System Effects on Bioreactor Landfill Performance based on Coupled Hydro-Bio-Mechanical Modeling

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Abstract: A newly developed and validated numerical model, that accounts for the coupled hydro-bio-mechanical processes in municipal solid waste (MSW) landfills, was employed to assess influence of various field conditions and system variables on the performance of bioreactor landfills. The numerical model integrates a hydraulic two-phase flow model which assumes landfill leachate and gas as two immiscible phases, a mechanical model based on plain-strain formulation of Mohr-Coulomb constitutive law, and a first-order decay biodegradation model for modeling coupled hydro-bio-mechanical processes in bioreactor landfills. The influence of typical field conditions and system variables namely, the landfill slope configuration, geometric configuration of leachate recirculation system and mode of leachate injection on the bioreactor landfill performance were evaluated. The bioreactor landfill performance was investigated with regards to hydraulic behavior (e.g., moisture distribution, waste saturation, pore water and capillary pressures), extent of biodegradation and mechanical response (e.g. slope stability, landfill settlement, and in-plane shear behavior of composite liner system) during the operations of leachate injection. Overall, this parametric study concluded that various field conditions and system variables significantly influence the performance of bioreactor landfills. Therefore, these system variables must be properly accounted when optimizing the performance of bioreactor landfills undergoing coupled hydro-bio-mechanical processes during the leachate injection operations.

Keywords: Bioreactor landfill, coupled hydro-bio-mechanical process, leachate recirculation, municipal solid waste, settlement, pore pressures, interface shear behavior.

Introduction

The effective disposal of ever growing amounts of municipal solid waste (MSW) is one of the critical challenges faced by many urban settings worldwide. Landfilling of MSW in engineered landfills has been considered as one of the most feasible options available in waste management practices. In the past two decades, bioreactor landfill technology has been practiced increasingly, as waste management industries strive towards sustainability. Bioreactor landfills incorporate the operations of leachate recirculation through leachate recirculation systems (LRS) within the MSW to increase the moisture levels in the MSW (Barlaz et al. 1989; Reinhart and Townsend1997; Sharma and Reddy 2004; Haydar and Khire 2005; Jain et al. 2010). This in turn accelerates the anaerobic decomposition of MSW thereby leading to early waste stabilization. Meanwhile, the MSW undergoes complex interrelated coupled behavior comprised of hydraulic, mechanical, biological, and thermal processes. Moreover, due to such complex and dynamic coupled behavior, the geotechnical properties of the MSW change both spatially and temporally, and it becomes increasingly difficult to accurately predict the overall performance of such landfill systems.

The performance evaluation of bioreactor landfills must be based on a holistic assessment of the coupled hydro-bio-mechanical processes in the landfilled MSW. The leachate injection in the MSW causes rapid waste degradation and simultaneous changes in the geotechnical properties of MSW (e.g. unit weight, stiffness, shear strength parameters and saturated hydraulic conductivity). Higher moisture levels could also generate excess pore fluid pressures that would reduce the effective stress, which further affects the volumetric deformation in the waste. Similarly, the faster biodegradation of MSW exacerbates changes in the mechanical behavior, and causes changes in the void ratio, which ultimately results in large overall waste settlement. It has been widely reported that secondary biodegradation induced settlement could be as large as 50% of the initial waste height (Sowers 1973; McDougall 2007).

On the other hand, changes in mechanical behavior (e.g., volumetric deformation, void ratio, effective stresses) could affect the flow and distribution of moisture in bioreactor landfills (El-Fadel and Khoury 2000; McDougall 2007; Chen et al. 2012). Moreover, as a result of continuous leachate recirculation, the decomposed MSW may have a behavior that resembles more of the clayey soils, potentially representing soft waste conditions that could considerably influence the in-plane shear behavior (shear stress and shear displacement) of the underlain composite liner system. Consequently, it is critical to understand the in-plane shear behavior of liner systems during the leachate injection to ensure their integrity and serviceability over the entire design life period (Reddy et al. 1996; Jones and Dixon 2005; Reddy et al. 2017a). Therefore, the bioreactor landfills subjected to coupled processes must be analyzed and designed holistically, with adequate consideration given to hydraulic behavior (e.g., moisture distribution and resultant buildup of pore fluid pressures), landfill slope stability, settlement, and interface shear behavior of the composite liner systems (side and bottom liners) during and after the periods of leachate injection operations (Reddy et al. 2017b).

There is quite limited information available in the literature regarding the optimization of the performance of bioreactor landfills that undergo coupled hydro-bio-mechanical processes. McDougall (2007) presented a one-dimensional (1-D) coupled hydro-bio-mechanical mathematical framework that accounted for hydraulic behavior of MSW using the Richards' equation (1931), while accounting for the unsaturated hydraulic conductivity using van Genuchten functions (van Genuchten 1980). The MSW biodegradation process ranging from enzymatic hydrolysis to methanogenesis was incorporated based on a two-stage anaerobic digestion model. Meanwhile, the mechanical settlement was calculated based on small-strain finite element model that included the creep effects and biomechanical compression. Nonetheless, McDougall (2007) did not consider the effects of periodic leachate recirculation on coupled hydro-bio-mechanical processes in the landfilled MSW. Moreover, landfill slope stability and interface shear behavior of landfill liners while the MSW undergoes degradation were not considered.

Hettiarachchi et al. (2009) also developed a 1-D mathematical model to account for the effects of moisture and landfill gas pressure in determining the overall landfill settlement. The modelers used first-order decay kinetics to account for the MSW biodegradation and subsequent biodegradation induced waste settlements. However, they ignored the spatial and temporal variation in MSW settlement. Moreover, the model did not represent a realistic field coupled hydro-bio-mechanical MSW behavior as the influence of leachate distribution in the MSW were not considered, since the operations of leachate recirculation were not performed. Furthermore, changes in geotechnical properties with waste decomposition were neglected. A similar approach was adopted by Chen et al. (2012) who proposed a 1-D coupled hydro-bio-mechanical framework. The model incorporated the changes in degree of saturation with time and the subsequent MSW biodegradation. However, the changes in geotechnical properties due to biodegradation were not considered. Furthermore, the effects of biodegradation on the MSW settlement calculation were neglected as the rate of secondary compression was kept constant in the coupled modeling approach.

None of the previous studies have investigated the influence of bioreactor landfill slope configurations, geometric configuration (e.g., spacing/layouts) of the leachate recirculation systems such as horizontal trench systems (HTs) and the effect of leachate injection mode (continuous vs. intermittent) on the overall performance of bioreactor landfills, including the composite liner and cover system, subjected to coupled hydro-bio-mechanical processes.

A two-dimensional mathematical framework that accounts for the coupled hydro-bio-mechanical processes in the MSW is developed to perform detailed parametric modeling during the operations of leachate injection. The parametric study is performed to assess: (a) the impact of landfill slope configuration by comparing a typical 1V:3H slope with a steeper 1V:2H landfill slope, (b) the effect of geometric configuration of HTs by varying the horizontal spacing and layouts between successive HTs (e.g., closely spaced vs. relatively widely-spaced), and (c) influence of the mode of leachate injection (e.g., continuous leachate injection vs. a one-week-on-off intermittent injection mode). In particular, the influence on the hydraulic behavior (e.g., moisture distribution, leachate saturation, pore water and capillary pressure), biodegradation parameters (e.g., degree of degradation with leachate injection duration), landfill slope stability, overall mechanical settlement, and interface shear behavior of composite liner systems are evaluated for bioreactor landfills undergoing the coupled hydro-bio-mechanical processes during the operations of leachate injection.

Coupled Hydro-Bio-Mechanical Model

A coupled hydro-bio-mechanical model that integrates a two-phase flow hydraulic model, a first order decay biodegradation model and a plain-strain formulation of the Mohr-Coulomb mechanical model is used to predict the MSW behavior and examine the interface shear response of composite liner system under the influence of coupled hydro-bio-mechanical processes

(Reddy et al. 2017c). In particular, the two-phase flow hydraulic model simulates the flow/transport of each fluid phase (liquid and gas) through Darcy's law and is extended to unsaturated fluid flow using the relative permeability functions given by van Genuchten (1980). The entire numerical model was formulated in Fast Lagrangian Analysis of Continua (FLAC) a finite difference program (Itasca, 2011). A schematic of the numerical framework and a detailed explanation on each of these individual models and the entire numerical framework is presented in Reddy et al. (2017c).

Modeling System Effects

Modeling Scenarios

This study examines the influence of various system designs and operational conditions on the performance of bioreactor landfill subjected to coupled hydro-bio-mechanical processes. Specifically, the parametric study is performed to assess: (a) the impact of landfill slope configuration by comparing a typical flatter slope (1V:3H) with a steeper landfill slope (1V:2H), (b) the effect of geometric configuration of HTs by varying the horizontal spacing and layouts between successive HTs (i.e., closely spaced dense HT system vs. relatively widely-spaced HTs), and (c) the influence of the mode of leachate injection (i.e., continuous leachate injection vs. one-week-on-off intermittent injection).

Effects of Landfill Slope Configuration

A parametric study was performed to evaluate the impacts of bioreactor landfill slope configuration on the overall performance of bioreactor landfill under the influence of coupled hydro-bio-mechanical processes. In this study, two most commonly adopted field bioreactor landfill slopes, 1V:3H (case C-1) and 1V:2H (case C-2) are simulated to assess the effects of landfill slope configuration. In the case of bioreactor landfill C-2, the total model width is reduced to 100 m in order to have same number of zones as in case C-1 for comparison, while the total height remains the same as C-1 (i.e., 35.5 m), and the width of flat portion of the final cover remains the same (i.e., 70 m). Leachate is continuously injected in both the C-1 and C-2 landfill models through a total of 4 HTs (each 1m x 1m) at an injection pressure of 100 kPa until the waste stabilization is attained in each of the landfill models. The spacing between the successive HTs in the landfill C-2 remains the same as that of typical landfill C-1 (refer Table 1). The results obtained for C-2 (1V:2H) were compared with the landfill C-1 (1V:3H) to investigate the effects of the landfill slope configuration.

Effects of Horizontal Trench Configuration

The effects of the geometric configuration of the HTs were simulated by varying the spacing between consecutive HTs. In the bioreactor landfill case C-1, a total of four HTs are placed with a horizontal spacing of 30 m and a vertical spacing of 10 m between any two HTs. In order to evaluate the effects of trench configurations, another bioreactor landfill case, C-3 was considered with similar landfill configuration as that of C-1, except in case C-3, a total of seven HTs were placed to represent the behavior of closely spaced HTs during the periods of continuous leachate injection. In the bioreactor landfill C-3, the horizontal spacing between any two successive HTs was reduced to 15 m, while the vertical spacing was kept the same (i.e., 10 m). Moreover, the leachate was continuously injected in all seven HTs with an injection pressure of 100 kPa until the waste stabilization was attained. The results obtained from the typical C-1 landfill were compared with landfill C-3 to assess the effects of the trench configuration in bioreactor landfill subjected to coupled hydro-bio-mechanical process.

