Calculation Model and Governing Equation of Leachate Head under Clogging Conditions*

Figure 2 is a schematic diagram of single-layer drainage system of landfills. $T$ is thickness of drainage layer (measured perpendicular to the bottom surface, $B = T/cos\alpha$), $k_0$ is initial hydraulic conductivity, and $k(x,t)$ is the hydraulic conductivity at distance $x$ and time $t$. $L$ is total horizontal drainage length, and $\alpha$ is slope angle of drainage layer.

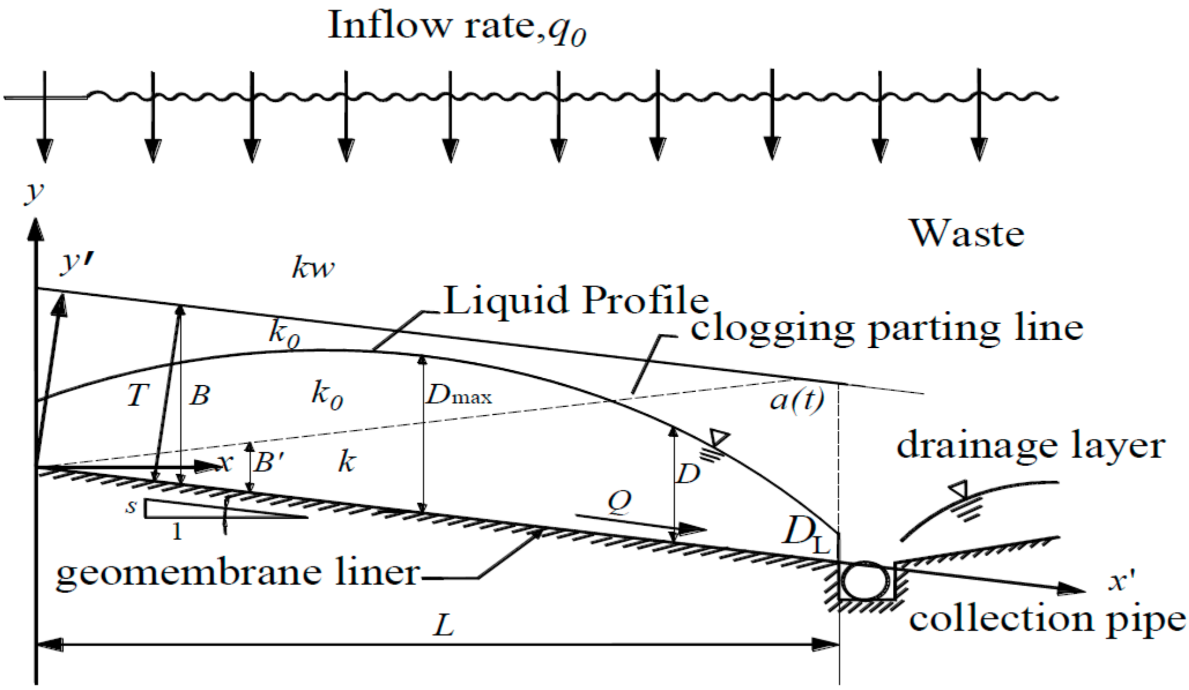


**Figure 2.** Cross-sectional view of leachate drainage system.

In steady-state conditions, the drainage flow rate at any position equals inflow rate of upstream because of the continuity of flow.

$$Q = q_0 \times x \tag{1}$$

where $Q$ is the lateral drainage flow rate through unit width of drainage layer, $q_0$ is vertical inflow rate reaching drainage layer per unit area, and $x$ is horizontal distance to the boundary at upstream.

In a homogeneous medium, formulation of total flow rate on vertical section was proposed by McEnroe [11] as follows:

$$Q \approx -kD\frac{dy}{dx}\cos^2\alpha \tag{2}$$

where $k$ is hydraulic conductivity of the homogeneous medium, $D$ is leachate depth at any position (vertical), and $y$ is vertical distance to the top of slope. The relationship between $D$ and $y$ is as follows:

$$D = y + x\tan\alpha. \tag{3}$$

For a specific slope in layered drainage system, combining Equations (2) and (3), the extended Dupuit formula can be rewritten as the following formula:

$$Q = -\int_0^D k(t)dt\frac{dy}{dx}\cos^2\alpha = -\int_0^D k(t)dt(\frac{dD}{dx} - \tan\beta)\cos^2\alpha. \tag{4}$$

According to the clogging model in Appendix A, the relevant parameters are substituted into Equation (4). See Equation (5) below.

$$Q(x,t) = \cos^2\alpha \begin{cases} -k(x,t)D(x,t)(\frac{\partial D(x,t)}{\partial x} - \tan\alpha) \\ \text{when } D(x,t) < B'(x,t) \\ -[(k(x,t)B'(x,t) + k_0(D(x,t) - B'(x,t))](\frac{\partial D(x,t)}{\partial x} - \tan\alpha) \\ \text{when } B'(x,t) \le D(x,t) \le B \\ -[(k(x,t)B'(x,t) + k_0(B - B'(x,t)) + k_w(D(x,t) - B)](\frac{\partial D(x,t)}{\partial x} - \tan\alpha) \\ \text{when } D(x,t) > B \end{cases} \tag{5}$$

A unit is selected from seepage area for analysis. Based on the above assumptions, change of liquid volume in the unit mainly depends on the vertical leachate recharge from overlying waste, the inflows from upstream section and the outflows to downstream section. Inflows and outflows of the unit during $dt$ are keeping balance, so there is:

$$Q(x,t)dt + q_0dxdt - Q(x+dx,t)dt - q(x,t)dxdt = n_e[D(x,t+dt) - D(x,t)]dx \tag{6}$$

where $n_e$ is effective porosity of drainage layer.

