Clogging of leachate collection systems with coarse sand for different slopes and infiltration rates

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ABSTRACT
A numerical model has been developed to examine different leachate collection system designs. The model predicts the fate and transport of key constituents in leachate and simulates the mass accumulation in the porous media by the growth of biomass, sedimentation of suspended particles, and precipitation of minerals. The accumulated clog mass decreases the hydraulic conductivity of porous media and causes the leachate to build up within the leachate collection system. This paper examines the effect of different drainage layer slopes and infiltration rates on the rate of clogging and service life of leachate collection systems with a coarse uniform sand drainage layer. The numerical results show that an increase in the slope of drainage layer extends the service life of leachate collection system while an increase in infiltration rate accelerates the leachate mounding within leachate collection system if the mass loading is correspondingly increased.

RÉSUMÉ
Un modèle numérique a été développé avec succès dans le but d'examiner différentes conceptions de systèmes drainants de lixiviats. Le modèle prédit le devenir et le transport des constituants clés dans le lixiviat et simule l'accumulation de masse dans le milieu poreux par la croissance de la biomasse, la sédimentation de particules en suspension et la précipitation des minéraux. L'accumulation de la masse colmatée diminue la conductivité hydraulique du milieu poreux et induit l'augmentation de la charge hydraulique du lixiviat dans la couche drainante. Cet article examine l'effet de différentes pentes du drainage et du taux d'infiltration sur le taux de colmatage et la durée de vie des systèmes drainants comportant une couche drainante constituée de sable grossier. Les résultats du modèle numérique montrent qu'une augmentation de la pente de la couche drainante prolonge la durée de vie des systèmes drainants tandis qu'une augmentation du taux d'infiltration accélère l'augmentation de la charge hydraulique du lixiviat si la charge en masse est augmentée en conséquence.

1 INTRODUCTION

Leachate generated within municipal solid waste landfills, by the percolation of rainwater through the waste and by biodegradation of the waste, contains both dissolved and suspended contaminants which may have potential impacts on the surrounding environment and human health (Rowe et al. 2004). Modern landfills typically have a leachate system intended to limit the escape of contaminants to groundwater and surface water to negligible levels (Rowe 2005). The base barrier system is typically comprised of (Figure 1): (a) a leachate collection system, and (b) a liner system. The leachate collection system is critical for a well designed landfill since it controls the leachate head (and hence the driving force for leakage) acting on the liner. Generally the initial hydraulic conductivity of a coarse sand drainage layer (1×10^{-3} m/s) is sufficient to transmit leachate to the perforated collection pipes and to control the initial leachate head to less than the thickness of the drainage layer (0.3-0.5 m depending on the requirement of local regulation, Rowe et al. 2004), when the infiltration rate is 0.2 m/year.

However clogging of porous media when permeated with landfill leachate has been reported in both field exhumations (Bass 1986; Brune et al. 1991; Koerner et al. 1993, 1994; McBean et al. 1993; Rowe 1998; Fleming et al. 1999; Craven et al. 1999; Maliva et al. 2000; Bouchez et al. 2003; Levine et al. 2005) and laboratory studies (Brune et al. 1991; Rowe et al. 2000a, 2000b, 2002; Fleming and Rowe 2004, VanGulck and Rowe 2004a, 2004b; McIsaac and Rowe 2006, 2007). The growth of biomass, deposition of suspended solids, and precipitation of minerals within the porous media reduced the void spaces and therefore the hydraulic conductivity of the porous media. Leachate mounding within the landfill caused by the clogging of granular material increases the driving force for contaminant transport through the bottom liner. The service life of the drainage layer is often taken to be the time when the drainage layer can not longer control the head to the design value (typically to within the thickness of the granular drainage layer). However to estimate this service life it is necessary to be able to model the effect of clogging of the granular drainage layer on the leachate mounding within the leachate collection system.