Effects of Mode of Leachate Injection

In field practices, continuous leachate injection (24 hours a day and seven days a week) is not feasible as it would requires long operator time devoted for running leachate injection systems at elevated pressure conditions. Therefore, an intermittent mode of injection is preferred. In this study, a one-week-on-off intermittent leachate injection mode is adopted by continuously injecting the leachate in the bioreactor landfill for a week followed by a one week rest period. This particular landfill case is considered as C-4 (Table 1). The intermittent injection cycle was performed through a total of 4 HTs using injection pressure of 100 kPa till the waste stabilized in the bioreactor landfill C-4. The results obtained from the case C-4 were compared with the results of C-1 to investigate the effects of mode of leachate injection (continuous vs. intermittent).

A parametric modeling study was performed by carrying out the coupled hydro-bio-mechanical simulations using the proposed mathematical framework for each of the four landfill cases (C-1 through C-4) until their respective waste stabilization period was achieved. Simulation results were obtained for the moisture flow and distribution (wetted MSW area), degree of saturation, pore-water and pore gas pressures, degree of degradation (DOD), variations of MSW unit weight with DOD, total mechanical landfill settlement, and global factor of safety. In addition, interface shear stress-displacement behavior of the composite bottom liner system is reported to understand the overall performance of bioreactor landfill under the influence of coupled processes.

A 120-m-wide and 35.5-m-deep bioreactor landfill was selected for the coupled hydro-bio-mechanical modeling simulations. A complete detail of the landfill dimensions is presented in Fig. 1. A composite liner system comprised of a 1V:2H side liner and 85 m long base liner. The composite landfill lining system consists of 1-m-thick compacted clay overlain by a 12-oz/yd^2 non-woven geotextile over a 60-mil smooth high-density polyethylene (HDPE) geomembrane. A 3 m long flat run-out anchor trench was selected based on the anchor trench's capacity to hold together both the geomembrane and geotextile (Sharma and Reddy 2004). A 0.5 m thick layer of high permeability drainage material (e.g., gravel) was placed above the liner to represent it as the bottom leachate collection and removal system (LCRS).

The total initial waste height was selected to be 30 m and the waste layer was divided into 10 different layers, each 3 m thick. For the bioreactor landfill case, C-1, a total of four HTs are placed such that two HTs are located in the shallow layers and the other two HTs are situated in deep layers of MSW landfills. As shown in Fig. 1, the two leftmost HTs are placed at a lateral distance (i.e., setback) of 30 m away from the MSW face slope to maintain the stability of landfill slopes in all four considered bioreactor landfill scenarios (C-1, C-2, C-3, and C-4). In addition, the HTs within the shallow MSW layers are situated 10 m vertically below the top of the MSW landfill surface. Moreover, the horizontal and vertical spacing between the successive HTs are 30 m and 10 m, respectively, in all the selected landfill scenarios except for the C-3 configuration. The spacing and layouts of HTs considered in this study are based on the practical application as exercised in typical bioreactor landfills in the USA (Giri and Reddy 2014a, b).

Lastly, a final cover system is placed over the MSW. As shown in Fig. 1, the final cover system has a flat run-out, a 1V:*n*H MSW face slope and 70-m-wide horizontal portion. The MSW face slope remains 1V:3H in selected landfill cases C-1, C-3, and C-4. In landfill C-2, a 1V:2H face side slope is considered to evaluate the effects of landfill slope configuration. The wider flatter portion (i.e., 70 m wide) was considered to adequately capture the influence of the coupled hydro-bio-mechanical processes in the MSW on a relatively larger landfill area. In addition, a comparatively wider landfill surface could minimize the boundary effects during the leachate spread in the bioreactor landfill. The final cover system is comprised of 1 m thick erosion (vegetative) soil layer underlain by the interface of a 12-oz/yd^2 geotextile and 60-mil HDPE geomembrane. The geomembrane is underlain by 1 m thick layer made of compacted clay.

Material Properties

As shown in Fig. 1, the design components of the engineered bioreactor landfill are comprised of native soils (silty clay, CL), a layer of compacted clay (primarily silty clay, CL) in the composite liner system as well as in the final cover system, a bottom drainage layer made of highly permeable granular soil (e.g., gravel), and an erosion layer (vegetation soil) at the top in the final cover to minimize the infiltration within the landfill. Table 2 shows the geotechnical properties of these landfill soil layers selected based on previous studies (Reddy et al. 1999; HELP Manual, USEPA 1994). In both the composite liner and the final cover system, an interface material comprised of a smooth HDPE geomembrane and a nonwoven geotextile was considered to represent the weakest surface in the landfill (Reddy et al. 1996; Jones and Dixon 2005). Moreover, the shear strength and the stiffness properties of the interface were adopted from previous studies (Wasti and Ozduzgun 2001; Sia and Dixon 2012).

The landfilled MSW was divided into ten distinct layers and each layer being 3-m-thick with varying MSW properties along the landfill depth to represent true field conditions (i.e., heterogeneous MSW). Table 3 shows the initial geotechnical properties of the MSW and their variation (e.g., unit weight, saturated hydraulic conductivity, initial porosity, and initial saturation) along the landfill. The MSW unit weight was varied along the depth using the formulation given by Zekkos et al. (2006):

$$\gamma = \gamma_i + \frac{z}{\alpha+\beta z} \tag{1}$$

Where γ = unit weight at depth z; α and β are 3 m^4/kN and 0.2 m^3/kN, respectively, for typical MSW; and γ_i = near surface in-place unit weight. In this study, the value of γ_i was taken as 7.5 kN/m^3

The saturated vertical hydraulic conductivity of MSW was varied with landfill depth and overburden stress as follows (Reddy et al. 2009):

$$k_v = k_{v0}\left[1+\left(\frac{\sigma'}{P_a}\right)\right]^{-5.3} \tag{2}$$

Where k_{v0} = initial saturated hydraulic conductivity at zero normal stress (10^{-2} cm/s), k_v is the saturated hydraulic conductivity under effective overburden of σ', and P_a = atmospheric pressure

The initial porosity of the waste was varied with landfill depth using the mass-volume relationship as:

$$n = 1 - \frac{\rho_{dry}}{G_s \rho_w} \tag{3}$$

Where ρ_{dry} is the waste dry density; G_s is the specific gravity of fresh MSW and was assumed to be 1.25 based on Yesiller et al. (2014); and ρ_w is the density of water.

The initial shear strength parameters and the initial stiffness properties of MSW were kept constant along the landfill depth, and these values were based on previous studies (Xu et al. 2012; Sia and Dixon 2012). The biochemical methane potential (BMP) of MSW was assumed to be 100 m^3/Mg (Faour et al. 2007) and did not vary with landfill depth. The unsaturated hydraulic properties of the MSW were taken from the experimental study performed by Breitmeyer and Benson (2011) as listed in Table 4. The initial and boundary conditions applied in this modeling simulation are similar to the ones reported in Reddy et al. (2017c).

Results and Discussion

Moisture Distribution

The uniform and adequate spread of the injected leachate through the HTs in the MSW is one of the primary objectives of leachate recirculation operations in bioreactor landfills. The MSW wetted area that represents landfill area with saturation greater or equal to 60% (ITRC 2006) is plotted against injection duration for the different landfill configurations in Fig. 2. It can be inferred that MSW wetted area is approximately 93% in all the landfill cases, at the end of their respective stabilization period. The total MSW wetted area was calculated as the MSW area with saturation greater than 60% divided by the total MSW area. Pressurized leachate addition through the closely spaced staggered HTs (a total of 7) in landfill C-3 resulted in the largest wetted area with the shortest leachate injection period, representing a higher level of moisture distribution in the MSW. Moreover, the steeper 1V:2H MSW face slope in landfill C-2 brought about a smaller wetted area and longer stabilization period than the relatively flatter slope of 1V:3H in C-1. That could be due to the relative flatness of 1V:3H slope in which the leachate spread laterally and accumulates near the side slopes faster than in case of the steeper 1V:2H slope. Thereafter, as a result of the impermeable slope boundary, the leachate would eventually migrate vertically down and wet more areas in the 1V:3H landfill slope. Similar observations were made by Giri and Reddy (2014a, b), who predicted a larger wetted area for a flatter landfill slope (1V:3H) than in a steeper slope (1V:2H) while assessing the minimum setback distance of HTs from the side slope for safe and efficient design of the bioreactor landfill.

Similarly, Fig. 3 shows the degree of saturation for all four landfill systems along a lateral section A-A’ (see Fig. 1) during different periods of leachate injection. A variation in the MSW saturation is clearly evident during leachate injection operations in different landfill cases considered. The degree of saturation ranges from the initial 40% to 100% in all of the landfill cases. However, the levels of saturation were lower for the landfill C-4 compared to rest of the landfill cases during the first 10 years of leachate injection, as a result of the intermittent mode of injection. As previously mentioned, the closely spaced dense HT system in C-3 resulted in saturation levels as high as 100% within the first year of continuous injection. The influence of the bioreactor landfill slope configuration was examined by comparing MSW face slope of 1V:3H (C-1) with a relatively steeper 1V:2H (C-2) slope. As shown in Fig. 2, the steeper 1V:2H face slope resulted in a relatively smaller MSW wetted area and longer injection duration to effectively distribute the injected leachate in the MSW.

The effect of the horizontal trench systems were evaluated by reducing the horizontal spacing between successive HTs, based on the typical practice adopted in the USA. In total, seven HTs are employed in landfill C-3 compared to only four HTs in case of landfill C-1 (refer

Table 1). Reducing the horizontal spacing of HTs considerably improved the overall efficiency of the leachate recirculation operations in the MSW. This was achieved based on an enlarged MSW wetted area (i.e., approximately 93% of the total landfill area in only 13 years for C-3 than about 92% in 16 years for C-1) and thereby a relatively shorter injection duration for the attainment of MSW stabilization (13 years in C-3 compared to 16 years in C-1).

In this study, a one-week-on-off intermittent leachate injection mode is adopted by continuously injecting the leachate in the C-4 bioreactor landfill configuration for a week followed by a one week of gravity drainage, such that two out of the four horizontal trenches would be in operation at any moment of time. The injection cycle was performed using the injection pressure of 100 kPa until waste stabilization period. The overall leachate spread and moisture distribution in the MSW was significantly reduced due to the intermittent mode of injection, as represented by smaller MSW wetted area with time, when compared to the evolution of wetted area in C-1. Moreover, the MSW saturation gradually increased to high values unlike the bioreactor landfill C-1. However, at the end of waste stabilization period (i.e., 28 years of total intermittent injection), the wetted area for C-4 landfill system was almost same as for C-1 landfill after 16 years.