In the process of clogging, $n_e$ is an average value at position $x$, and is changing with time. It can be derived by the following equation:

$$n_e = \frac{1}{D}\int_0^D ndt = \begin{cases} n_0 - v_{fx} \\ \text{when } D(x,t) < B'(x,t) \\ [(n_0 - v_{fx})B'(x,t) + n_0(D - B'(x,t))]/D(x,t) \\ \text{when } B'(x,t) \le D(x,t) \le B \\ [(n_0 - v_{fx})B'(x,t) + n_0(B - B'(x,t)) + n_w(D(x,t) - B)]/D(x,t) \\ \text{when } D(x,t) > B \end{cases}. \tag{7}$$

Governing Equation (6) can be written as:

$$\begin{aligned} &Q(x,t)dt + q_0dxdt - [Q(x,t) + \tfrac{\partial Q(x,t)}{\partial x}dx]dt - q(x,t)dxdt \\ &= n_e\left[D(x,t) + \tfrac{\partial D(x,t)}{\partial t}dt - D(x,t)\right]dx \end{aligned}. \tag{8}$$

Equation (8) can be simplified as:

$$n_e\frac{\partial D(x,t)}{\partial t} = -\frac{\partial Q(x,t)}{\partial x} + q_0 - q(x,t). \tag{9}$$

On the basis of Darcy's law, the leakage rate through underlying liner $q$ can be written as:

$$q = k_l(\frac{D+d}{d}). \tag{10}$$

Substituting Equations (5) and (10) into Equation (9), we have the governing equation of leachate head under clogging conditions.

$$n_e\frac{\partial D(x,t)}{\partial t}=\begin{cases}\cos^2\alpha\left\{\frac{\partial}{\partial x}\left[k(x,t)D(x,t)\left(\frac{\partial D(x,t)}{\partial x}-\tan\alpha\right)\right]\right\}+q_0-k_l\left(\frac{D+d}{d}\right)\\ \text{when } D(x,t)<B'(x,t)\\ \cos^2\alpha\left\{\begin{array}{l}\frac{\partial}{\partial x}\left[\begin{array}{l}(k(x,t)B'(x,t)+k_0(D(x,t)\\ -B'(x,t))\end{array}\right]\\ \left(\frac{\partial D(x,t)}{\partial x}-\tan\alpha\right)\end{array}\right\}+q_0-k_l\left(\frac{D+d}{d}\right)\\ \text{when } B'(x,t)\le D(x,t)\le B\\ \cos^2\alpha\left\{\begin{array}{l}\frac{\partial}{\partial x}\left[\begin{array}{l}(k(x,t)B'(x,t)+k_0(B-B'(x,t))\\ +k_w(D(x,t)-B)\end{array}\right]\\ \left(\frac{\partial D(x,t)}{\partial x}-\tan\alpha\right)\end{array}\right\}+q_0-k_l\left(\frac{D+d}{d}\right)\\ \text{when } D(x,t)>B\end{cases} \quad (11)$$

$$\text{where } k(x,t)=\begin{cases}e^{-b_k\sqrt{\frac{3cq_0v_f^{*}t}{B\rho_c f_{Ca}}}\cdot\frac{x}{L}}\times k_0\\ \text{when } 0<t\le t_1\\ e^{-b_k v_f^{*}\cdot\frac{x}{L-a(t)}}\times k_0\\ \text{when } t_1<t\le t_2,\ x<L-a(t)\\ e^{-b_k v_f^{*}}\times k_0\\ \text{when } t_1<t\le t_2, L-a(t)\le x\le L\end{cases},\ a(t)=\frac{3cq_0Lt}{2Bv_f^{*}\rho_c f_{Ca}}-\frac{L}{2}.$$

The clogging of the collection pipe is equivalent to the clogging of the drainage material. In this way, the collecting pipe can be set as the drainage boundary to solve the leachate head. The flow rate on the left boundary of the model is set to zero on the basis of symmetry principle. According to the results of Harr [29], hydraulic gradient at the outlet of downstream is about −1. Such assumption was also adopted by McEnroe [11,30], and the boundary effects under free-draining conditions were summarized and discussed by Giroud et al. [31].

Boundary conditions of the model calculating free surface of landfill saturation line are simplified as follows:

(1) Flow rate on the left boundary of model is 0:

$$Q(0,t)=0; \quad (12)$$

(2) Hydraulic gradient on the right boundary of model is −1:

$$\frac{dy}{dx}=\frac{d(D-x\tan\alpha)}{dx}=\frac{dD}{dx}-\tan\alpha=-1. \quad (13)$$

Initial condition of the model: as the initial leachate head in the drainage layer is zero, the initial condition is expressed as

$$D(x,0)=0. \quad (14)$$

## 3. Analysis and Verification of Method

The pdepe function of MATLAB software is used to solve the above model. Based on the actual situation of landfill, parameters in Case 1 are set as follows: thickness of drainage layer under waste $T$ = 30 cm, maximum drainage distance $L$ = 50 m, slope $S$ = 2%; initial hydraulic conductivity of drainage layer $k_0$ = 0.01 cm/s, initial porosity of drainage layer $n_0$ = 0.35, hydraulic conductivity of waste $k_w$ = 5 × $10^{-4}$ cm/s, porosity of waste $n_w$ = 0.2; percentage of calcium in total clog material $f_{Ca}$ = 20%; dry density of clog material $\rho_c$ = 1.8 × $10^3$ kg/m$^3$; inflow rate $q_0$ = 0.375 m/a; concentration of calcium in leachate $c$ = 1500 mg/L; referring the results of Cooke [32], the maximum porosity reduction of drainage layer $v_f$* = 0.24; coefficient in relationship between hydraulic conductivity and porosity $b_k$ = 38.2.