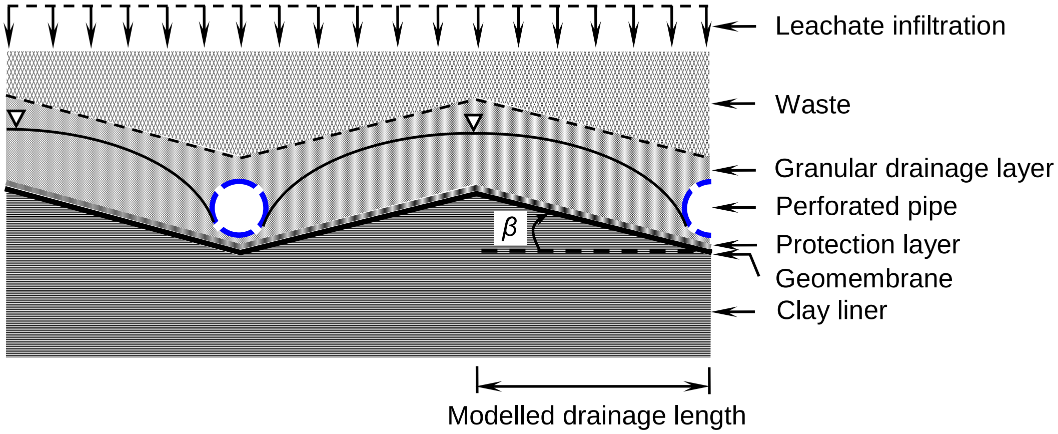

Figure 1. Profile of a landfill barrier system with a leachate collection system and a bottom liner system.

The BioClog model has been developed to study the clogging of granular material permeated with landfill leachate, taking account of biological, physical, and chemical clogging mechanisms. The BioClog-1D model was developed by Cooke et al. (2005a) and was subsequently extended to 2D by Cooke and Rowe (2008a). Cooke et al. (2005b) used BioClog-1D to examine laboratory column tests and they found that the clog mass accumulated within the porous media along the columns was well predicted when compared with measured values. The prediction of concentrations of volatile fatty acids and calcium in the effluent of columns agreed well with the measured data. Cooke and Rowe (2008b) modelled 2D-laboratory mesocosms with the BioClog-2D and found that the clog mass in the upper regions of saturated gravel was well estimated when compared with the measured values while the model underestimated the accumulation of clog mass in the lower regions. Recent enhancements of BioClog-2D by the writers have addressed the shortcoming of the original model and have extended the models ability to examine more general design scenarios for leachate collection systems.

The objective of this paper is to use the enhanced BioClog-2D model to investigate the effect of the slope of drainage layer bottom and infiltration rate on the clogging of granular drainage layers. The service life of leachate collection systems with a coarse uniform sand drainage layer will be compared for different slopes and infiltration rates. The distribution of porosity within the saturated granular drainage layer will be shown, as well as the distribution of hydraulic conductivity.

2 MODEL SUMMARY

The fate and transport of nine species in leachate were modelled. The biodegradation of three volatile fatty acids was considered since they contribute most of chemical oxygen demand (COD) in leachate and provide the primary nutrients for bacterial growth within a typical municipal solid waste leachate collection system. The model also considers the fate of suspended organic biomass (suspended acetate, butyrate, and propionate degraders, and suspend inert biomass) and suspended inorganic solids in leachate. Finally, the model considers the biologically induced precipitation of calcium carbonate.

The clog mass within the porous media was quantified in terms of the thicknesses of five films on the surface of porous media (acetate, butyrate, and propionate degraders film, inert biofilm, and inorganic solids film). The active biofilm (i.e., the acetate, butyrate, and propionate degraders film) increases in mass due to the growth of active biofilm and deposition of suspended active biomass, and decreases in mass due to decay and detachment of the biofilm. The inert biofilm increases in mass due to the deposition of suspended inert biomass and from the accumulation of a portion of decayed active biofilm. The mass loss of inert biofilm was due to the detachment. The mass of the inorganic solid film was increased by the deposition of suspended inorganic solid particles and precipitation of calcium carbonate and other minerals.

As the total thickness of films on the surface of porous media increased due to the accumulation of clog mass, the porosity of porous media decreased and therefore so too did the hydraulic conductivity. The reduction in hydraulic conductivity reduced the capacity of the granular material to transmit the leachate into the perforated drainage pipes and caused the leachate head to build up within the drainage layer. Failure of leachate collection systems was deemed to have occurred when the maximum leachate head, under average infiltration conditions, exceeded the thickness of granular drainage layer.

