MODELLING LEACHATE COLLECTION SYSTEM DESIGN OPTIONS FOR
A CANADIAN LANDFILL

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ABSTRACT

A modern municipal solid waste (MSW) landfill generally requires a leachate collection system (LCS) at the base to collect and remove leachate for treatment, and therefore to reduce the potential impact of contaminants in the landfill on the surrounding environments and human health. LCSs can be clogged by the organic and inorganic mass accumulated within the drainage layers due to the biogeochemical reactions when granular and geosynthetic materials contact with MSW leachate. The paper uses a numerical model ‘BIOCLOG’ to examine several LCS design options for a Canadian landfill and to compare the performance among them based on the calibrated input leachate characteristics using measured data in effluent from existing landfill cells. The paper concludes that the performance and service life of MSW landfill LCSs depends on the granular and geosynthetic materials used in the drainage layers and the design of LCSs must be based on the site-specific conditions.

1. INTRODUCTION

The disposal of municipal solid waste (MSW) in landfills is still a significant waste management option in many countries around the world. The leachate is generated within the landfill from rainfall or snow-melt permeating through the waste, biodegradation of organic waste, and the release of original moisture within the waste. It contains both dissolved and suspended contaminants (Rowe et al. 2004). A high permeability leachate collection system (LCS) is generally required above the low permeable liner at the base of landfill to collect and remove leachate for treatment, thereby reducing the potential for contamination of groundwater and surface water by minimizing the head (driving force) for contaminant migration and the mass or contaminant available for transport (e.g., Rowe et al. 2004; Rowe 2005). Modern landfill LCSs are designed using a granular drainage blanket with a slope to the perforated drainage pipes and thus to allow leachate to flow freely under gravity from the drainage layers to the pipes and the sumps. The leachate head within the landfill is generally required to be less than the thickness of the granular drainage layers (e.g., 0.3-0.5 m depending on the local regulations).

Field and laboratory studies have shown that the granular materials in LCSs can clog due to growth of organic mass, deposition of suspended solids, and precipitation of minerals on the surface of the granular material (e.g., Young et al. 1982; Bass 1986; Brune et al. 1991; Koerner et al. 1993, 1994; McBean et al. 1993; Rowe 1998; Craven et al. 1999;
Fleming et al. 1999; Maliva et al. 2000; Bouchez et al. 2003; Levine et al. 2005; Brune et al. 1991; Paksy et al. 1995, 1998; Peeling et al. 1999; Rowe et al. 2000a, 2000b, 2002; VanGulck and Rowe 2004a, 2004b; Rowe and McIsaac 2005; McIsaac and Rowe 2005, 2006, 2007, 2008). The accumulation of clog mass within the granular drainage layers reduces the drainage capacity of LCSs and causes leachate to build up within the landfill. A numerical model ‘BIOCLOG’ has been developed to examine the performance and service lives of LCSs based on past 20-year research in clogging of LCSs. BIOCLOG was initially developed in 1D by Cooke and Rowe (2005a), extended to 2D by Cooke and Rowe (2008a), substantially enhanced by Yu and Rowe (2012a), and calibrated by Rowe and Yu (2013) using laboratory mesocosm cells permeated by MSW leachate.

The objectives of this paper are to use BIOCLOG to calibrate the input leachate characteristics based on the measured effluent data from existing landfill cells and then to examine the performance and service lives of several design options for a Canadian landfill using site-specific leachate characteristics.

2. MODEL SUMMARY

BIOCLOG predicts the fate and transport of key constituents in leachate (nine species in total), and it simulates the accumulation of organic and inorganic clog mass within the porous media (Cooke and Rowe 2005; Cooke 2007; Yu and Rowe 2012a; Yu 2012). The acetate, butyrate, and propionate are considered because they contribute most of the chemical oxygen demand (COD) in normal MSW leachate. These particular fatty acids are also relatively easily biodegraded to produce carbonic acid in leachate. The carbonic acid together with calcium in leachate precipitate as calcium carbonate. Thus the dissolved calcium in leachate is modelled. The model also considers both the suspended organic biomass (including the suspended active biomass and inert biomass) and inorganic solids in leachate.

The organic and inorganic clog mass within the porous media is calculated using thicknesses of five separate films attached on the surface of idealized spheres with a regular packing arrangement (including three active biofilms, an inert biofilm, and an inorganic solids film). The biofilm associated with acetate, butyrate, and propionate degraders increases the thickness from the deposition of suspended active biomass and growth of active biofilms, and decreases the thickness by decay and through detachment from the shear stress induced by flowing leachate. The increase in inert biofilm thickness is due to the decay of active biofilms and the deposition of suspended inert biomass, and the decrease in thickness of the inert biofilm is through detachment from shearing. The deposition of suspended inorganic solid particles and precipitation of calcium carbonate and other minerals increase the thickness of the inorganic solids film.