Pore Fluid Pressure

Fig. 4 shows the evolution and distribution of pore water pressures and capillary pressures along the horizontal landfill section A-A’ for all the landfill cases (C-1 to C-4). As can be seen from all four plots (Fig. 4a-d), pore-water pressure ranges from an initial negative value of approximately -5 kPa (representing matric suction due to unsaturated MSW) to as high as 100 kPa at the trench locations for all the selected landfill configurations. Pore-water pressures near trench locations were highest (approximately 80-100 kPa) in C-3 due to the closely spaced HTs, but the lowest in C-4 as the developed pore pressure had sufficient time to dissipate due to the one-week-on-off intermittent leachate injection. Conversely, the value of capillary pressure decreases with the leachate injection as the moisture is distributed with time in the MSW. All the landfill cases had an initial capillary pressure of approximately 19-21 kPa. Capillary pressure reduced to zero (along the section A-A') within a year of continuous leachate injection in C-1, C-2 and C-3. However, a relatively small capillary pressure ranging approximately from 3-10 kPa was observed in the landfill C-4, even after one year of leachate injection, due to the intermittent drying of MSW during the drainage period resulting in some portion of landfill area being unsaturated. The build-up of excessive pore water pressure was relatively lower in the steeper MSW slope (C-2), while the capillary pressure during the initial unsaturated MSW state was similar (as high as 21 kPa) in both 1V: 2H slope (C-2) and the 1V:3H landfill slope (C-1).

Moreover, the excessively developed pore water pressure at any given time was found to be higher for the bioreactor landfill with closely-spaced dense HTs (C-3) due to high pressure injection at several locations. Nevertheless, the capillary pressure due to initial unsaturated MSW was approximately the same within the first six months of continuous injection, irrespective of the recirculation trench configuration.

The intermittent leachate injection in landfill system C-4 provided enough time for the developed pore water pressure across the landfill section to dissipate during the rest period (gravity drainage), and this resulted in a safer landfill system than the landfill C-1. The pore pressures in case C-4 were relatively lower than the pore pressures in case C-1 due to intermittent injection. Moreover, the continuous injection of leachate in C-1 led to a higher pore water pressures, reducing the effective stress and thereby the shear strength of MSW.

Degree of Waste Degradation

One of the primary purposes of bioreactor landfill is to help accelerate waste stabilization by enhancing anaerobic decomposition of organic matter. Hence, it is important to understand the extent of waste degradation along the landfill depth with leachate injection. Fig. 5 shows the variation of waste degree of degradation (DOD) along with landfill depth for all the four landfill configurations. As it is evident, the DOD increases with the leachate injection in all landfill scenarios. Moreover, the DOD slightly increases with landfill depth as the leachate tends to accumulate in the deeper layers of landfill due to gravity and makes the anaerobic decomposition process relatively faster at deeper layers.

As the landfilled waste degrades, the geotechnical properties of MSW such as unit weight and shear strength properties are altered. Variations in MSW unit weight along the landfill depth (section B-B' in Fig. 1) for different leachate injection periods are plotted in Fig. 6. Changes in unit weight are quite evident with landfill depth as well as leachate injection time; higher MSW unit weights are observed in the deeper MSW layers due to relatively higher DOD. Unit weights range from 8 kN/m^3 to 12 kN/m^3 at the top MSW layer due to relatively low DOD and from about 11.5 kN/m^3 to 17 kN/m^3 at the bottom MSW layer because of higher levels of waste degradation. Moreover, rapid variations in MSW unit weight were found in the case of C-3 as a result of rapid waste degradation. In addition, the values of MSW unit weight obtained in this study are well within the reported range (Matasovic and Kavazanjian 1998; Zekkos et al. 2006).

In addition, it is important to note that no much variation was observed in the MSW unit weight at the end of 1-year of leachate injection in all four landfill systems, primarily due to the low degree of degradation. However, as the anaerobic biodegradation of the landfilled waste was expedited due to the increased moisture levels, a significant variation in the MSW unit weight could be noticed. At the end of 10 years of leachate injection, the MSW unit weight in landfill C-3 (with closely spaced HTs) was the highest with approximately 11.2 kN/m^3 at the top MSW layer to as much as 16.4 kN/m3 at the bottom layer, mainly due to the large extent of waste degradation in C-3 resulting from the increased level of overall moisture in a shorter time. The landfill C-4 with intermittent injection showed the smallest variation in the unit weight (10.7 kN/m^3 at the top layer to about 15 kN/m^3 at the bottom MSW layer) at the end of 10 years due to low DOD.

It was found that, at any given injection period, the degree of waste degradation in the 1V:2H landfill slope was lower due to slightly lower moisture levels than the 1V:3H slope; yielding in waste stabilization period of around 18 years compared to 16 years of continuous leachate injection in case C-1 with 1V:3H slope. In addition, the changes in unit weight were more pronounced in the flatter 1V:3H slope than the steeper 1V:2H (Fig. 6).

As a result of closely-spaced HTs, the waste degradation in bioreactor landfill C-3 was much faster compared to the typical bioreactor landfill C-1. As shown in Fig. 5, almost 98% of the waste degradation resulting in the MSW stabilization was attained within 13 years of the continuous leachate injection in C-3 compared to 16 years for C-1. As a result of the rapid waste degradation, changes in the geotechnical properties such as MSW unit weight were more predominant and were found to be higher than the MSW in the bioreactor landfill C-1.

Furthermore, the degree of waste degradation (DOD) were relatively less (approximately 40-50%) throughout the landfill C-4 than the DOD (60-75%) found in C-1 at the end of 5 years. As a result of the low DOD, the changes in geotechnical properties such as MSW unit weight along the landfill depth were relatively lower in the first 5 years of intermittent leachate injection. However, at the end of waste stabilization period (i.e., 28 years), the DOD was close to 97% across the landfill C-4, which resulted in MSW unit weight that was as high as 16.5 kN/m^3 at the bottom most layer.

Landfill Settlement

Prediction of total landfill settlement, both spatially and temporally, is one of the most challenging aspects of assessing the overall performance of bioreactor landfills. Dynamic conditions resulting from ever-changing geotechnical properties of MSW due to anaerobic waste decomposition makes it difficult to accurately determine the overall landfill settlement. Fig. 7 shows total surface settlement for all four selected landfill configurations during different periods of leachate injection. It is evident that as the waste degradation increases with the injection duration, large amount of landfill surface settlement is observed. This is primarily due to organic mass loss into biogas leading to more compressible and soft MSW with time due to anaerobic waste decomposition in the presence of adequate moisture. In addition, the volumetric deformation due to fluid flow (pore pressure dissipation) and changing unit weight and stiffness of MSW also contribute towards MSW settlement. As shown in Fig. 7, the total surface settlement varies from the initial primary compression of 3.4 m, to as much as approximately 10.8 m (in case of C-3 and C-4) of total landfill MSW settlement, towards the end of waste stabilization.

It is worth mentioning that the slower MSW degradation in the steep 1V:2H landfill slope condition led to a relatively smaller landfill surface settlement compared to the flatter 1V:3H landfill face slope at the end of their respective waste stabilization period. Similarly, a larger total surface settlement was observed in a relatively shorter duration in C-3, showing the efficacy of leachate recirculation operations through closely spaced HTs to uniformly distribute the moisture across the landfill.

In addition, due to the low moisture level and slow waste decomposition, the total MSW surface settlement in the bioreactor landfill C-4 was considerably less (approximately 8.8 m after 16 years) compared to the typical bioreactor landfill C-1 with continuous injection at the end of 16 years. However, the total settlement at the end of stabilization period (after a total duration 28 years) in C-4 with intermittent injection was as large as observed for the bioreactor landfill C-1.

Slope Stability

It is critical to assess the physical stability of bioreactor landfills to account for excessively generated pore fluid pressures caused by leachate injection in MSW. Factor of safety (FOS) was computed during the periods of leachate injection for all four landfill conditions and is plotted in Fig. 8. Initial values for factor of safety were the same (4.42) for C-1, C-3 and C-4, while the C-2 observed an initial FOS of 2.64 due to its 1V:2H landfill slope. The continuous leachate injection in C-1, C-2 and C-3 considerably reduced the FOS to as low as 1.57 in C-3 after 5 years of leachate injection. However, all the selected landfill conditions were found to be stable (i.e., FOS > 1.0) at the end of their respective waste stabilization period. The intermittent injection in C-4 showed lower pore fluid pressures than rest of the cases, thus resulting in significantly higher factors of safety compared to other landfill cases.

The change in landfill slope configuration during leachate operation did not influence the overall physical stability of bioreactor landfill, since both the steeper slope (1V:2H) and the flatter landfill slope (1V:3H) were found to be physically stable at the end of their respective waste stabilization period. However, the factors of safety were considerably lower in case C-2 because of steeper slope (1V:2H).

As expected, due to the build-up of excessively high pore fluid pressure, the computed FOS was lowest in C-3 (e.g., landfill with closely-spaced HTs) than C-1 (e.g., typical bioreactor landfill). Nevertheless, the bioreactor landfills were found to be physically stable (FOS > 1.0) at the end of their respective waste stabilization period for the site specific conditions and the material properties assumed.

The intermittent mode of leachate injection resulted in the bioreactor landfill slope being far more stable (due to low pore fluid pressure) than the bioreactor landfill case C-1 with continuous leachate injection. Meanwhile, it is important to note that the FOS values in all the cases showed a decreasing trend initially due to increasing pore pressures and thereafter increased for a certain time and later stabilized towards the end of the waste stabilization period. This is due to the changes in shear strength properties of MSW with degradation. During the initial few years the increase in pore pressures decreased the effective stress in MSW and thereby reducing its shear strength. However, the changes in the shear strength parameters of MSW (increase in cohesion and a decrease in friction angle) was significant after the initial few years leading to an effective increase in the shear strength of MSW during this course. The settlement also contributed to stability of the slope due to subsidence. Later, towards the end of waste stabilization the factor of safety slightly decreases and remains constant as waste stabilizes. It is worth mentioning that, the failure surface was initially around the face of MSW slope and with time the failure surface occurred deeper into the MSW region, causing rotational type of failure. In this study, since the MSW properties and the site conditions remained same, the trend in the variation of FOS values for all the landfill cases was nearly same. However, the magnitudes of these values were different, thereby capturing the effects of landfill slope, HT configuration and mode of leachate injection and thus signifying the importance of operational conditions on the performance of bioreactor landfill.