3 PROBLEM DEFINITION

The leachate collection systems examined in this paper were assumed to have a 0.3 m thick coarse sand drainage layer. The coarse sand was assumed to have a uniform 2 mm diameter particle size, an initial porosity of 0.37 and an initial hydraulic conductivity of 1×10^{-3} m/s. Two different drainage lengths were considered: 20 m and 30 m (corresponding to a pipe spacing of 40 m and 60 m, respectively for a layout as shown schematically in Figure 1). For each drainage length and an infiltration rate of 0.2 m/year, drainage layers with a bottom slope, β (Figure 1) ranging from 0 to 3 % were examined. Also examined were leachate collection systems subjected to infiltration rates ranging from 0.15 to 0.4 m/year for a drainage layer bottom slope of 1 %. The source concentrations of key constituents in leachate that were considered are listed in Table 1. The total COD in leachate was 22000 mg/L and the initial calcium concentration entering the collection system was 1500 mg/L. The concentration of volatile suspended solids (VSS) was 1000 mg/L within which the concentration of suspended active biomass was 700 mg/L and the concentration of suspended inert biomass was 300 mg/L. The fixed (inorganic) suspended solids (FSS) were modelled with an initial concentration of 1000 mg/L.

Table 1. Source concentrations of key constituents in leachate (based on Cooke and Rowe 2008a).

Key components	Concentration
Acetate, Ac (mg/L)	10,000
Butyrate, Bu (mg /L)	2,000
Propionate, Pr (mg /L)	10,000
Calcium, Ca (mg /L)	1,500
Volatile suspended solids, VSS (mg /L)	1,000
Fixed suspended solids, FSS (mg /L)	1,000
VSS % active	70
VSS ratio Pr:Ac:Bu	1:1:1

4 RESULTS AND DISCUSSIONS

4.1 Service Life of LCSs with Different Slopes

The calculated service life of LCSs having drainage layers with different bottom slopes (for an infiltration rate of 0.2 m/year) is shown in Figure 2. For the LCSs with the 20-m drainage length, the service life was about 20 years when the slope of drainage layer bottom was equal to zero, while it was increased to about 30 years when the 1% slope was considered. The calculated service life of LCS was about 38 years for the granular drainage layer graded at 3 % to the perforated drainage pipes. For the LCSs with the 30-m coarse sand drainage layer, the service life was about 13 years when there was no bottom slope and increased to about 25 years when the bottom slope was 1 %. For a 3 % slope, the service life of LCS was about 37 years. Thus the model indicated that, for the conditions examined, increasing the slope of the base of a uniform coarse sand drainage layer from 0 to 3 % increased the service life of the LCS by up to almost a factor of three.

4.2 Service Life of LCSs with Different Infiltration Rates

Figure 3 shows the calculated service life of LCSs with a uniform coarse (2mm) sand drainage layer having a 1 % base slope and for infiltration rates ranging from 0.15 to 0.4 m/year (assuming the same input concentrations-Table 1). For a 20-m drainage length, the service life of LCS was over 40 years for an infiltration rate of 0.15 m/year. This decreased to about 30 years when the infiltration rate was increased to 0.2 m/year. At an infiltration rate of 0.4 m/year, the service life of LCS was reduced to about 10 years. With the 30-m granular drainage length, the service life of LCS was just under 40 years when the infiltration rate was 0.15 m/year. The service life decreased to about 25 years when the infiltration rate was 0.2 m/year. For the infiltration rate of 0.4 m/year, the service life of LCS was less than 10 years. Thus, other things being equal, the increased mass loading associated with a higher infiltration rate resulted in a substantial decrease in the service life of LCSs examined.

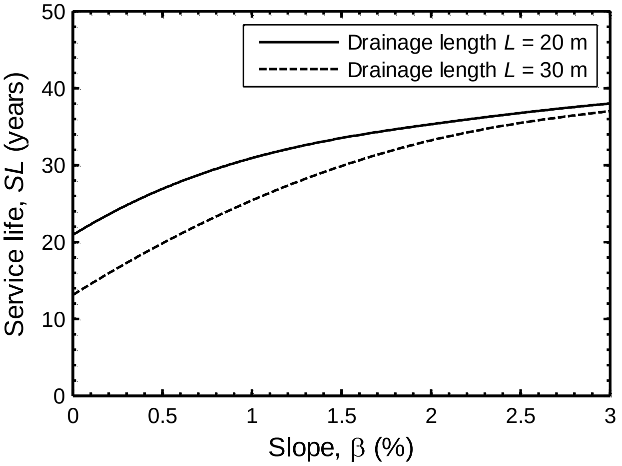

Figure 2. Effect of base slope on the calculated service life of a uniform coarse (2mm) sand drainage layer (infiltration rate = 0.2 m/year).