### 3.1. Analysis of Clogging Process

Substituting the above parameters into the model, it can be derived that $t_1$ = 5608 d = 15.36 a, $t_2$ = 16,824, and d = 46.08 a. Within the entire drainage length, clogging is severe at the place close to the pipe, while the clogged depth is 0 at the place far from the pipe ($x = 0$); that is, there is no clogging on the left boundary. The portion of depth subject to clogging in the drainage layer reduced linearly with the increase of distance. As shown in Figure 3, in the process of clogging, the hydraulic conductivity of the drainage layer at the position of the pipe decreases rapidly in the early stage and reaches $1.04 \times 10^{-6}$ cm/s after 5608 days (15.36 years, $t_1$)when the clogging achieves the most serious condition and remains stable.

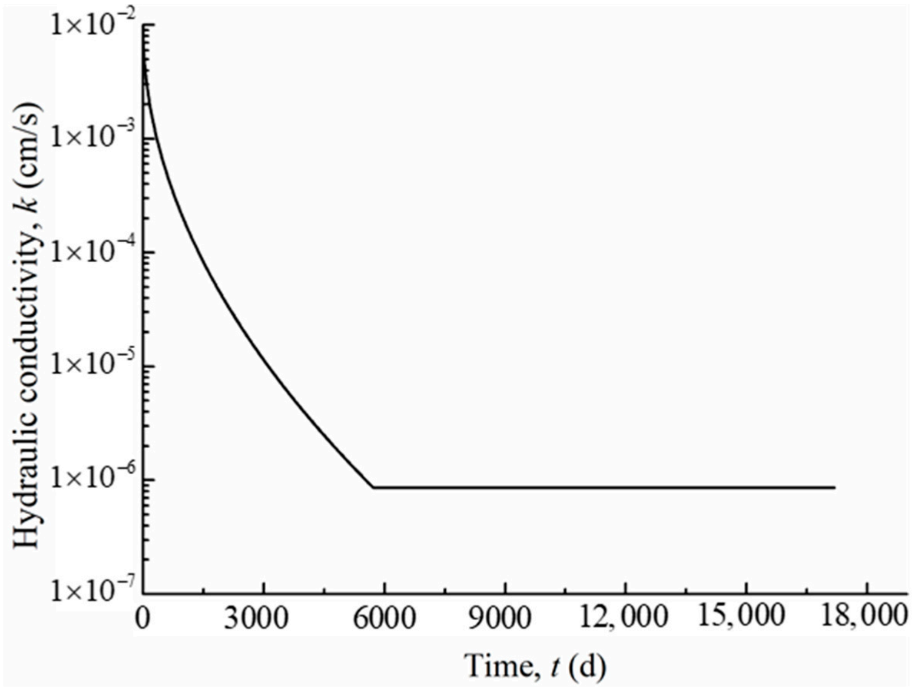


**Figure 3.** Change of hydraulic conductivity at the pipe with time.

### 3.2. Comparison with Steady-State Method and Transient-State Method

To verify the reliability of the method presented in this paper, the results of Case 1 calculated with both the proposed method and the steady-state method are compared. Figure 4 shows the complete variations of maximum leachate heads in Case 1 with time under clogging and non-clogging conditions. As can be seen from the figure, for non-clogging conditions where the hydraulic conductivity remains unchanged, the leachate head calculated with the steady-state method is only 21.24 cm; for complete clogging conditions where the clogged distance $a(t) = L$, the drainage layer is completely clogged, and the hydraulic conductivity is quite low ($1.04 \times 10^{-6}$ cm/s). The leachate head calculated with the steady-state method under complete clogging conditions is 213.46 cm. The leachate head calculated with the proposed method rises with time under clogging conditions; it increases rapidly to 21 cm in the first 100 days, and then increases steadily until about the 5608th day ($t_1$, 15.36 a) when there appears to be a turning point. After that, the leachate head rises continually until about the 16,824th day ($t_2$, 46.08 a) when the drainage layer is completely clogged, and the final leachate head remains stable at 213.4 cm.