Interface Shear Behavior

The in-plane shear behavior (i.e., shear stress and shear displacement) of the composite landfill liner system with respect to its distance from the MSW slope toe at GL (see Fig. 1), for all selected bioreactor landfills are shown in Fig. 9 and 10. The induced shear stress along the flat, side slope liner and base liner during different periods of leachate injection are plotted in Fig. 9, while the mobilized shear strength along the composite liner system for the four landfill conditions is plotted in Fig. 11. In all the simulations the induced shear stress was found to increase from the far left end of the side slope liner along the interface reaching a maximum value and then sharply decreases to zero at the end of side slope liner. Similarly, the induced shear stress was found to increase initially from the left end along the base liner reaching a maximum value and then gradually decreases to zero towards the end of base liner. It is evident that side slope liner experienced higher induced shear stress (approximately 37.1 kPa in C-1, C-2 and C-3 to about 41 kPa in C-2) immediately after the placement of waste in layers. However, the base liner in all four landfill cases showed low induced shear stresses; the highest induced shear stress in base liner being approximately 4.8 kPa in case of C-1, C-3 and C-4 to around 2.3 kPa in case of C-2) at the end of waste placement in layers. It is important to note that the induced shear stresses in side slope decreased while the shear stresses in base liner increases with time in all the landfill cases. This is mainly attributed to changes in shear strength and stiffness of MSW with degradation. However, the magnitude of the shear stresses and shear displacement depends upon the rate at which the MSW degrades. The MSW was observed to be relatively less stiff (representing soft MSW conditions) with time when compared to initial fresh MSW. However, the MSW stiffness was found to increase along landfill depth in all the four landfill simulations. Similar trends of induced shear stress and shear displacement for the composite liner interface consisting of smooth HDPE geomembrane and nonwoven geotextile, in case of stiff and soft waste conditions have been reported in literature (Reddy et al. 1996). Moreover, it is worth mentioning that the steeper landfill slope (C-2) resulted in higher shear stress at the side slope and relatively lower shear stress at the base liner compared to the flatter bioreactor landfill slopes (i.e., C-1, C-3 and C-4).

The mobilized shear strength values in each of the selected landfill conditions were calculated at the end of their respective leachate recirculation period along the composite liner using the Coulomb shear strength failure criterion, and were compared with the respective induced interface shear stress at the end of waste stabilization period in each landfill case simulation. As shown in Fig. 11, the mobilized shear strength along the liner interface between the geomembrane and geotextile was higher than the induced shear stress for each landfill configuration. This criterion represents a stable and fully functional composite liner system in the landfills even after the complete waste stabilization period. However, this observation is valid only for the assumed site specific conditions and material properties. In addition, the mobilized shear strength ranged from 0 kPa at far left of interface (flat-run-out) to about 158 kPa at far right of the interface (end of base liner), and it was found to be higher at base liner than the side slope liner interface.

The interface shear displacement along the composite liner system follows the similar pattern as that of induced shear stress (i.e., higher shear displacements for the side slope liner and lower shear displacements for the bottom liner during initial waste placement) for all selected landfill configurations.

The effect of landfill slope gradient on the interface shear behavior (shear stress-displacement) of the composite landfill liner system is shown in Fig. 9 and Fig. 10. During the initial baseline condition (i.e., stiff MSW with no leachate injection), the side liner experienced greater induced shear stress (as high as 41 kPa) for the steeper landfill slope gradient of 1V:2H than the flatter 1V:3H slope gradient. Similar patterns of landfill slope gradient on interface shear stress, during the initial waste placement (stiff MSW), were observed by Reddy et al. (1996). The interface shear displacement along the side slope and bottom liners followed a similar trend as that of induced shear stress (Fig. 10), where the 1V:2H slope gradient encountered a larger shear displacement (as much as 17.5 mm) along the side slope than the 1V:3H landfill slope (15.8 mm). The bottom liner did not have any significant difference in shear displacement due to the change in landfill slope gradients, after the initial waste placement in layers. It is also important to note that the variation in shear displacement along the side slope liner in case C-2 is slightly different from the rest of the landfill cases. The shear displacements are found to be more concentrated towards the toe of the slope. This can be attributed to the fact that the slope configuration had its influence on the interface shear behaviour. A slope of 1V:2H can accommodate slightly more MSW on the side slope than the other landfill slope (1V:3H) considered thereby inducing higher lateral pressure on the side liner. Hence, the geometric configuration and the boundary conditions have significant impact on the interface shear behaviour of composite liner systems.

As the leachate is continuously injected, the landfill MSW becomes soft and dense due to anaerobic decomposition and settlement of MSW. As shown in Fig. 9, the soft MSW conditions resulted in lower values of induced shear stress than the stiff MSW conditions along the side slope liner for both C-1 and C-2 landfill conditions. Furthermore, the side slope liner in case C-2 (1V:2H slope) had higher induced shear stress than C-1 (1V:3H slope) with time. However, the bottom liner was observed to have higher shear stress for the flatter 1V:3H landfill slope gradient than for the steeper 1V:2H landfill slope. The interface shear displacement along the side liner, at the end of MSW stabilization period, was larger in case of steeper 1V:2H slope gradient (around 10 mm) than the flatter 1V:3H slope (about 6.7 mm). Similar to shear stress, the bottom liner was observed to have higher shear displacement for the flatter 1V:3H landfill slope gradient (13.5 mm) than for the steeper 1V:2H landfill slope (8.1 mm) at the end of waste stabilization.

In case of closely spaced dense HTs in bioreactor landfill C-3, the interface shear stress and the shear displacement along the side liner reduced drastically by approximately more than 17% and 15%, respectively, compared to the bioreactor landfill C-1, after 5 years of leachate injection. However, the interface shear stress and the shear displacement along the base liner for the landfill C-3 were (8% and 9% higher) than the landfill C-1, respectively, after 5 years of leachate injection. Moreover, the rapid degradation of MSW resulted in drastic changes in shear stresses and shear displacements when compared to the degradation of MSW in case C-1. Therefore, the horizontal trench layout and spacing is important for effectively performing leachate injection operations and also has its influence on the liner interface behavior in bioreactor landfill.

Additionally, as shown in Fig. 9 and Fig. 10, the intermittent leachate injection along the side slope liner in C-4 resulted in a gradual reduction in the peak interface shear stress and, peak shear displacement when compared to C-1. However, the interface shear stress and shear displacement along the bottom liner did not have any noticeable changes during the intermittent mode of leachate injection when compared to C-1. The relatively low degradation of MSW caused the MSW to stay relatively stiff resulting in slight decrease in shear stresses along the side slope liner. Furthermore, the mobilized shear strengths along the composite side slope and bottom liner system were much higher than the induced shear stress; representing a safe and fully operational liner system at the end of waste stabilization period in all the landfill simulations. A summary of the interface shear response for all the landfill simulations for different scenarios is presented in Table 5.

Conclusions

In this study, numerical simulations were performed to assess the influence of major system variables on the performance of bioreactor landfills subjected to coupled hydro-bio-mechanical processes under realistic field conditions. A newly developed and validated mathematical model was implemented to carry out the parametric study and investigate various field conditions such as: (a) the influence of bioreactor landfill slope configurations by comparing a typical 1V:3H face slope with a relatively steep 1V:2H face slope, (b) the impact of varying the geometric configuration of the horizontal trench systems (HTs) during the continuous leachate recirculation operations under pressurized conditions, and (c) the effect of leachate injection modes (i.e., continuous vs. one-week-on-off intermittent) of leachate injection on the overall performance of bioreactor landfills. The coupled modeling simulations for different landfill scenarios were performed until each MSW landfill attained its respective waste stabilization. In addition, for all coupled numerical simulations the geotechnical properties of the waste such as unit weight, saturated hydraulic conductivity, initial saturation, and initial porosity were varied along the landfill depth. Moreover, the interface shear behavior (shear stress-displacement) of the composite landfill liner (side liner and base liner) was assessed during all the aforementioned field conditions by considering an interface of 12-oz/yd^2 non-woven geotextile underlain by a 60-mil smooth HDPE geomembrane. The following conclusions were drawn from the parametric study:

- Varying the configuration of the bioreactor landfill MSW face slope from 1V:3H to a relatively steeper 1V:2H brought about a comparatively lesser spread of moisture, and relatively low build-up of pore fluid pressures in the MSW, low degree of degradation, and, consequently, a longer period of continuous leachate injection to attain the MSW stabilization. In addition, the overall MSW settlement and the variation in the geotechnical properties of the waste were subdued. However, during the initial stiff MSW conditions, the side liner experienced larger interface shear stress and shear displacement than the 1V:3H side slope. But, the soft MSW at the end of stabilization period that resulted from waste degradation led to smaller interface shear stress and shear displacement for the base liner with the 1V:2H landfill slope compared to 1V:3H side slope.
- Continuous leachate recirculation through closely spaced horizontal trenches (i.e., reduced spacing between successive HTs) resulted in the more uniform and rapid spread of moisture, relatively high pore fluid pressures, greater extent of waste degradation and subsequently, shorter leachate injection operations to attain complete waste stabilization

than the bioreactor landfill with widely-spaced HTs (C-1). Additionally, the overall MSW settlement and the variation in geotechnical properties were large. Furthermore, due to high rates of MSW degradation with increased moisture levels there was drastic decrease in shear stresses and shear displacements along the side slope liner and a rapid increase in shear stress and shear displacements along base liner when compared to case C-1. The increased number of HTs also contributed to high pore pressures and consequently leading to reduction in shear strength of MSW and thereby the stability of MSW slope considerably.

- An intermittent mode of leachate injection in the bioreactor landfill was found to be effective and the most suitable approach for adding the leachate in the landfilled waste since, the intermittent injection mode was able to uniformly spread the moisture and attain waste stabilization. It also maintained a relatively low pore pressure across the waste due to significant amount of rest periods in between the leachate operation to ensure the dissipation of excessively developed pore pressure. Moreover, the landfill slope was more physically stable due to the relatively low excess pore-fluid pressure with time. The intermittent flow led to lower wetted area and thereby low rates of biodegradation initially. However, with time the leachate was distributed more uniformly and ensured favourable moisture for biodegradation of MSW. In addition, in the first 15 years the interface shear stresses and shear displacements were found to decrease along the side slope liner but to a lower extent when compared to case C-1. However, by the end of waste stabilization the induced shear stresses were similar. A higher value for the factor of safety with time indicates the efficacy of intermittent injection over continuous injection without compromising the stability of landfill slope.

Overall, this parametric study showed the importance of assessing various system and operational conditions for optimal design and performance of bioreactor landfills considering the influence of coupled hydro-bio-mechanical processes during the leachate injection operations.