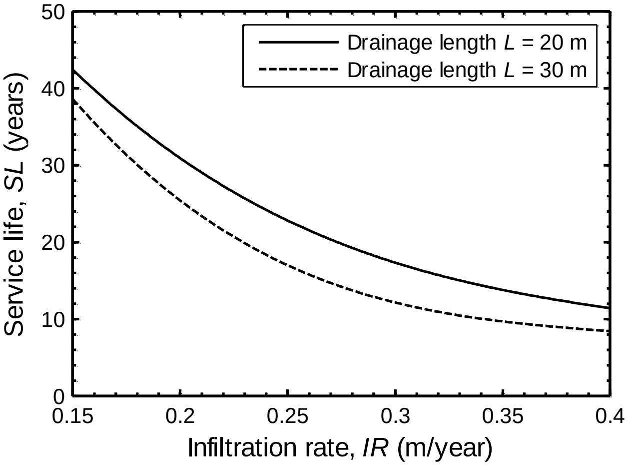

Figure 3. Effect of infiltration rate on the calculated service life of a uniform coarse (2 mm) sand (base slope, β = 1 %).

4.3 Leachate Mound Profiles

The calculated leachate mound at different times (2, 4, 6, and 8 years) for a 30-m long coarse sand drainage layer and a 1 % bottom slope is shown in Figure 4 for an infiltration rate of 0.4 m/year. Figure 5 shows the surface of the leachate mound for a 3 % base slope and an infiltration of 0.2 m/year at 10, 20, 30, and 37 years for a 30-m drainage length. Figures 4 and 5 both showed that the location of maximum thickness of leachate mound moved away from the perforated drainage pipes as the leachate mound gradually built up within the granular drainage layer. In both cases, the thickness of leachate mound at the upstream end was about 0.2 m at failure.

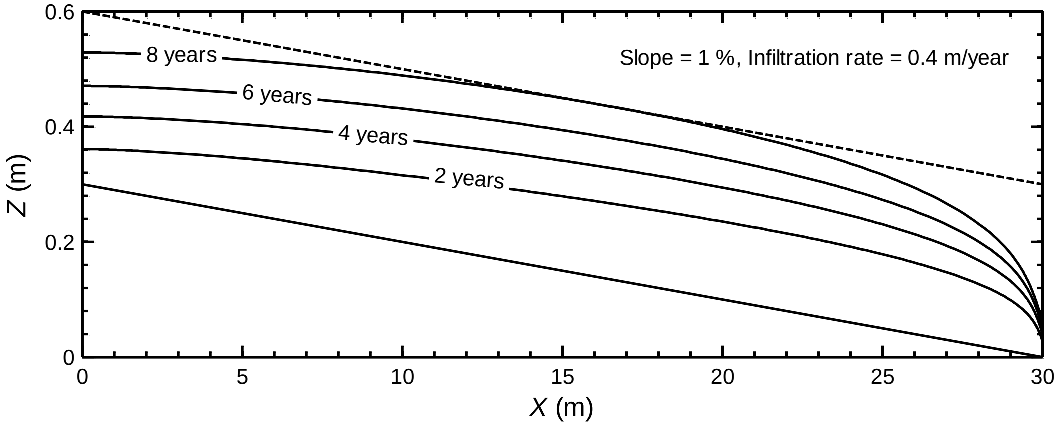

Figure 4. Surface of leachate mound within the 30-m long coarse sand drainage layer with a 1 % bottom slope and an infiltration rate = 0.4 m/year.