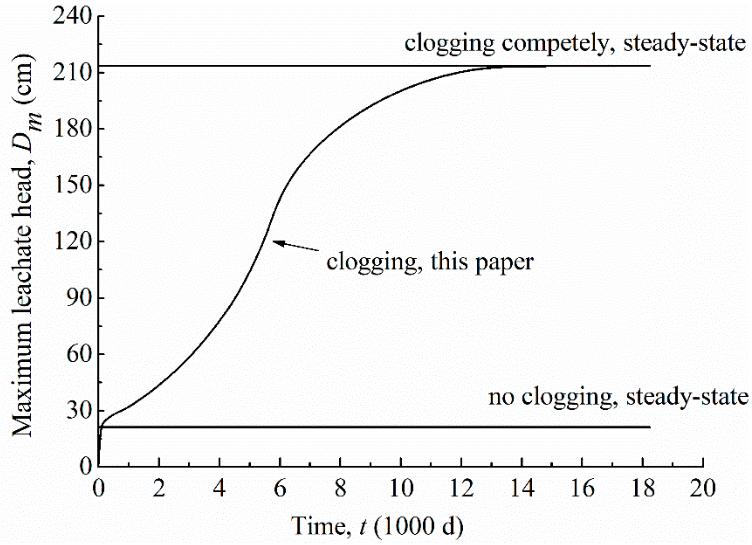


**Figure 4.** Increment procedure of the maximum leachate head.

Figure 5 presents the variation tendency of the leachate head at different distances. In the figure, the phreatic surface of the proposed method agrees well with that of the steady-state method under complete clogging conditions ($t_2$, 46.08 a), which proves the reliability of the method proposed in this paper. In addition, the proposed method can be regressed to the transient case under non-clogging conditions if the ion concentration is set to a small value (e.g., $c = 1 \times 10^{-10}$ mg/L).

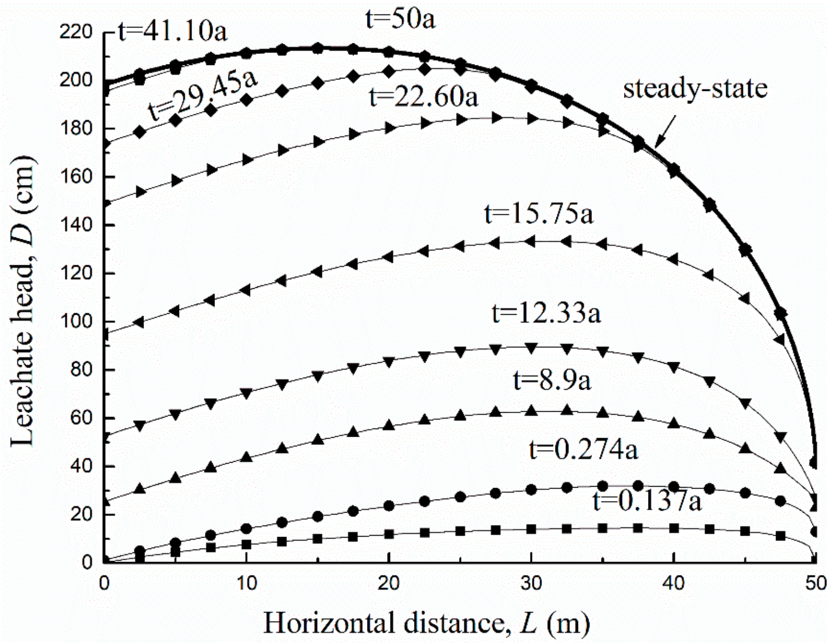


**Figure 5.** Increment procedure of the leachate head at different distances.

As can be seen from the above analysis, if clogging of landfill is not considered previously in the design, the maximum leachate head calculated by the conventional transient-state or steady-state method (21.24 cm) can also meet the requirements of relevant standards. In reality, due to clogging, the leachate head will exceed 30 cm after about two years and finally reach 213 cm, which will pose a serious threat to the environment. Therefore, clogging of the drainage layer must be considered in the design in order to accomodate the realistic situation.

### 3.3. Comparison with Cooke's Results

A Bioclog model was proposed by Cooke [32]. It is an active biochemical transport model considering biological growth, chemical precipitation, and the attachment and detachment of organic and inorganic particles. After establishing a finite element model with variable triangular meshes, the depth of leachate flow can be calculated through iteration method. Since the Bioclog model can simulate the whole process of clogging, Cooke's results are compared with the result of this paper. Three sets of simulation cases were designed by Cooke, and the basic parameters are shown in Table 1. The values of other relevant parameters are listed in Cooke [32].

**Table 1.** Basic parameters in Cooke's test.

| Cases | $k_0$ (cm/s) | $n_0$ | $v_f{}^*$ |
|---|---|---|---|
| Case 2 | 0.1 | 0.37 | 0.3 |
| Case 3 | 0.01 | 0.35 | 0.24 |
| Case 4 | 0.001 | 0.33 | 0.18 |

Figure 6 presents the comparison between the results of this paper and Cooke's results. In both Cooke's method and the proposed method in this paper, the smaller the initial hydraulic conductivity of the drainage layer, the faster the leachate head rises. In the first 100 days or so, there are good agreements between the results of the two methods in the three cases. In Case 2, the results of the two methods are always very close; the leachate depths after two years are 5.99 cm (Cooke), 5.71 cm (this paper), respectively. In Case 3 and Case 4, with the increase of time, the results of this paper are slightly less than Cooke's results. In Case 3, the results after two years are 15.93 cm (Cooke) and 13.40 cm (this paper), respectively. In Case 4, the results after one year are 39.66 cm (Cooke) and 36.28 cm (this paper), respectively. Dash lines in the figure are the leachate heads under non-clogging conditions. Relatively comprehensive factors are taken into account in the model proposed by Cooke [32]; however, the valuing of parameters in different landfills lacks sufficient reference, and calculation is also a bit complicated. The model in this paper is relatively simple and is more conveniently applied in practical engineering. Since factors in reality are more complicated than those in the two models and are hard to accurately predict, the authors tend to think that the differences between the two methods can be accepted.