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Table 1. Different bioreactor landfill scenarios considered in the study

Bioreactor Landfill Scenarios	MSW Slope Face (1V:*n*H)	Total Number of HTs	Horizontal Spacing between HTs, H (m)	Vertical Spacing between HTs, V (m)	Setback from the side slope (m)	Mode of Leachate Injection
C-1	1V:3H	4	30	10	30	Continuous
C-2	1V:2H	4	30	10	30	Continuous
C-3	1V:3H	7	15	10	30	Continuous
C-4	1V:3H	4	30	10	30	Intermittent (1-Week-On-Off)

Table 2. Material properties for landfill liners and final cover systems

Properties	Native Soil	Compacted Clay	Drainage Layer	Vegetative Soil	Interface between smooth HDPE geomembrane & non-woven Geotextile
Density (kg/m^3)	2100	2030	1835	1835	-
Cohesion (kPa)	80	48	0	72	2*
Friction Angle (Deg)	0	0	32	0	14*
Bulk Modulus (Pa)	2 x 10^8	1 x 10^8	3 x 10^8	9 x 10^7	-
Shear Modulus (Pa)	1 x 10^8	6 x 10^7	2 x 10^8	6 X 10^{7†}	-
Total Porosity (%)	43.7	41.3	45.7	43.7‡	-
Normal Stiffness (Pa)	-	-	-	-	3 x 10^{7§}
Shear Stiffness (Pa)	-	-	-	-	3 x 10^{6§}

*Wasti and Özdüzgün (2001)

†Reddy et al. (1999)

‡HELP Manual, USEPA (1994)

§Jones and Dixon (2005); Sia and Dixon (2012)

Table 3. Initial properties of MSW considered for model simulations

MSW Layers	Depth (m)	Unit Weight γ (kN/m^3)^1	Vertical Hydraulic Conductivity k_v (cm/s)^2	Saturation (%)	Porosity (%)^3
10 (Top)	0-3	8	9.1×10^{-4}	36	54
9	3-6	8.7	6.8×10^{-4}	37	50
8	6-9	9.2	3.1×10^{-4}	38	47
7	9-12	9.6	1.5×10^{-4}	39	44
6	12-15	9.9	9.5×10^{-5}	40	42
5	15-18	10.1	8.0×10^{-5}	41	40
4	18-21	10.3	4.3×10^{-5}	42	39
3	21-24	10.5	2.5×10^{-5}	43	38
2	24-27	10.6	1.4×10^{-5}	44	37
1 (Bottom)	27-30	10.8	9.3×10^{-6}	45	36

[1] Zekkos et al. (2006)
[2] Reddy et al. (2009)
[3] Calculated from mass-volume relationships

Table 4: Unsaturated hydraulic MSW parameters based on Breitmeyer and Benson (2011)

Parameter	**Value**
Unit Weight (kN/m^3)	7.8
Matric suction α (1/kPa)	1.18
Saturated moisture content θ_s	0.41
Residual moisture content θ_r	0.03
van Genuchten ‘n’	1.33
van Genuchten ‘m’	0.25

Table 5. Summary of the shear response of liner interface for all the landfill simulations

Landfill Case	Time (Years)/MSW Condition	Maximum shear stress (kPa)		Maximum shear displacement (mm)	
		Side slope	Base	Side slope	Base
C-1	End of MSW Placement (Stiff)	37.1	4.8	15.8	1.9
	5 (Intermediate)	24.1	29.2	11.2	11.4
	16 (Soft)	14.3	34.5	7.6	13.5
C-2	End of MSW Placement (Stiff)	41	2.3	17.5	1
	5 (Intermediate)	29.9	17.4	13.5	6.8
	18 (Soft)	22.3	20.9	9.9	8.1
C-3	End of MSW Placement (Stiff)	37.1	4.8	15.8	1.9
	5 (Intermediate)	20.1	31.7	9.5	12.4
	13 (Soft)	13.9	35.5	6.5	14
C-4	End of MSW Placement (Stiff)	37.1	4.8	15.8	1.9
	5 (Intermediate)	31.7	23.7	14.4	9.1
	28 (Soft)	14.5	34.5	6.7	13.5

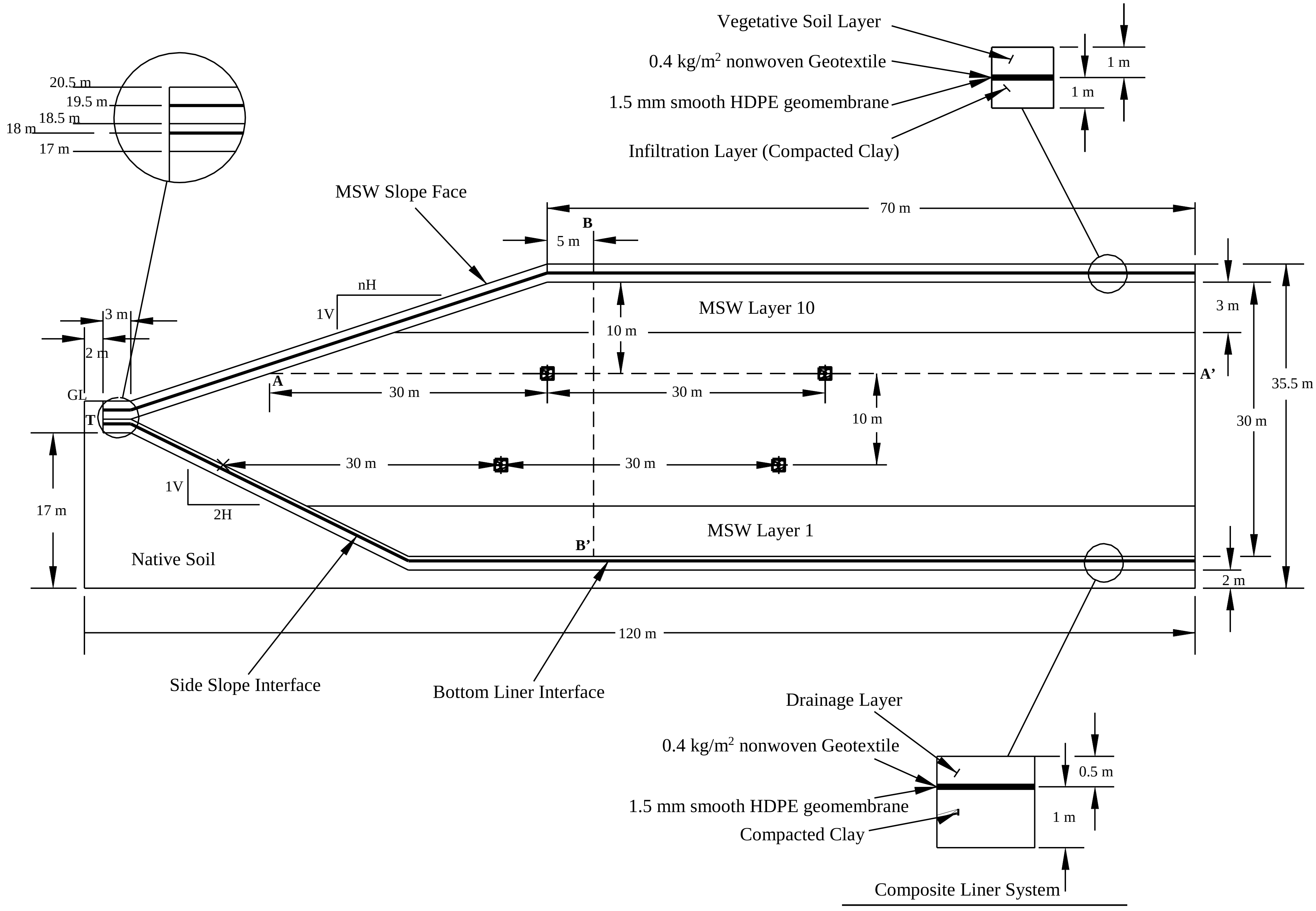


Fig. 1. Typical bioreactor landfill configuration along with its various components selected for numerical simulations

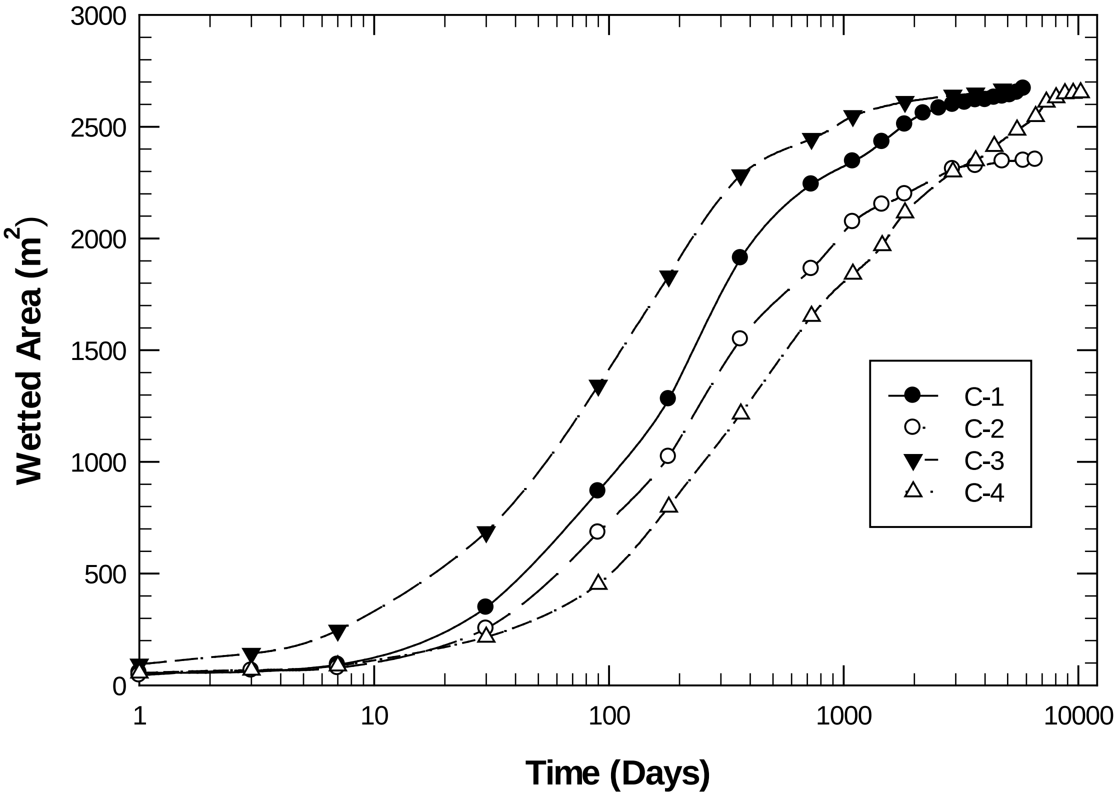
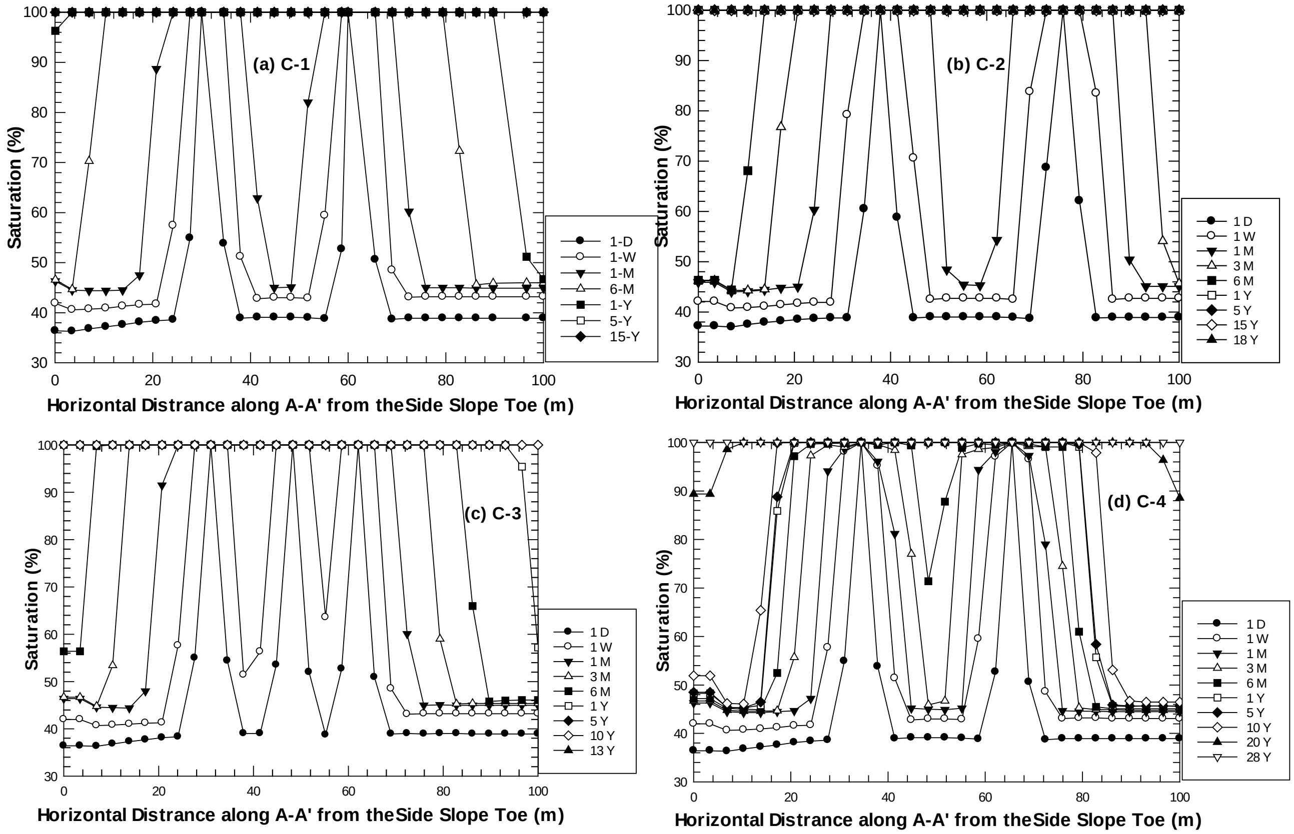