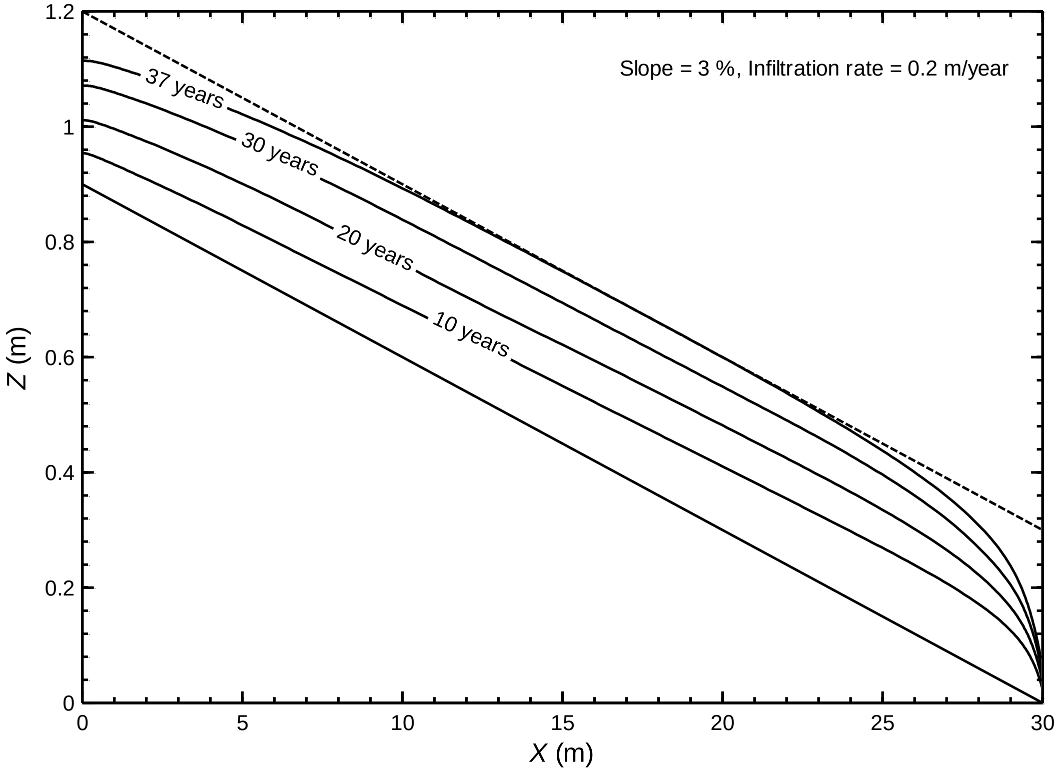

Figure 5. Surface of leachate mound within the 30-m long coarse sand drainage layer with a 3 % bottom slope and an infiltration rate = 0.2 m/year.

4.4 Porosity of Clogged Coarse Sand

The distribution of porosity within the saturated granular drainage layer at 4 and 8 years is shown in Figure 6 for a LCS with the slope of 1 % subjected to the infiltration rate of 0.4 m/year. The average porosity of clogged coarse sand within the leachate mound after 4-year permeation of leachate was about 0.30 (a decrease from an initial porosity of 0.37). After about 8 years when the maximum thickness of leachate mound reached the thickness of drainage layer, the average porosity of clogged coarse sand was reduced to about 0.29. As shown in Figure 6(b), the minimum porosity within the leachate mound was about 0.19 near the perforated drainage pipe where the mass loading was greatest.

Figure 7 shows the distribution of porosity at 18 and 37 years within the saturated drainage layer for the LCS with the 3 % slope and subjected to the infiltration rate of 0.2 m/year. After 18-years of leachate permeation, the average porosity of coarse sand within the leachate mound had decreased to about 0.24 from the initial value of 0.37. At failure, when the maximum thickness of leachate mound reached the thickness of granular drainage layer (at about 37 years), the average porosity of clogged coarse sand was about 0.22 and the minimum porosity within the leachate mound was about 0.16 near the collection pipe (Figure 7b).

4.5 Hydraulic Conductivity of Clogged Coarse Sand

For the LCS with the slope of 1 % and subjected to the infiltration rate of 0.4 m/year, the distribution of hydraulic conductivity at the failure of LCS within the saturated drainage layer is shown in Figure 8. The minimum hydraulic conductivity of clogged coarse sand was about 1×10^{-6} m/s near the perforated drainage pipe, reduced from the initial hydraulic conductivity of 1×10^{-3} m/s. Within the leachate mound, the reduction in the hydraulic conductivity was about 1 to 3 orders in magnitude (Figure 8).

The distribution of hydraulic conductivity within the leachate mound is shown in Figure 9 for the LCS with the 3 % base slope and an infiltration rate of 0.2 m/year when the maximum thickness of leachate mound reached the thickness of granular drainage layer at about 37 years. The hydraulic conductivity of clogged coarse sand within the leachate mound was reduced by about 1 to more than 3 orders in magnitude (Figure 9) with the minimum hydraulic conductivity of clogged coarse sand being about 4×10^{-7} m/s near the perforated drainage pipe.