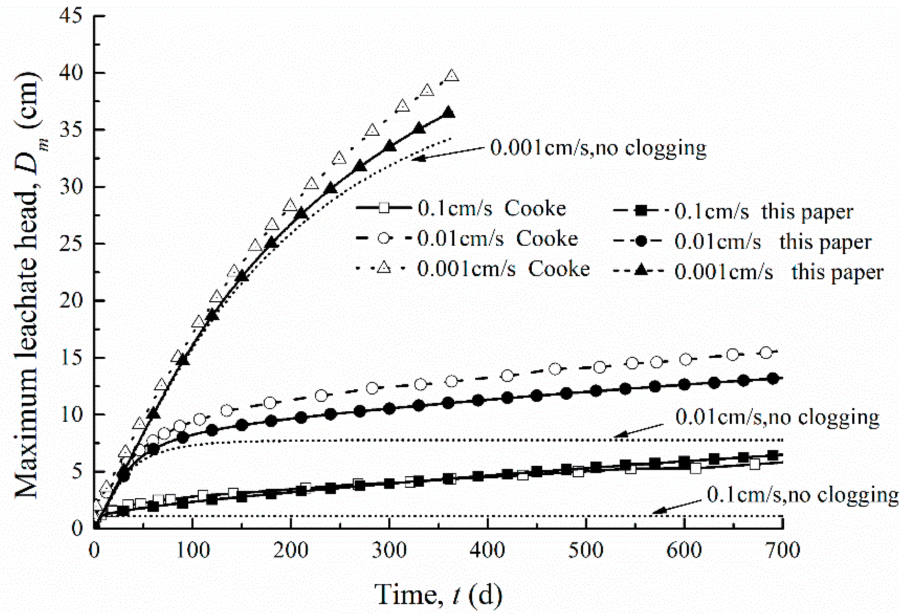


**Figure 6.** Comparison of the maximum leachate head in this paper and Cooke [22] in two years.

Although the calculated results of the proposed model in this paper agree well with Cooke's model, the verification is still insufficient as it is difficult to find suitable experimental data for comparison, especially field data. It is suggested to install leachate-monitoring pipes in the drainage layer to obtain the variation of the leachate head with landfilling process. The verification with the measured data is helpful to further improve the proposed model, thus providing theoretical support for the design of the drainage layer.

## 4. Parameters Analysis

The influences of the initial hydraulic conductivity of drainage layer $k_0$, slope of drainage layer $S$, horizontal drainage distance $L$, inflow rate $q_0$, and leachate concentration $c$ ($Ca^{2+}$ usually) on the maximum leachate head are studied in this section. Basic parameters of the following examples are the same as those in Case 1. To reflect the issues better, the maximum leachate heads under non-clogging conditions are also given in each figure.

Figure 7 shows the increment procedures of the maximum leachate heads with different initial hydraulic conductivities. In Figure 7, the maximum leachate heads under clogging and non-clogging conditions vary widely. The leachate head under non-clogging conditions reaches steady state quickly. If the initial hydraulic conductivity $k_0$ = 0.1, 0.01, 0.001 cm/s, the hydraulic conductivity after completely clogging decreases to $1.05 \times 10^{-6}$, $1.04 \times 10^{-6}$, and $1.03 \times 10^{-6}$ cm/s, respectively. Therefore, under clogging conditions, leachate heads of drainage layers with different initial hydraulic conductivities ultimately tend to be steady and the values are almost on the same level, which is also in line with the field situation (VanGulck [33], Qian et al. [34]). Completion time $t_2$ varies according to different initial hydraulic conductivity $k_0$. The smaller the $k_0$, the smaller the $t_2$; that is, the more easily the drainage layer will be clogged completely. At the beginning, the smaller the initial hydraulic conductivity, the faster the leachate head rises. After $t_1$, the larger the initial hydraulic conductivity, the faster the leachate head rises. It is suggested that the influence of clogging on the leachate head of the drainage layer with a large hydraulic conductivity is small in the early stage but will become greater as time passes, and vice versa. Thus, using gravels with large initial hydraulic conductivity in the drainage layer will lead to a significant effect in delaying the completion time of clogging, as well as controlling the maximum leachate head in the early stage of clogging.