Fig. 2. Evolution of MSW wetted area with injection time for (a) C-1, (b) C-2, (c) C-3, and (d) C-4 bioreactor landfills using an injection pressure of 100 kPa



**Note: D, W, M, and Y here represent day, week, month, and year, respectively*

Fig. 3. Degree of saturation along the landfill section A-A’ with leachate injection time for (a) C-1, (b) C-2, (c) C-3, and (d) C-4 bioreactor landfills using an injection pressure of 100 kPa

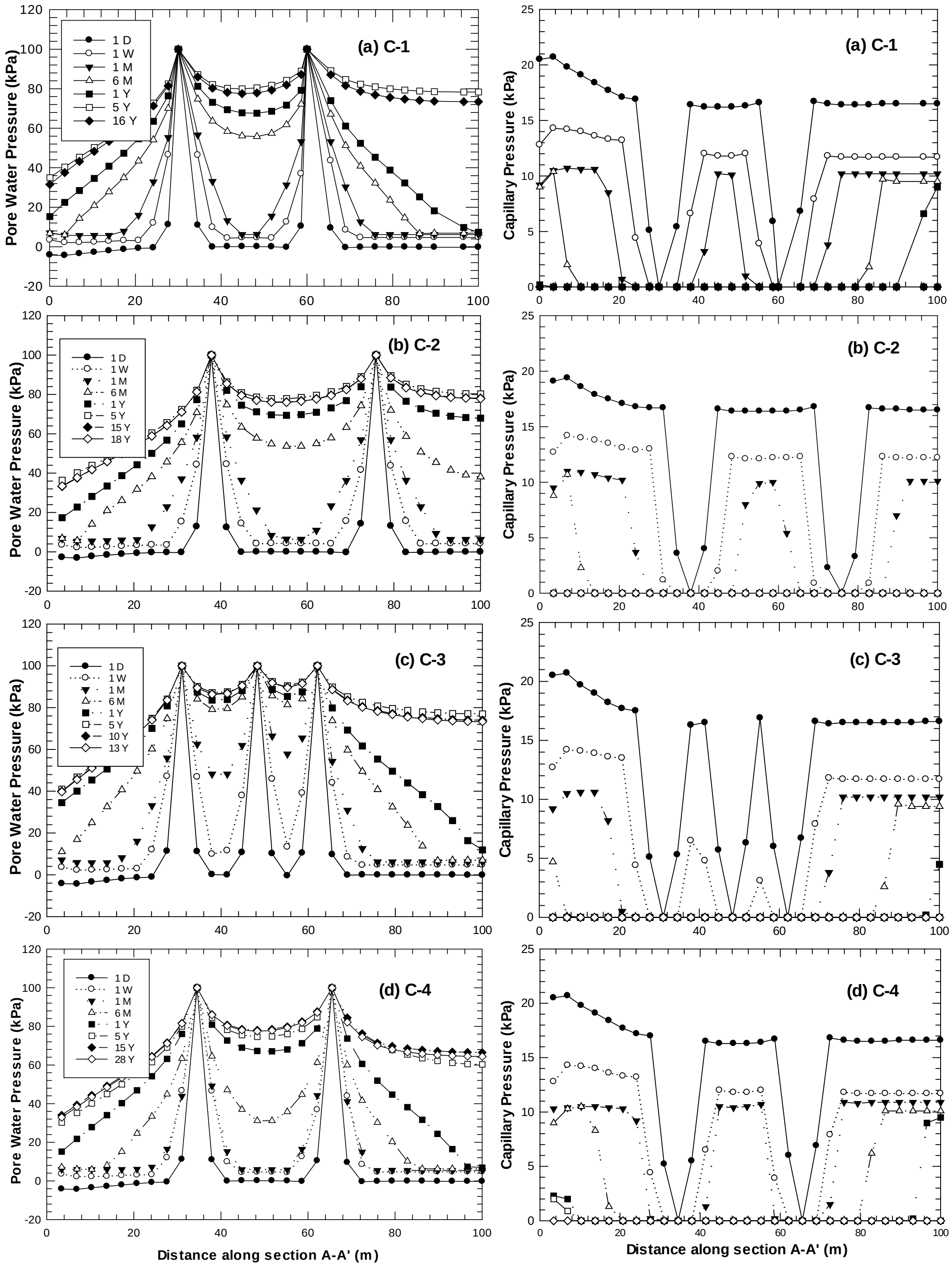


Fig. 4. Pore-water and capillary pressure distribution along landfill section A-A' with leachate injection time for (a) C-1, (b) C-2, (c) C-3, and (d) C-4 bioreactor landfills.

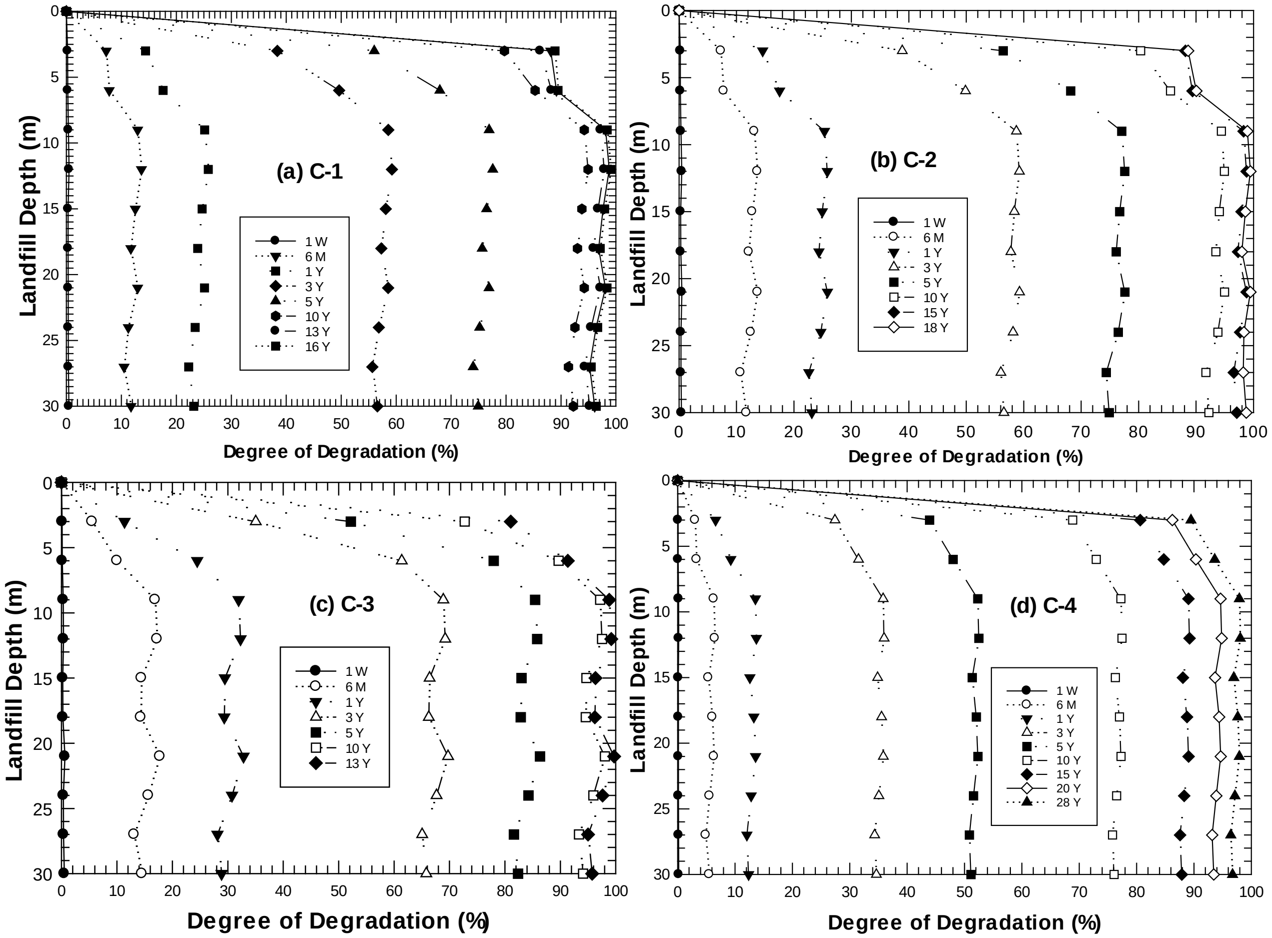


Fig. 5. Degree of waste degradation with depth along section B-B’ with leachate injection time for (a) C-1, (b) C-2, (c) C-3, and (d) C-4

