Technical Note

Influence of Spatial Variation of Hydraulic Conductivity of Municipal Solid Waste on Performance of Bioreactor Landfill

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Abstract: The current study analyzes the leachate distribution in the Orchard Hills Landfill, Davis Junction, Illinois, using a two-phase flow model to assess the influence of variability in hydraulic conductivity on the effectiveness of the existing leachate recirculation system and its operations through reliability analysis. Numerical modeling, using finite-difference code, is performed with due consideration to the spatial variation of hydraulic conductivity of the municipal solid waste (MSW). The inhomogeneous and anisotropic waste condition is assumed because it is a more realistic representation of the MSW. For the reliability analysis, the landfill is divided into 10 MSW layers with different mean values of vertical and horizontal hydraulic conductivities (decreasing from top to bottom), and the parametric study is performed by taking the coefficients of variation (COVs) as 50, 100, 150, and 200%. Monte Carlo simulations are performed to obtain statistical information (mean and COV) of output parameters of the (1) wetted area of the MSW, (2) maximum induced pore pressure, and (3) leachate outflow. The results of the reliability analysis are used to determine the influence of hydraulic conductivity on the effectiveness of the leachate recirculation and are discussed in the light of a deterministic approach. The study is useful in understanding the efficiency of the leachate recirculation system. **DOI: 10.1061/(ASCE)GT.1943-5606.0000930.**

CE Database subject headings: Landfills; Moisture; Biological processes; Solid wastes; Municipal wastes; Pore water; Two phase flow; Hydraulic conductivity; Numerical models.

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Introduction

The moisture distribution (recirculated leachate) in a bioreactor landfill greatly depends on parameters, such as the leachate recirculation system (LRS), leachate injection rates, mode of leachate recirculation, and permeability of municipal solid waste (MSW). Existing landfills show large variation in their performance with regard to moisture distribution, for example in the Orchard Hills Landfill. Field investigations indicated that there is not enough leachate generated for the leachate recirculation using the existing horizontal trench (HT) system (Reddy et al. 2009b). Likewise, observations show that the zone of influence of the leachate injection system is low and the extent of the enhanced waste degradation is insignificant. Haydar and Khire (2004) numerically studied the effect of heterogeneity and anisotropy in the hydraulic properties of waste on the magnitude of leachate flux using a LRS consisting of HTs. They found that introduction of heterogeneity and anisotropy resulted in greater leachate flux than when waste was assumed homogeneous and isotropic.

Haydar and Khire (2005a) proposed design guidelines for leachate recirculation in MSW landfills consisting of HTs. The design parameters evaluated in the study included (1) leachate injection pressure head, (2) hydraulic conductivity of trench backfill and MSW, (3) dimensions of the trench, and (4) spacing and geometric formation of trenches. Haydar and Khire (2005b) further studied the effect of heterogeneity and anisotropy in the hydraulic conductivity of MSW on the leachate flux that can be recirculated at a steady-state flow condition, and they established that heterogeneity and anisotropy in hydraulic conductivity of MSW allow recirculating of greater leachate flux than homogeneous and isotropic waste under equivalent conditions. However, heterogeneity and anisotropy results in relatively nonuniform wetting of MSW. Although these studies provide valuable input in assessing the performance of MSW landfills, a study of moisture distribution in a heterogeneous MSW with due consideration to the effect of the spatial variability of the hydraulic properties of MSW on its performance is not yet established. Hence, the objectives of the current study are:

1. To conduct numerical analysis using finite-difference code (*FLAC 2D*), developed by Itasca Consulting Group (2008), considering MSW saturated hydraulic conductivity as spatially variable within the waste mass and perform Monte Carlo simulations to capture the statistical response on the mean and SD of output parameters; that is, wetted area, pore pressure (PP), and outflow rate; and to compare and examine those results in the light of a deterministic approach; and
2. To utilize statistical information with respect to the output parameters for the reliability analysis that uses the first-order reliability method; and to provide guidelines for improving the performance of LRS.