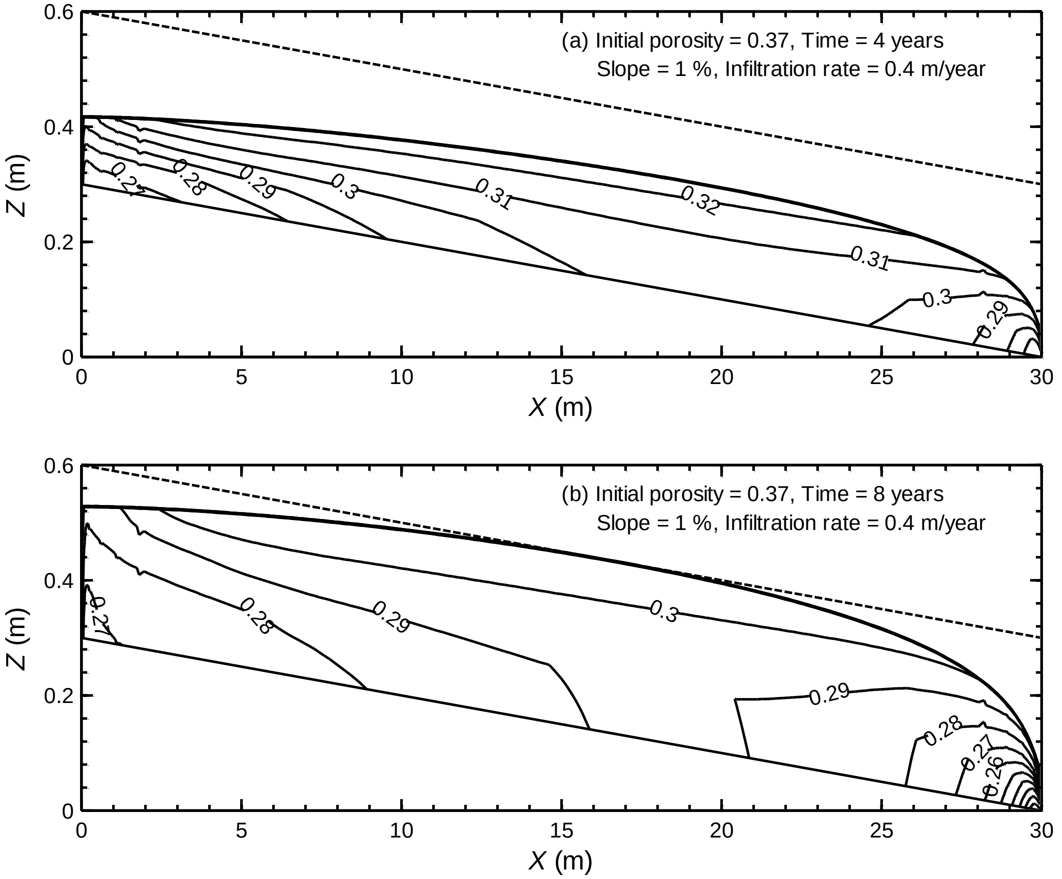

Figure 6. Distribution of porosity within the saturated coarse sand drainage layer with the 1 % bottom slope and infiltration rate of 0.4 m/year at (a) 4 years and (b) 8 years.