The accumulation of clog mass (quantified using the total thickness of films) reduces the void spaces within the porous media. The reduction in porosity and specific surface of porous media due to clogging are calculated based on a geometric model from Yu and Rowe (2012b). The decrease in porosity results in a reduction in hydraulic conductivity of porous media and causes leachate mounding into the previous unsaturated zone. More details regarding the modelling are provided in Yu (2012).
3. PROBLEM DEFINITION

The original design of leachate collection system (LCS) for a Canadian landfill (Gondim et al. 2016) involved a 30-cm thick gravel drainage blanket and an overlying 30-cm thick sand filter-separator layer (Base Case; Figure 1). The drainage path is 40 m and slope is 2%. Based on the grading curve of drainage material, the nominal diameter of gravel is $d_g = D_{60} = 30$ mm (initial porosity $n_0 = 0.41$ and initial hydraulic conductivity $k_0 = 0.12$ m/s). The sand is assumed to have a nominal diameter of $d_g = 2$ mm (initial porosity $n_0 = 0.37$ and initial hydraulic conductivity $k_0 = 0.001$ m/s).

![Diagram of original design](image)

Figure 1. Original design of a Canadian MSW landfill using a gravel drainage layer and a sand filter layer.

A number of alternative design options for this landfill were presented by Gondim et al. (2016). However, this paper only focused on using a medium/coarse sand layer with and without underlying geocomposite (e.g., Alternative A from Gondim et al. 2016) because: (a) the design options associated with a fine sand drainage layer had calculated service lives less than 100 years (thus they should not be used), (b) the benefit of using tire shreds as the filter layer is limited, (c) the design options associated with a stone drainage layer had calculated service lives much longer than 100 years (thus the economical alternative design options should be explored which is main purpose of this paper). The choice of 100-year service life for LCSs is based on Ontario Regulations (MOECC 1998). The cases examined in this paper using BIOCLOG are summarized as below:

1. Case 1: 30-cm thick medium uniform sand drainage layer (the grain size of sand $d_g = 1$ mm, initial porosity $n_0 = 0.35$, initial hydraulic conductivity $k_0 = 0.0001$ m/s) as shown in Figure 2a, drainage path = 40 m, slope = 2%, drainage only at the downstream end (Figure 3a).
2. Case 2: 30-cm thick medium uniform sand drainage layer (the grain size of sand $d_g = 1$ mm, initial porosity $n_0 = 0.35$, initial hydraulic conductivity $k_0 = 0.0001$ m/s) as shown in Figure 2a, drainage path = 20 m, slope = 2%, drainage at the downstream and upstream end (Figure 3b).
3. Case 3: 30-cm thick coarse uniform sand drainage layer (the grain size of sand $d_g = 2$ mm, initial porosity $n_0 = 0.37$, initial hydraulic conductivity $k_0 = 0.001$ m/s) as shown in Figure 2b, drainage path = 40 m, slope = 2%, drainage only at the downstream end (Figure 3a).
4. Case 4: 30-cm thick coarse uniform sand drainage layer (the grain size of sand $d_g = 2$ mm, initial porosity $n_0 = 0.37$, initial hydraulic conductivity $k_0 = 0.001$ m/s) as shown in Figure 2b, drainage path = 20 m, slope = 2%, drainage at the downstream and upstream end (Figure 3b).

5. Case 5: geonet (equivalent thickness of 1.2 cm) with 30-cm thick coarse uniform sand filter layer (the grain size of sand $d_g = 2$ mm, initial porosity $n_0 = 0.37$, initial hydraulic conductivity $k_0 = 0.001$ m/s) as shown in Figure 2c, drainage path = 40 m, slope = 2%, drainage only at the downstream end (Figure 3a).

6. Case 6: geonet (equivalent thickness of 1.2 cm) with 30-cm thick coarse uniform sand filter layer (the grain size of sand $d_g = 2$ mm, initial porosity $n_0 = 0.37$, initial hydraulic conductivity $k_0 = 0.001$ m/s) as shown in Figure 2c, drainage path = 20 m, slope = 2%, drainage at the downstream and upstream end (Figure 3b).

![Figure 2](image1.png)

Figure 2. Drainage layer using (a) 1-mm sand, (b) 2-mm sand, (c) geocomposite.