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Numerical Modeling of Municipal Solid Waste Landfill

Landfill Model

The bioreactor landfill cell used in this study is from the Orchard Hills Bioreactor Landfill, Davis Junction, Illinois. It is 150 m wide and has an average height of 30 m. The section of the landfill model is shown in Fig. 1. It consists of four HTs, located in two layers, which function as a LRS. Initially, under an unsaturated condition, MSW experiences the flow of the generated leachate and landfill gas until all of the pores in the MSW solids are filled with the injected leachate. Therefore, the moisture distribution in the MSW has to be considered using two-phase flow criteria. To account for the flow in unsaturated MSW, the two-phase flow represents the two immiscible fluids, which may be water and gas, filling the void spaces. In the numerical analysis using Fast Lagrangian Analysis of Continua (FLAC), fluid flow is described by Darcy's law, and the unsaturated hydraulic conductivity parameters are modeled using the van Genuchten (1980) function considering the whole water retention curve. A detailed discussion of modeling appears in the Itasca Consulting Group (2008) reference manual. The general initial condition parameters, which are used across all of the model simulations, are summarized in Table 1 (Stoltz et al. 2012). In the numerical analysis, the bottom boundary is fixed and two boundaries on the vertical sides of the landfill are restrained horizontally.

Variability in Hydraulic Properties of Municipal Solid Waste

The available literature (Reddy et al. 2009a) shows large variation in the permeability data, and coefficients of variation (COVs) in the range of 165 (field data) to 385% (laboratory data) are reported. The values for mean vertical saturated hydraulic conductivity (k_v) in each layer are taken as Layer $1 = 5.0 \times 10^{-3}$, Layer $2 = 4.0 \times 10^{-3}$, Layer $3 = 3.5 \times 10^{-3}$, Layer $4 = 3.0 \times 10^{-3}$, Layer $5 = 2.5 \times 10^{-3}$, Layer $6 = 2.0 \times 10^{-3}$, Layer $7 = 1.7 \times 10^{-3}$, Layer $8 = 1.5 \times 10^{-3}$, Layer $9 = 1.0 \times 10^{-3}$, and Layer $10 = 8.0 \times 10^{-4}$ cm/s. Anisotropy of waste mass is simulated assuming the mean horizontal hydraulic conductivity (k_h) varying 10 times the mean vertical saturated hydraulic conductivity. Thus, the study considers inhomogeneous and anisotropic MSW compacted in 10 layers. Given the limited data

Table 1. Hydraulic Parameters That Were Kept Constant in Numerical Modeling of Municipal Solid Waste

Model parameter	Values chosen
Wetting fluid pore-water pressure	0
Nonwetting fluid pore pressure	0
Wetting fluid bulk modulus (Pa)	2×10^9
Nonwetting fluid bulk modulus (Pa)	1×10^5
Initial moisture content of municipal solid waste (θ_i) (percentage)	24
Residual moisture content (θ_r) (percentage):	
Municipal solid waste	20
Gravel as backfill in horizontal trench	2
van Genuchten parameter (α) (kPa):	
Municipal solid waste	2.9
Gravel as backfill in horizontal trench	5.7
van Genuchten parameter (a):	
Municipal solid waste	0.318
Gravel as backfill in horizontal trench	0.88
van Genuchten parameter (b)	0.50
van Genuchten parameter (c)	0.50
Porosity (n) (percentage):	
Municipal solid waste	60
Gravel as backfill in horizontal trench	47
Coefficient of pore-water pressure increment because of volumetric strain (β)	0
Viscosity ratio	37.5
Saturated hydraulic conductivity (k_{sat}) (cm/s):	
Gravel as backfill in horizontal trench	1.0×10^{-2}