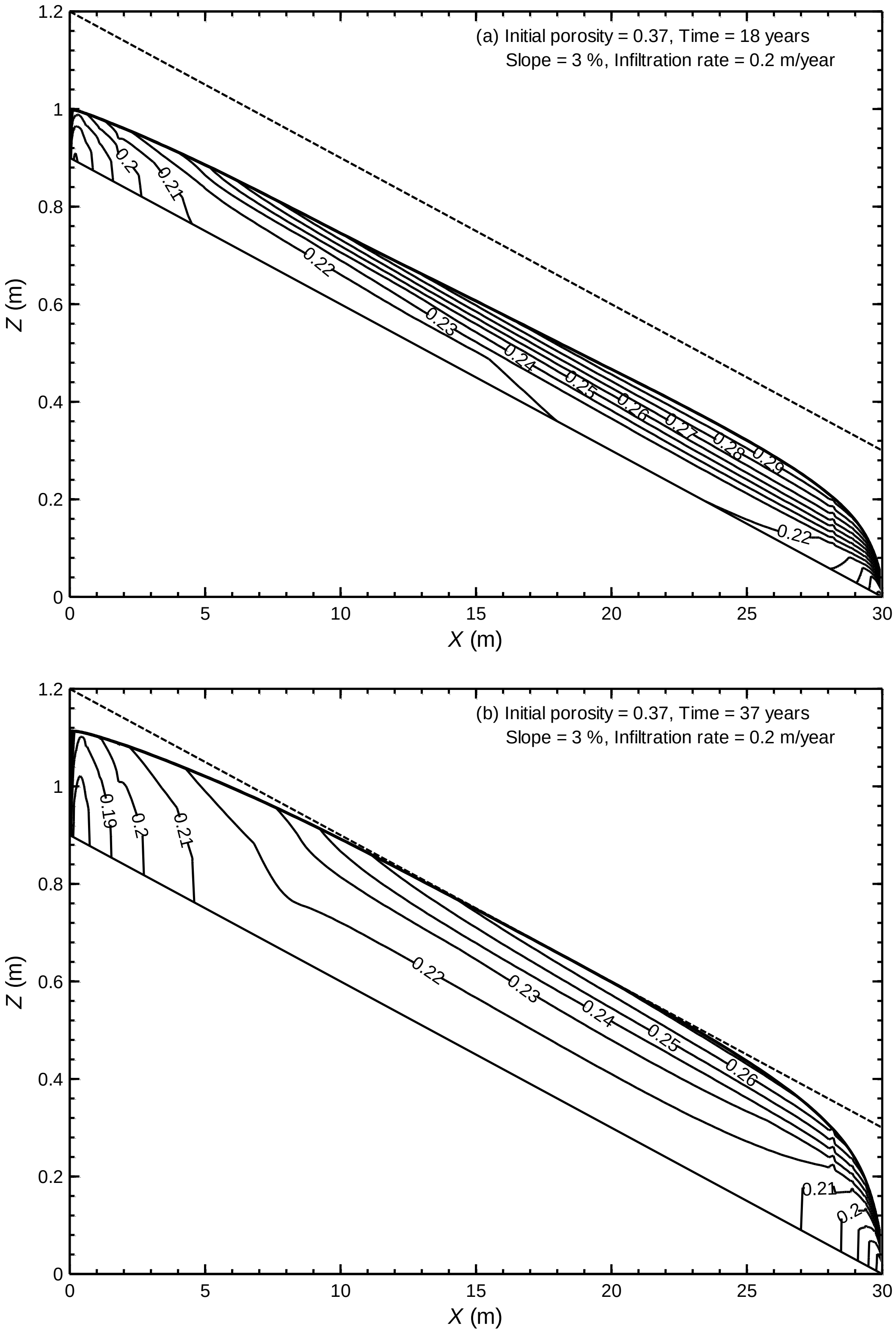

Figure 7. Distribution of porosity within the saturated coarse sand drainage layer with the 3 % bottom slope and infiltration rate of 0.2 m/year at (a) 18 years and (b) 37 years.

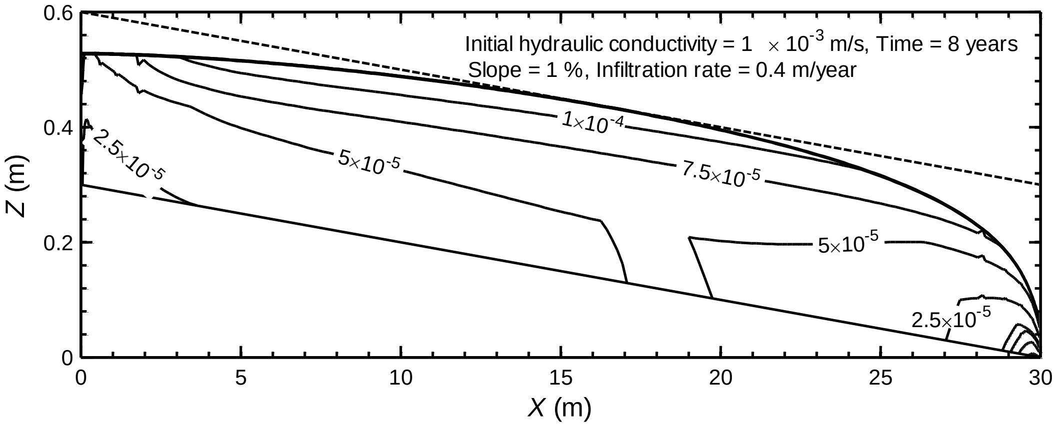

Figure 8. Distribution of hydraulic conductivity within the saturated coarse sand drainage layer with the 1 % bottom slope and infiltration rate of 0.4 m/year at 8 years.