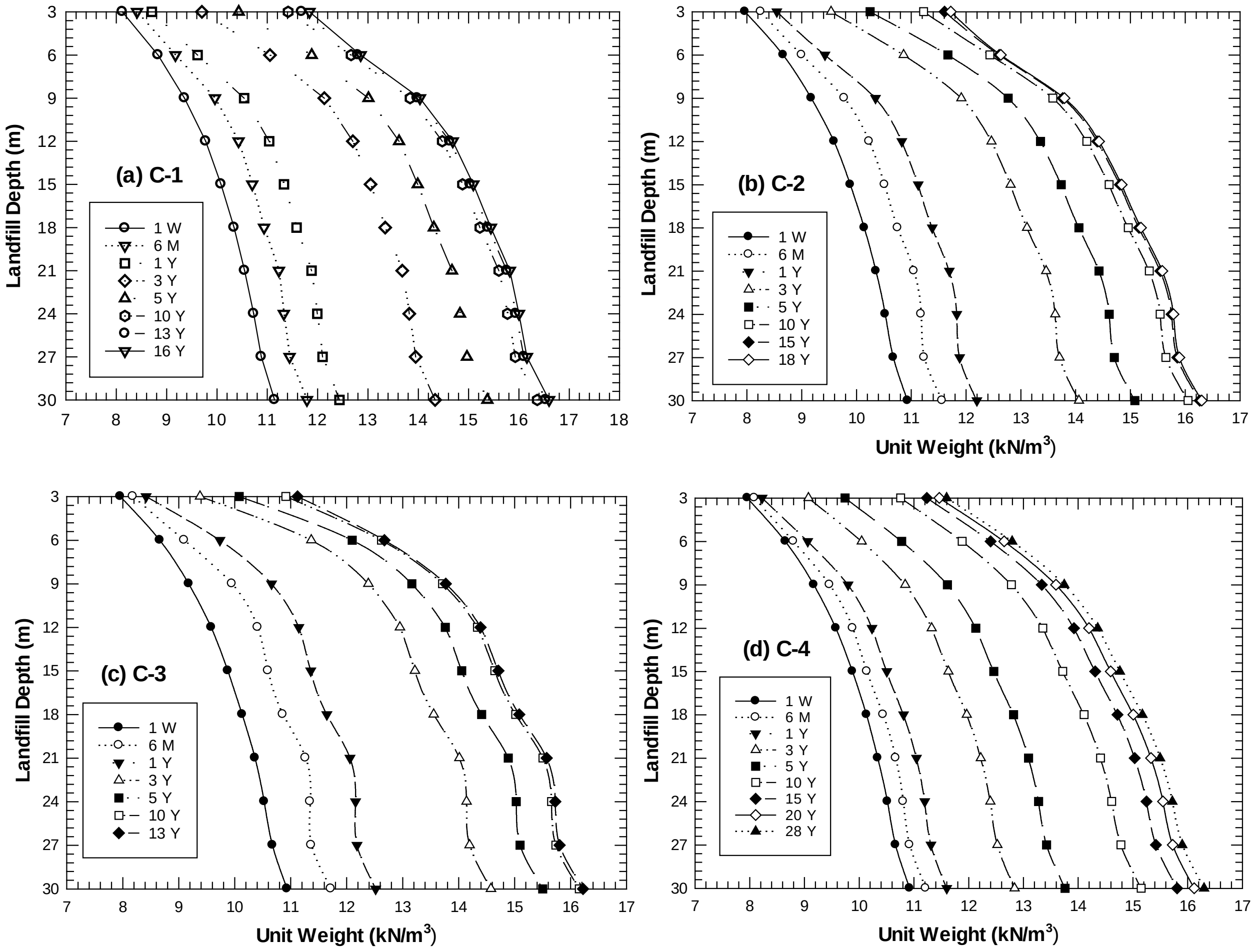


Fig. 6. Variation in MSW unit weight with depth along the section B-B' with leachate injection time for (a) C-1, (b) C-2, (c) C-3, and (d) C-4

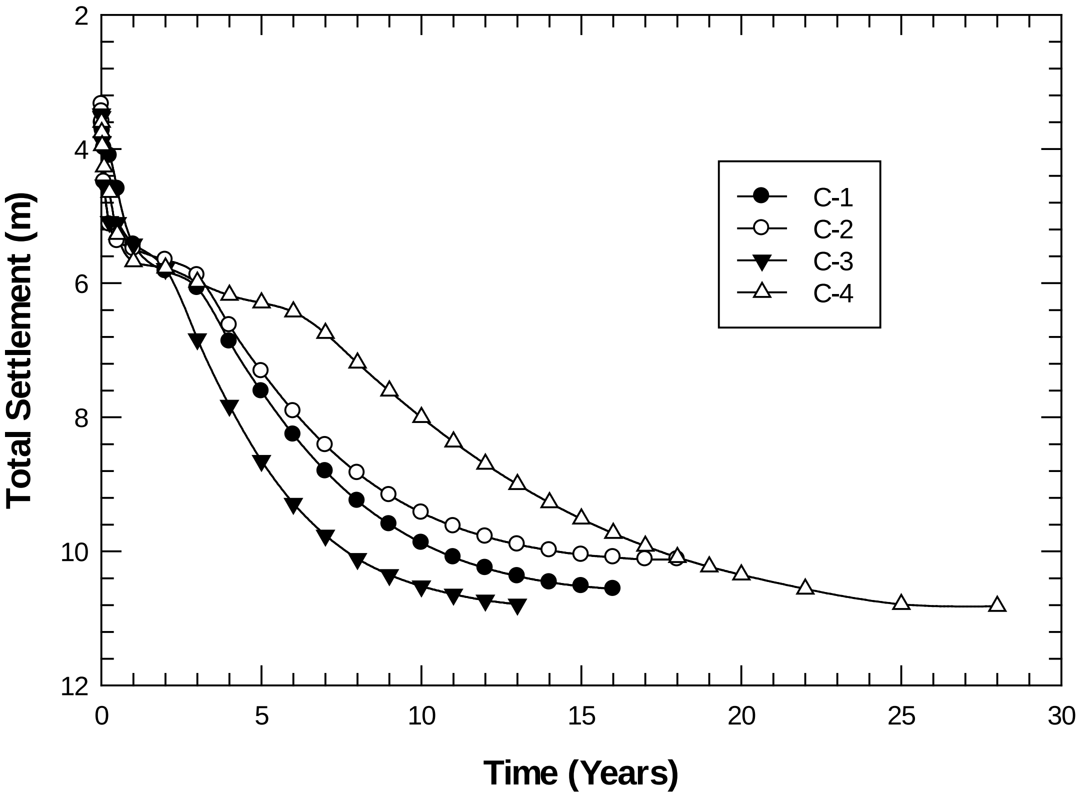


Fig. 7. Total landfill surface settlement with leachate injection time for the different system and landfill operating conditions considered

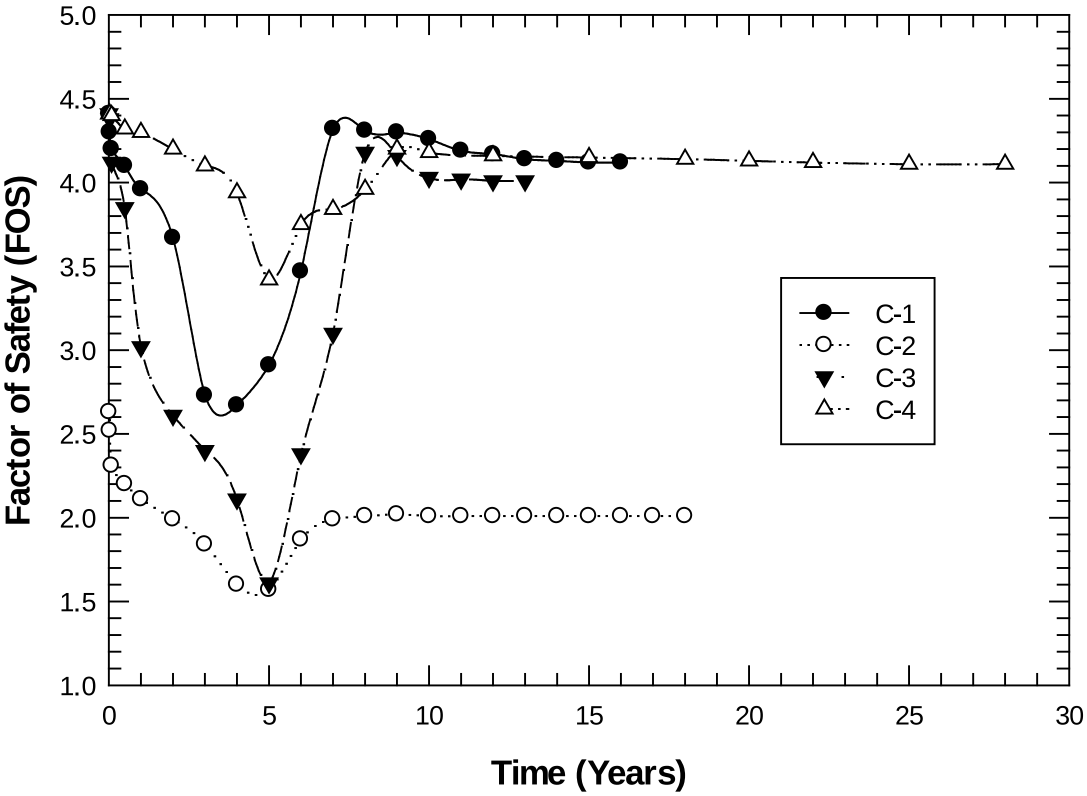


Fig. 8. Factors of safety with leachate injection time in bioreactor landfills with different system and landfill operating conditions considered