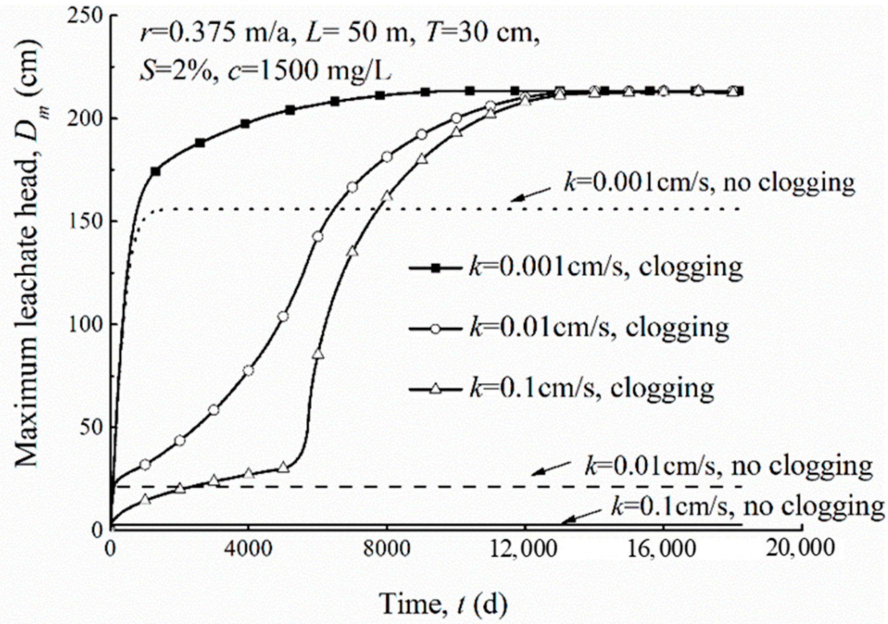


**Figure 7.** Increment procedure of the maximum leachate head with different initial hydraulic conductivity.

Figure 8 shows the increment procedures of the maximum leachate heads with different slopes. At the beginning, the leachate heads of clogging and non-clogging are almost the same and rise fast, and then the results of non-clogging tend to be steady, while those under clogging conditions increase continually and finally achieve stability (the stable values vary with slopes). Under clogging conditions, the smaller the slope, the larger the maximum leachate head, but the clogging completion times are close to each other. Appropriate increase of slope in the designing of landfills will effectively lower the maximum leachate head under clogging conditions.

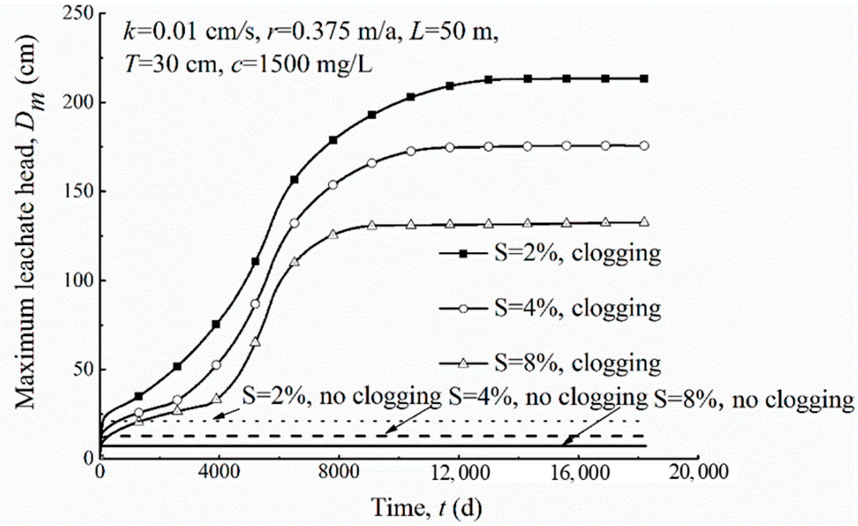


**Figure 8.** Increment procedure of the maximum leachate head with different slopes.

Figure 9 shows the increment procedures of the maximum leachate heads with different drainage distances. Under clogging conditions, the longer the drainage distance, the higher the leachate head in the developing process as well as in steady-state clogging. The stable values vary obviously with different drainage distances, and the difference between each other is larger than that of non-clogging cases. The clogging completion times of different drainage distance are close to each other. To maintain a low leachate head, the drainage distance should be controlled at 20 m.

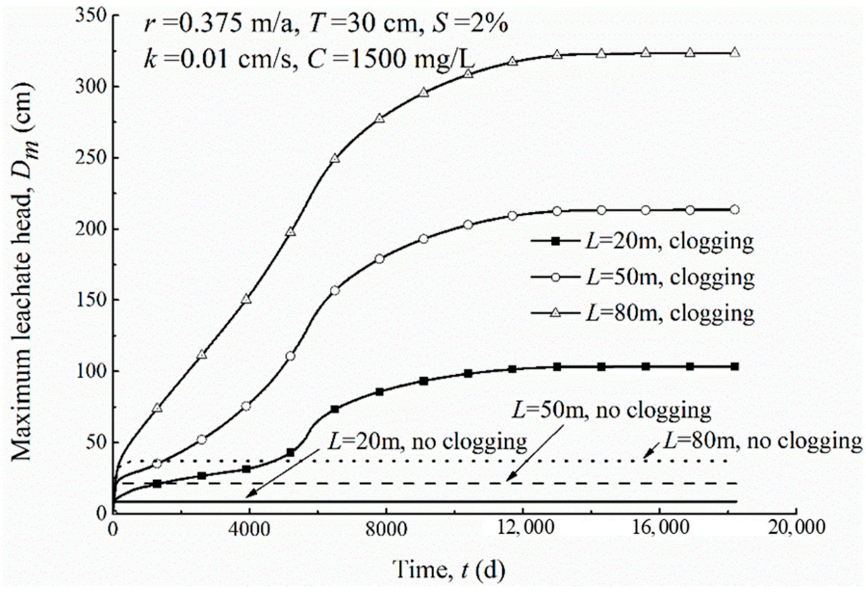


**Figure 9.** Increment procedure of the maximum leachate head with different drainage distances.

Figure 10 shows the increment procedures of the maximum leachate heads with different inflow rates. The larger the inflow rate, the higher the leachate head in the developing process as well as the steady state of clogging. The completion time of steady maximum leachate head varies widely with the different inflow rates. The larger the inflow rate is, the faster the leachate head rises. As the inflow rate will decrease obviously after the closure of landfill, and the impact of clogging will also be diminished, and the leachate head at this moment mainly depends on the inflow before closure. Therefore, timely covering of the geomembrane during landfilling will effectively reduce vertical inflow and diminish the influence of clogging on the leachate head.