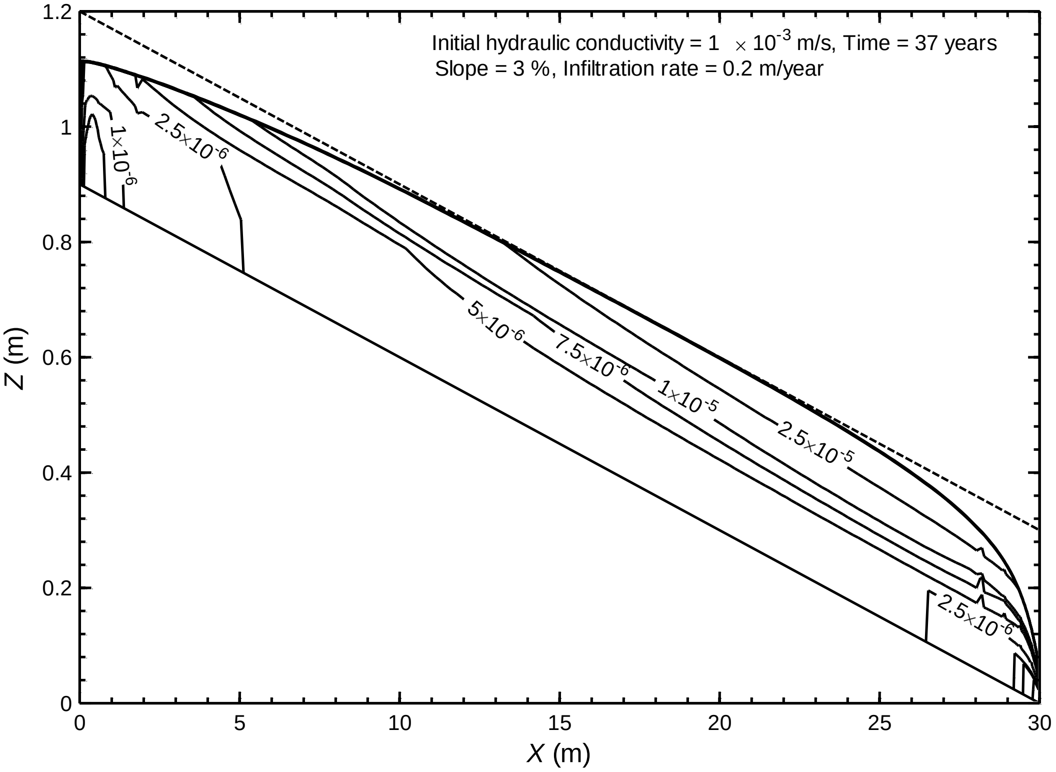

Figure 9. Distribution of hydraulic conductivity within the saturated coarse sand drainage layer with the 3 % bottom slope and infiltration rate of 0.2 m/year at 37 years.

5 CONCLUSIONS

The BioClog model was used to predict the service life and clogging of LCSs filled by coarse uniform (2 mm) sand for different bottom slopes of the drainage layer and different infiltration rates. The results showed that, other things being equal, increasing the base slope of a granular drainage layer increased the service life of the LCSs. When the leachate infiltration rate was increased (assuming similar input leachate), the service life of LCSs was decreased due to the increased total mass loading. The permeation of landfill leachate resulted in the accumulation of clog mass within the pore space of the granular material and reduced the porosity and hydraulic conductivity of the coarse sand granular drainage layer. In particular, the hydraulic conductivity of clogged coarse sand within the saturated drainage layer was reduced by 1 to 4 orders in magnitude which caused the leachate to build up within the granular drainage layer and eventually the failure of LCSs when the maximum thickness of leachate mound exceeded the thickness of granular drainage layer. The service lives given in this paper are for the conditions examined. Factors such as a more well graded distribution of particle size in the drainage layer or a change in leachate input strength with time could both have a significant effect on the actual service lives calculated, although the general effects of base slope and infiltration rate are likely to be similar.

ACKNOWLEDGEMENTS

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