![Figure 3](image2.png)

Figure 3. Leachate collection system with drainage layer using (a) only one drainage pipe at the downstream end, and (b) one drainage pipe at the downstream end and one drainage pipe at the upstream end.
4. RESULTS

4.1 Calibration of Input Leachate Characteristics (Base Case)

Calibration is required since there is a substantial change in leachate characteristics as it passes through the leachate collection system and, except at very early times before the biofilm is established, the concentrations of COD, BOD, Ca and TSS in the collected leachate are very different from those which entered the system (e.g., McIsaac and Rowe 2005, 2007, 2008). Thus using the leachate measured at the sumps as a direct input to a clogging model is fundamentally wrong. The calibration of influent leachate characteristics performed for this case was based on the original design (Base Case; Gondim et al. 2016) using BIOCLOG with modelling parameter values from Yu (2012) and the measured leachate generation rates and concentrations in the leachate sumps for the already built cells. The following influent leachate (before entering into the LCS) provided reasonable agreement between measured and predicted effluent COD, calcium, and TSSs (after passage through the LCS):

- The influent COD concentration increased linearly from 2500 to 83000 mg/L over the first 1 year and was stable at 83000 mg/L until year 6. The influent COD concentration decreased linearly from 83000 to 2500 mg/L between years 6 and 7, and after year 7 the COD concentration entering this LCS was stable at 2500 mg/L (Figure 4a).
- The influent calcium concentration increased linearly from 350 to 4700 mg/L over the first 1 year and remained stable at 4700 mg/L between years 1 and 6. It then decreased linearly from 4700 to 350 mg/L between years 6 and 7 and was stable at 350 mg/L after year 7 (Figure 4b).
- The influent TSS concentration increased linearly from 2000 to 4000 mg/L over the first 1 year. It remained stable at 4000 mg/L between years 1 and 6. The influent TSS concentration decreased linearly from 4000 to 2000 mg/L between years 6 and 7 and was stable at 2000 mg/L after year 7 (Figure 4c).
LCS with Medium Sand Drainage Layer (Cases 1 and 2)

To predict the service lives of the alternative design options, the time-dependent leachate infiltration rate was considered where the infiltration rate is constant at 0.088 m/year within the first 5 years, decreases linearly to 0.039 m/years at year 6, and is kept stable at 0.039 m/years after 6 years based on recommendations from Gondim et al. (2016) using historical leachate volumes pumped off-site from existing landfill cells. The influent leachate characteristics are the calibrated values from the previous section as shown in Figure 4.

Figure 5a shows the average porosity and maximum leachate mound changing with time within the 1-mm sand drainage layer where only one drainage pipe at the downstream end (Case 1). The average porosity decreased from the initial value of 0.35 to about 0.30 and 0.27 at 5 and 88 years, respectively. The reduction in porosity resulted in a decrease in hydraulic conductivity of the sand and caused the leachate to build up within the drainage layer. At Year 5, the maximum leachate mound was about 0.22 m. The subsequent decrease in leachate mound was because of the reduction in leachate infiltration rate due to the final cover after Year 5. The maximum leachate mound then increased due to more clogging until it reached the drainage layer thickness of 0.3 m at Year 88. Thus the service life of this system under the given leachate characteristics and infiltration rates is about 88 years for Case 1. This design does not satisfy the requirements of good regulations (e.g., 100-year service life from Ontario Regulations; MOECC 1998).

For Case 2 with one drainage pipe at the downstream end and one drainage pipe at the upstream end, the average porosity and maximum leachate mound changing with time within the 1-mm sand drainage layer are shown in Figure 5b. The average porosity decreased from the initial value of 0.35 to about 0.25 at Year 100 and the maximum leachate mound was about 0.23 m at Year 100. Thus the service of Case 2 is longer than 100 years. The service life of Case 2 longer than that of Case 1 was because of the shorter drainage length and one additional drainage pipe at the upstream associated with Case 2.
Figure 5. Average porosity and maximum leachate mound in drainage layer with 1-mm sand using (a) Case 1 - only one drainage pipe at the downstream end (Figure 3a), and (b) Case 2 - one drainage pipe at the downstream end and one drainage pipe at the upstream end (Figure 3b).

LCS with Coarse Sand Drainage Layer (Cases 3 and 4)

Figure 6a shows the average porosity and maximum leachate mound changing with time within the 2-mm sand drainage layer using only one drainage pipe at the downstream end (Case 3). The average porosity decreased from initial value of 0.37 to 0.24 at Year 100 and the maximum leachate mound increased to about 0.20 m at Year 100. Thus Case 3 has a service life longer than 100 years. For Case 4 as shown in Figure 6b, the average porosity at 100 years was about 0.23 and the maximum leachate mound at 100 years was about 0.15 m. Thus the service life of Case 4 is also longer than 100 years.