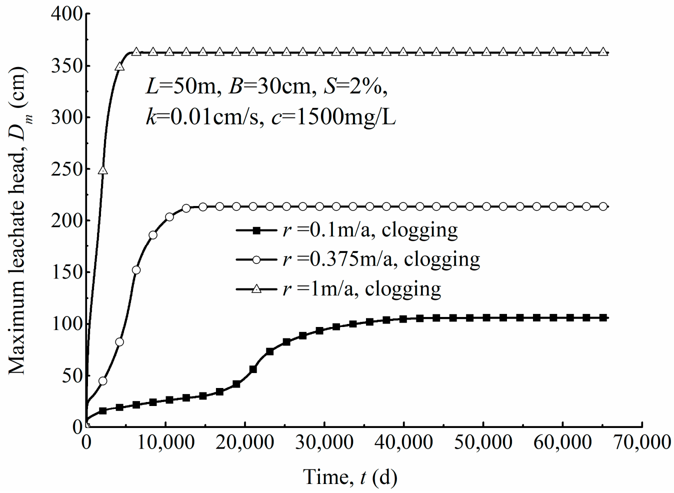


**Figure 10.** Increment procedure of the maximum leachate head with different inflow rates.

Figure 11 shows the increment procedures of the maximum leachate heads with different calcium concentrations. It is clearly seen that leachate heads under different conditions increase similarly at the start. After 100 days, the non-clogging leachate heads become steady, and the maximum leachate heads under clogging conditions rise continuously with different velocities; however, all tend, ultimately, to be 213.40 cm. The higher the ion concentration, the faster the leachate head rises. At many landfills in developing countries, there is relatively high organic content, which will lead to generally higher calcium concentration. The clogging influence caused by ion concentration should be paid more attention. If waste is recycled, reused, and recovered, the calcium concentration in the leachate will decrease, which helps to slow down the clogging process.

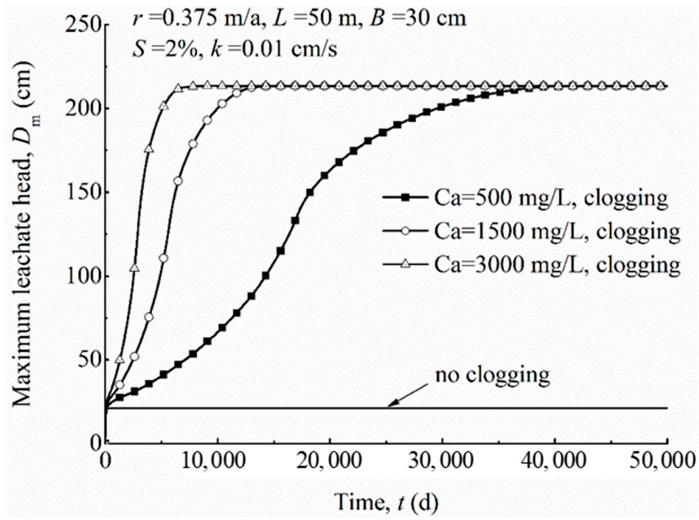


**Figure 11.** Increment procedure of the maximum leachate head with different calcium concentrations.

Since the proposed model is solved by MATLAB software, it may be difficult for landfill engineers to use this model. In the future, the model needs to be redeveloped into easy-to-use software or many reference diagrams should be provided for landfill engineers to use.

## 5. Conclusions

In this study, a simplified model considering the development of clogging is established through assuming the spatial and temporal distributions of clogging in a drainage layer of landfill. The governing equation and the calculation method of the maximum leachate head under clogging conditions are obtained through water equilibrium analysis. The main conclusions drawn from this study are as follows:

(1) The steady leachate head obtained through the method of this paper has a good agreement with the result of steady-state method under both clogging and non-clogging conditions. The greater the initial hydraulic conductivity of drainage layer, the smaller the influence of clogging on the leachate head in the early stage, and it will become greater over time. A longer drainage distance as well as a larger inflow rate or a higher ion concentration will lead to a greater influence of clogging on the leachate head. However, the variation of the slope exerts only a little influence on clogging. Among these factors, the completion time of clogging is more sensitive to the effect of inflow rate and ion concentration, which should be paid more attention;
(2) In order to effectively control the maximum leachate head in landfill under clogging conditions, it is suggested that material with large hydraulic conductivity such as pebbles or gravel should be considered, and the drainage distance should be controlled at 20 m in the design of landfill. The waste should be classified before being buried, and the buried waste should be covered in a timely manner to reduce vertical inflow;
(3) The method proposed in this paper lays a foundation for further study of the variation of the leachate head of the drainage layer under clogging conditions in landfills. It needs be noted that the parameters adopted in this paper are mainly based on the test results of Rowe, Cooke, and Qian et al., and the suitability of values should be considered when applied to other landfills. Meanwhile, with a deepening understanding of the clogging mechanism, the model in this paper can be further modified so as to simulate the real situation of landfill more successfully.

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## Appendix A

The relationship between hydraulic conductivity of drainage layer and porosity of material was proposed by researchers such as Rowe et al. [35], VanGulck [33], and Cooke [32]. It is expressed as follows:

$$k = A_k e^{b_k n} \tag{A1}$$

where $k$ is hydraulic conductivity of material, and $n$ is actual porosity; $A_k$ and $b_k$ are fitting coefficients which vary with particle diameter.