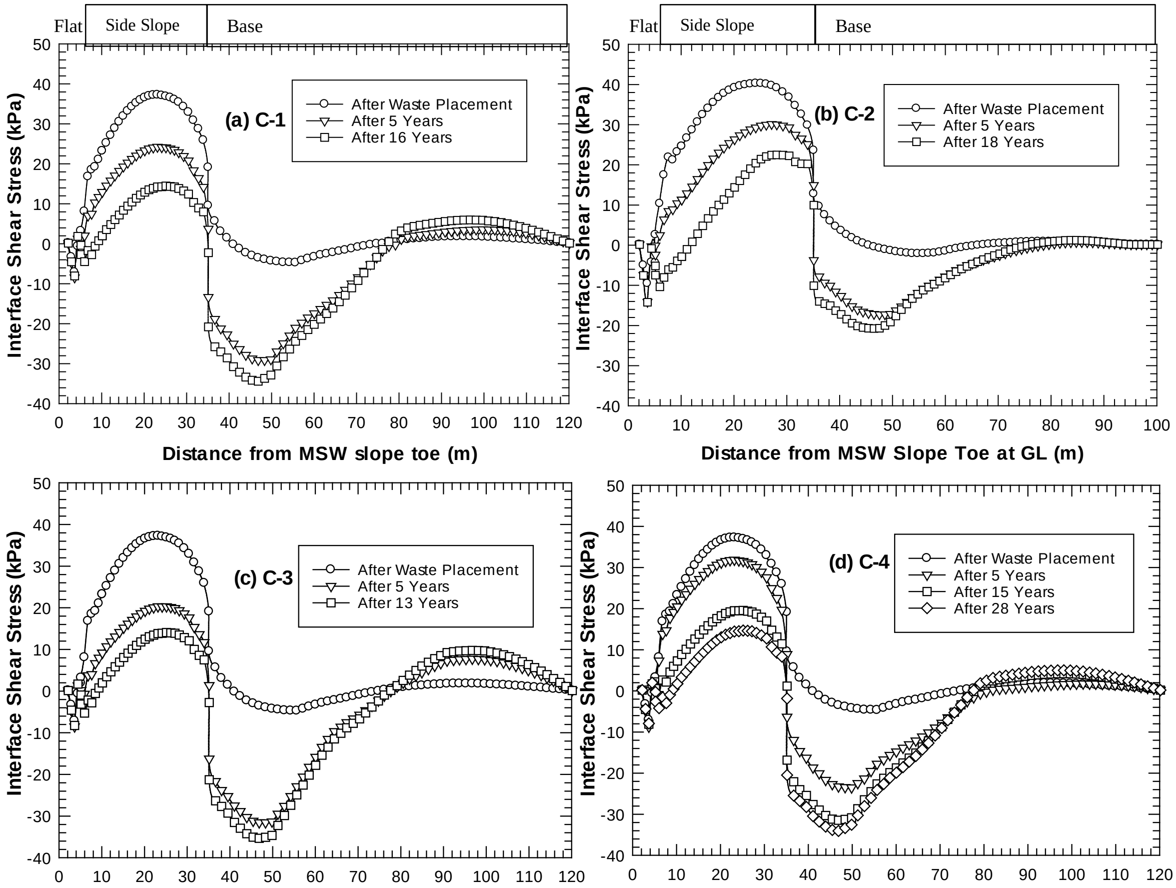


Fig. 9. Interface shear stress along the composite side and bottom liner system with leachate injection time for (a) C-1, (b) C-2, (c) C-3, and (d) C-4

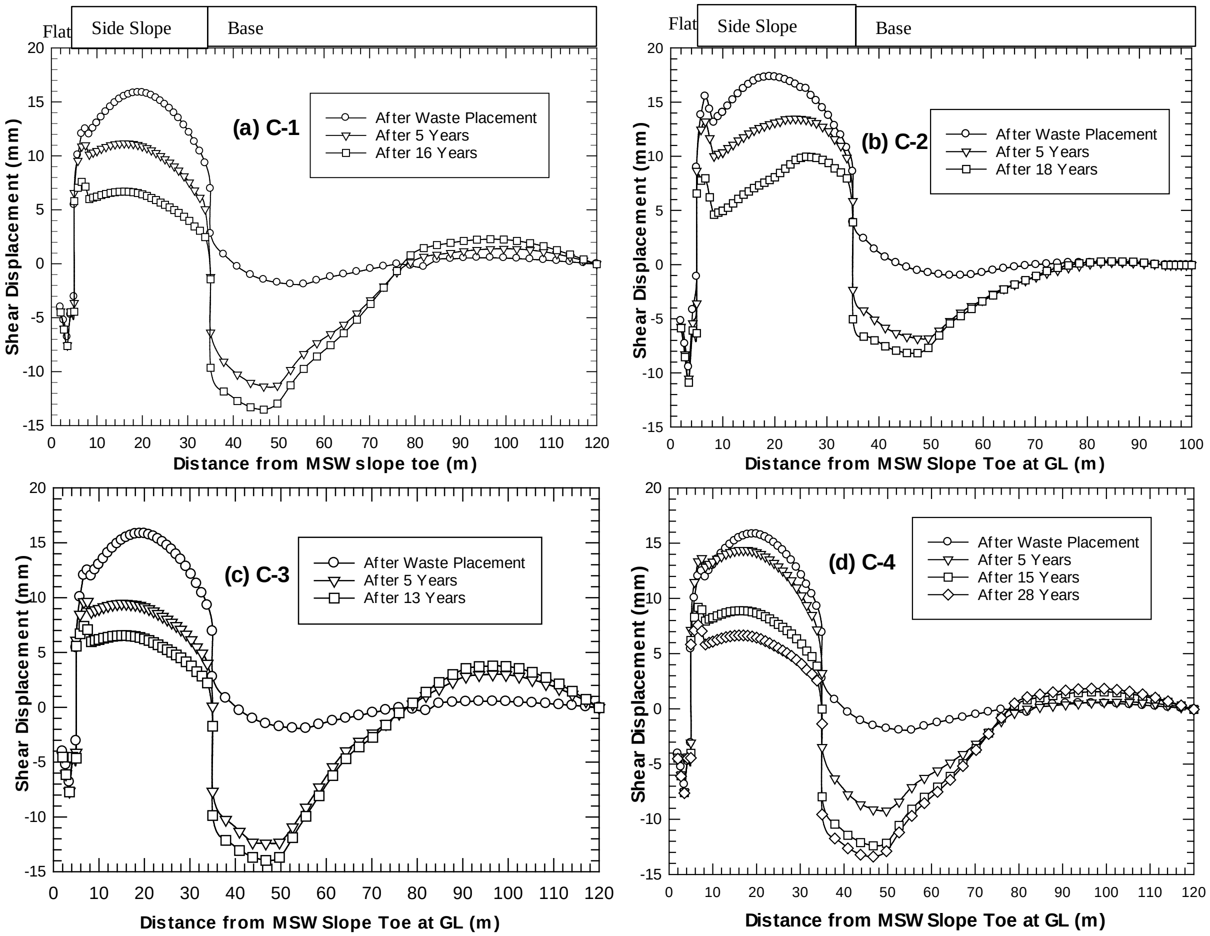


Fig. 10. Interface shear displacement along the composite liner system with leachate injection time for (a) C-1, (b) C-2, (c) C-3, and (d) C-4

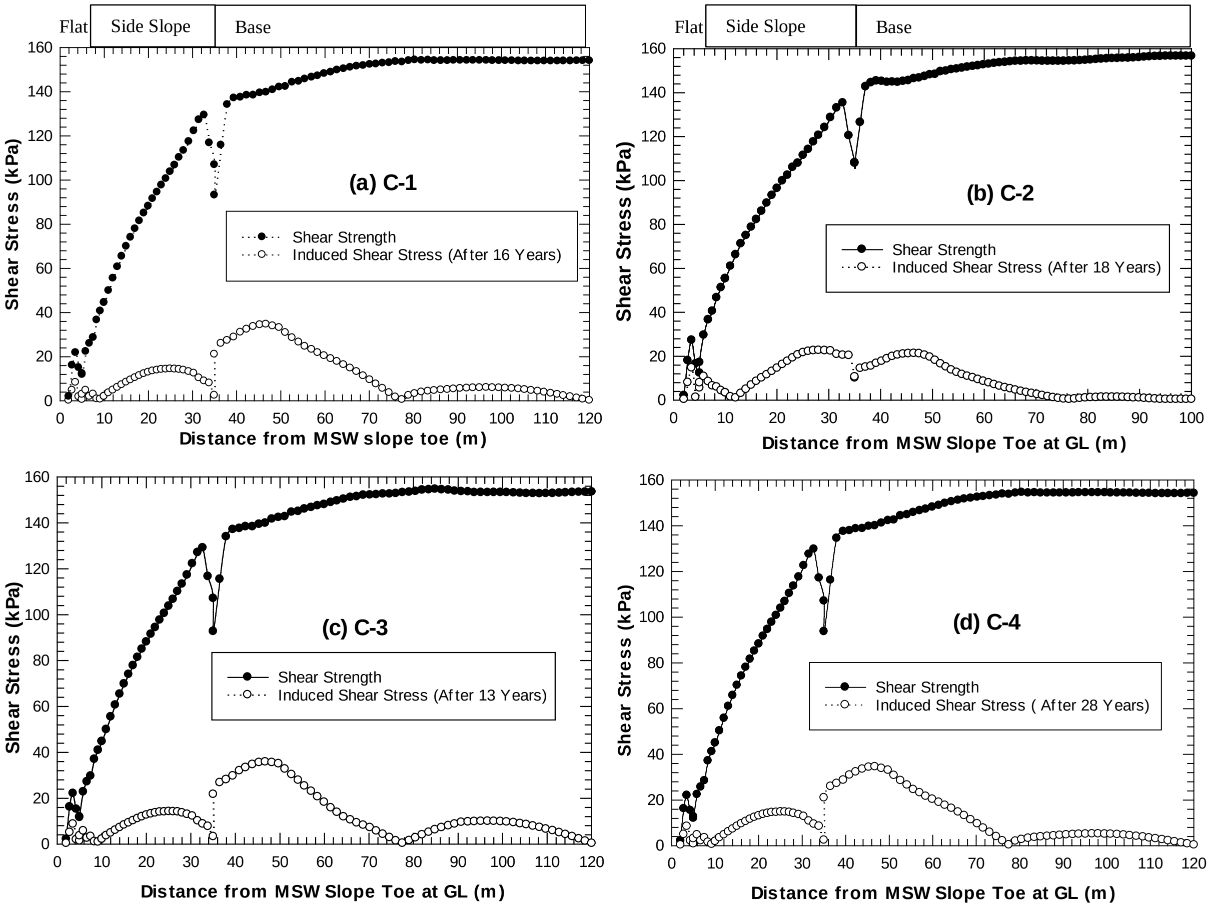


Fig. 11. Mobilized shear strength along the composite side and bottom liner system at the end of waste stabilization for (a) C-1, (b) C-2, (c) C-3, and (d) C-4