LCS with Geocomposite (Cases 5-10)

When modelled alone or with a 0.3-m-thick sand layer acting only as a filter (and not as a drainage medium) the geonet clogged in 18-40 years for one way drainage (Figure 3a; Case 5) and in 22-70 years with two way drainage (Figure 3b; Case 6). Thus relying on the geonet alone for drainage of leachate resulted in a service life much less than 100 years.
Figure 6. Average porosity and maximum leachate mound in drainage layer with 2-mm sand using (a) Case 3 - only one drainage pipe at the downstream end (Figure 3a), and (b) Case 4 - one drainage pipe at the downstream end and one drainage pipe at the upstream end (Figure 3b).

The calculated service lives for Case 5 and 6 are less than 100 years based on the geonet alone. However if the geonet is combined with a 0.3-m thick coarse sand layer over the geocomposite, then after the geonet is clogged, the coarse sand layer can take over as the drainage layer (not just as a filter as it would be until the geonet clogged). Based on the results from Case 3 and 4, a 0.3-m thick coarse sand layer has a service life longer than 100 years. Thus the geocomposite with a 0.3-m thick coarse sand layer when both are considered as the drainage layers (Cases 7 for 1-way drainage and Case 8 for two way drainage) both have a service life longer than 100 years.

The calculated service life with a medium sand layer alone and one way drainage (Figures 3a and 5a) was 88 years but if a 0.3-m-thick medium sand layer were combined with the geonet (Case 9) the service live of the entire system exceeded 100 years for one way drainage. Since the medium sand layer alone and two-way drainage (Figures 3b and 5b) already exceeded 100 years the combination with a geonet (Case 10) also gives a service life exceeding 100 years.

5. CONCLUSIONS

The leachate collection system (LCS) is a critical component for a successful MSW landfill design. The clogging of LCSs can occur after the drainage materials comes into contact with MSW leachate. The design of LCSs needs to take clogging of drainage materials into account. The numerical model ‘BIOCLOG’ provides a means to examine the clogging and to estimate the service life of LCSs. This paper has presented the modelling of several alternative design options for a Canadian landfill using BIOCLOG with the calibrated input leachate characteristics based on the measured effluent data from existing landfill cells. For the specific conditions examined, the following conclusions were reached:
The 0.3-m thick medium sand drainage layer had a service life less than 100 years when the drainage length is 40 m (Case 1) and longer than 100 years when the drainage length is 20 m (Case 2).

The service life of a 0.3-m thick coarse sand drainage layer was longer than 100 years when the drainage lengths are 40 m (Case 3) and 20 m (Case 4).

The 0.012 m geonet alone as the drainage layer (or with a 0.3-m thick coarse sand layer as the filter layer) had a service life much less than 100 years (Case 5 and 6).

When both geonet and 0.3-m thick medium or coarse sand layer are considered as the drainage layers (Cases 7 - 10) the service life was longer than 100 years.

The design of LCSs must consider the site-specific leachate characteristics and generation rates. The time-dependent leachate characteristics and flow rates used in this paper were based on existing cells from the same landfill site and should not be used as the input leachate information to design LCSs for other landfill sites. The demonstration that a LCS design has an expected service life longer than 100 years for one site does not mean that the same design will have a suitable service life and performance for a different site. The case examined here had a number of very particular characterises that allowed the conclusions above to be reached; namely, that this landfill was in a semi-arid area and had: (a) very low infiltration, (b) relatively small cells with a short (< 6-7 year) period of aggressive acetogenic leachate entering the leachate collection system, and (c) a maximum drainage path of 40 m and 2% base grade. Increasing the infiltration rate, and/or the thickness of waste, and/or the length of the drainage path, and/or decreasing the base slope would all decrease the service life. While coarse sand or medium sand and a 1.2 cm thick geonet proved adequate for this particular design (Gondim et al. 2016), this finding cannot be generalized beyond this case and neither sand nor a geonet should be relied on as a MSW leachate drainage layer without detailed calculations such as those reported herein, and in the absence of site specific data and detailed modelling a minimum of 0.3-m thick gravel drainage layer is still recommended.

ACKNOWLEDGEMENTS

The development of the BIOCLOG model was funded by Natural Science and Engineering Research Council of Canada. The specific work presented in this paper was funded by Dillon Consulting Limited, Oakville, Canada and Progressive Waste Solutions Canada Inc., Vaughan, Canada. The value of discussion with F. Gondim is much appreciated.
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