Assuming the initial hydraulic conductivity of drainage layer is $k_0$ and the initial porosity is $n_0$, the hydraulic conductivity at any moment can be expressed as follows:

$$k = \frac{A_k e^{b_k n}}{A_k e^{b_k n_0}} \times k_0 = e^{b_k(n-n_0)} \times k_0 = e^{-b_k v_f} \times k_0 \tag{A2}$$

where $v_f$ is porosity reduction, and $v_f = n_0 - n$.

According to the assumptions in Section 2.1, reduction of pore volume within the whole drainage distance is:

$$V_{tot} = \int_0^L v_f(x) B'(x) dx \tag{A3}$$

where $v_f(x) = v_{fL}(t)x/L$, $B'(x) = B'_L(t)x/L$, $v_{fL}(t)$ is porosity reduction at the position of collection pipe at time $t$, and $B'_L(t)$ is the portion of depth subject to clogging at the position of collection pipe at time $t$.

Equation (A3) is further expressed as:

$$V_{tot}(t) = \frac{v_{fL}(t) B'_L(t) L}{3}. \tag{A4}$$

According to the assumptions, there is relationship between porosity reduction $v_f$ and clogged depth $B'$ as follows:

$$\frac{v_f}{B'} = \frac{v_f^*}{B}. \tag{A5}$$

Substituting Equation (A5) into Equation (A4), there is:

$$V_{tot}(t) = \frac{v_{fL}^2(t) BL}{3 v_f^*}. \tag{A6}$$

The total volume of clog material produced within drainage distance $x$ at any time is as following:

$$V(t) = \int_0^t \frac{c_L(t) q_0 x}{\rho_c f_{Ca}} d\tau \tag{A7}$$

where $V(t)$ is total volume of clog material, $c_L(t)$ is concentration of calcium in leachate at time $t$, $q_0$ is vertical leachate inflow rate per unit area, $\rho_c$ is dry density of clog material, usually ranging from 1.6 to 2.0 $mg/m^3$, and $f_{Ca}$ is percentage of calcium in total clog material, usually ranging from 20 to 30%.

Thus, for the situation where the concentration of calcium in leachate always equals $c$, the porosity reduction at the position of collection pipe ($L = 0$) at any time $t$ can be derived from Equations (A4) and (A7):

$$v_{fL}(t) = \sqrt{\frac{3 c q_0 v_f^* t}{B \rho_c f_{Ca}}}. \tag{A8}$$

Substituting Equation (A8) into Equation (A5), porosity reduction and clogged depth at any time and position can be derived as follows:

When $0 < t < t_1$,

$$v_f(x) = \sqrt{\frac{3 c q_0 v_f^* t}{B \rho_c f_{Ca}}} \frac{x}{L}; \tag{A9}$$

$$B'(x) = \frac{B v_{fL}}{v_f^*} \frac{x}{L} = \sqrt{\frac{3 c q_0 B t}{\rho_c f_{Ca} v_f^*}} \frac{x}{L}. \tag{A10}$$

Similarly, when $t_1 < t < t_2$, there is:

$$v_f(x) = \begin{cases} v_f^* x/[L - a(t)] & x < L - a(t) \\ v_f^* & L - a(t) < x < L \end{cases}; \tag{A11}$$

$$B'(x) = \begin{cases} Bx/[L - a(t)] & x < L - a(t) \\ B & L - a(t) < x < L \end{cases}. \tag{A12}$$

Substituting Equations (A11) and (A12) into Equation (A3), there is:

$$V_{tot}(t) = \frac{v_f^* BL/[1 + 2a(t)/L]}{3}. \tag{A13}$$

For the situation where the concentration of calcium in leachate always equals $c$, expression of $a(t)$ when $t_1 < t < t_2$ can be derived from Equations (A7) and (A13):

$$a(t) = \frac{3cq_0Lt}{2Bv_f^*\rho_c f_{Ca}} - \frac{L}{2}. \tag{A14}$$

Substituting Equation (A14) into Equations (A11) and (A12), porosity reduction and clogged depth at any position along drainage layer and any time when $t_1 < t < t_2$ can be derived as follows:

$$v_f(x) = \begin{cases} v_f^* x/[\frac{3L}{2} - \frac{3cq_0Lt}{2Bv_f^*\rho_c f_{Ca}}] & \text{for } x < L - a(t) \\ v_f^* & \text{for } L - a(t) < x < L \end{cases}; \tag{A15}$$

$$B'(x) = \begin{cases} Bx/[\frac{3L}{2} - \frac{3cq_0Lt}{2Bv_f^*\rho_c f_{Ca}}] & \text{for } x < L - a(t) \\ B & \text{for } L - a(t) < x < L \end{cases}. \tag{A16}$$

Hydraulic conductivity of drainage layer at time $t$ can be derived from Equations (A2), (A9) and (A15).

When $0 < t < t_1$:

$$k(x,t) = \begin{cases} e^{-b_k v_f^* \cdot \frac{x}{L-a(t)}} \times k_0 & x < L - a(t) \\ e^{-b_k v_f^*} \times k_0 & L - a(t) \le x \le L \end{cases}. \tag{A17}$$

When $t_1 < t < t_2$:

$$k(x,t) = \begin{cases} e^{-b_k v_f^* \cdot \frac{x}{L-a(t)}} \times k_0 & x < L - a(t) \\ e^{-b_k v_f^*} \times k_0 & L - a(t) \le x \le L \end{cases}. \tag{A18}$$

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