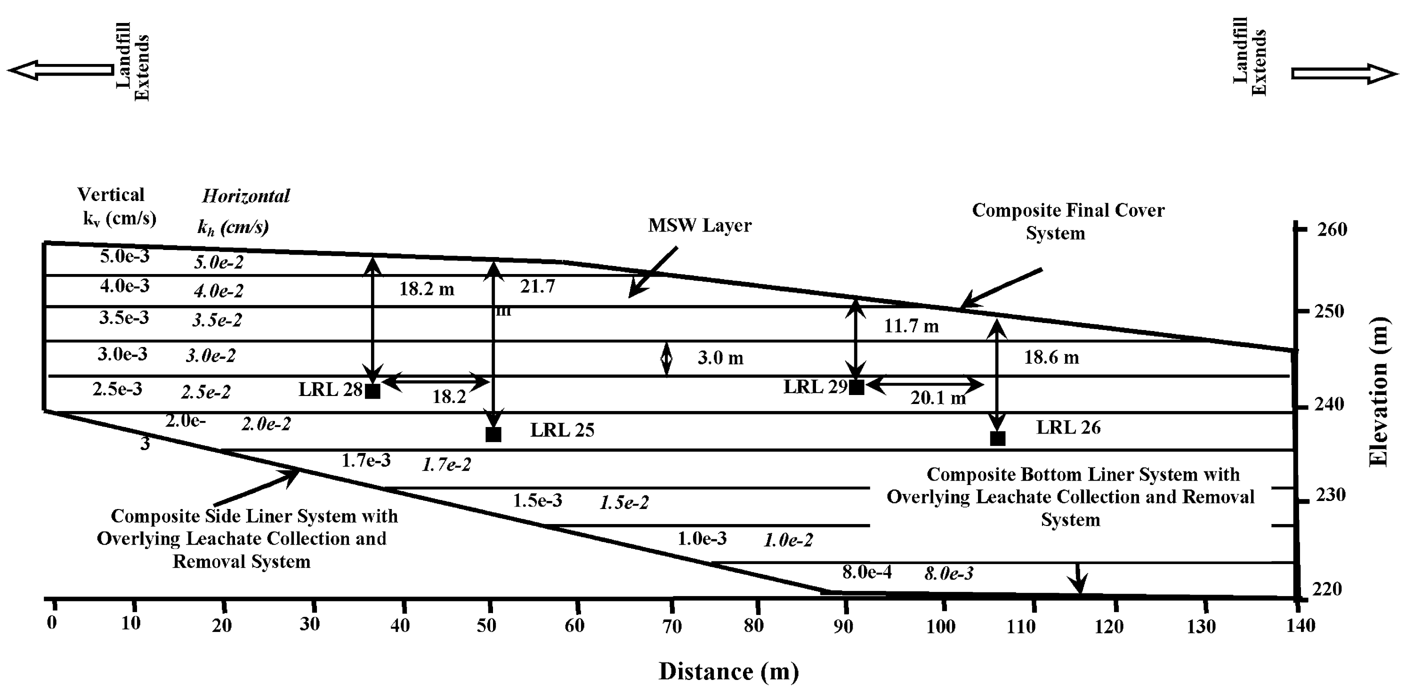

Fig. 1. Cross section of the Orchard Hills Landfill with leachate recirculation lines selected for modeling

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available, the unsaturated hydraulic conductivity parameters of MSW for the van Genuchten fitting function are taken, as recommended by Stoltz et al. (2012).

Reliability Analysis

Monte Carlo Simulations

To study the effect of random variation of hydraulic conductivity of MSW, a parametric study was carried out considering four different COV values, that is, 50, 100, 150, and 200%. In the current study, 100 numbers of simulations are found to be sufficient because there was no significant change in the value of δ_f (variance of the estimated mean of output parameters) after that.

Reliability Index (β)

The two parameters affecting the efficiency of LRSs and the overall efficiency of bioreactor landfills are (1) the percentage of area of influence (i.e., the ratio of the wetted area of MSW because of leachate recirculation to the total area of MSW) and (2) the ratio of PP to total stress (at the injection point). For proper biodegradation of MSW, the configuration of the LRS and leachate injection rate should be such that the percentage area of influence is 100%, and the injection rate should be such that the ratio of PP:total stress does not reach 1.0, which can be considered capacity (C). Demand (D) is the estimated values of the same performance parameters. If the performance function $G(x)$ is defined as $G(x) = C - D$, for uncorrelated C and D, the reliability index (β) value is evaluated using Eq. (1) (Baecher and Christian 2003)

$$\beta = \frac{\mu_C - \mu_D}{\sqrt{\sigma_C^2 + \sigma_D^2}} \tag{1}$$

The mean (μ_C, μ_D) and SD (σ_C and σ_D) in capacity and demand, respectively, are obtained through Monte Carlo simulations incorporating numerical analysis. The United States Army Corps of Engineers (1997) made specific recommendations on target reliability indexes (β) in geotechnical and infrastructure projects and suggested that a reliability index value of at least 3.0 is needed for an above-average performance of the system and a minimum reliability index of 5.0 is recommended for excellent performance.

Results and Discussion

In the waste mass that has the saturated hydraulic conductivity spatially distributed, the leachate was injected at the rate of 8 m^3d per meter length of the HT with an intermittent mode of leachate injection in alternate layer of HTs. The leachate was recirculated continuously for the first 2 weeks in the two shallow HTs [leachate recirculation lines (LRLs) 28 and 29]. Then, leachate was only recirculated in the deep HTs (LRLs 25 and 26). Next, the same sequence of leachate recirculation was followed through 8 weeks of flow. For Weeks 9 and 10 of flow, leachate recirculation was stopped in all the LRLs, and gravity drainage only was used. The results are compared for the influenced MSW wetted area, developed pore-water pressure, and outflow computed after 2, 8, and 10 weeks of flow. The modeling parameters that were kept constant are provided in Table 2. Results from the spatial variation analysis are discussed in light of a deterministic case in which the inhomogeneous and anisotropic waste condition is studied. Figs. 2 and 3 show the variation of mean and SD of the percentage area of influence PP total stress ratio and outflow, with different values of COVs of spatially varying hydraulic conductivity of MSW, respectively.

Wetted Area of Municipal Solid Waste

The percentage area of influence of the LRS is in the range of 8–15%, which is on the lower side of the expected range (60–70%). The extent of spatial variation in hydraulic conductivity of the MSW reduces both the mean and SD of the computed values of the percentage area of influence. This indicates that as the variability in the hydraulic conductivity increases, the leachate recirculation is more localized because the flow takes place through a highly permeable region in a spatial variable media, thereby reducing the performance.

Maximum Pore-Water Pressure

The mean and SD of the PP:total stress ratio reduces with an increase in the COV values of hydraulic conductivity. The variation of the ratio of the mean PP:total stress in the range of 0.2–0.3 corresponds to a higher COV (150–200% range) in hydraulic conductivity. Deterministic analysis results indicate that the ratio of the mean PP: total stress is 0.35–0.45, providing a factor of safety in the range of 2–3. With due consideration to the spatial variation in hydraulic conductivity, the PP that develops within the landfill mass is further reduced.

Effects on Outflow

The higher COV values reduce the outflow collected in the leachate collection and removal system (LCRS), and a large variation in outflow is expected. The amount of outflow estimated with due consideration of spatial variable permeability property is significantly less than that obtained from the deterministic approach. With an increase in COV values, the SD of the outflow value has increased, indicating a large variation in the outflow.

Reliability Indexes

Table 3 shows the reliability index values calculated for different values of the percentage area of influence of MSW and its COV, ranging from 5 to 30%. The reliability index values increase with the increase in the percentage area of influence of MSW and, at the same time, decrease with an increase in COV values. The results of the reliability analysis suggest that the LRS should be redesigned such that, the percentage area of influence of MSW is not less than 60% to achieve the excellent performance level in a worst case scenario (highly heterogeneous MSW giving 30% COV).

Table 2. Model Input Parameters (Mechanical Properties Kept Constant)

Model parameter	Values chosen
Bulk modulus of municipal solid waste (Pa)	4.0×10^5
Shear modulus of municipal solid waste (Pa)	1.0×10^5
Bulk density (kg/m^3):	
Municipal solid waste	1,100
Gravel as backfill in horizontal trench	1,500
Cohesion of municipal solid waste (c) (kPa)	10
Friction angle of municipal solid waste (φ) (degree)	30
Tension (kPa)	0.0
Dilation angle (ψ) (degree)	0.0

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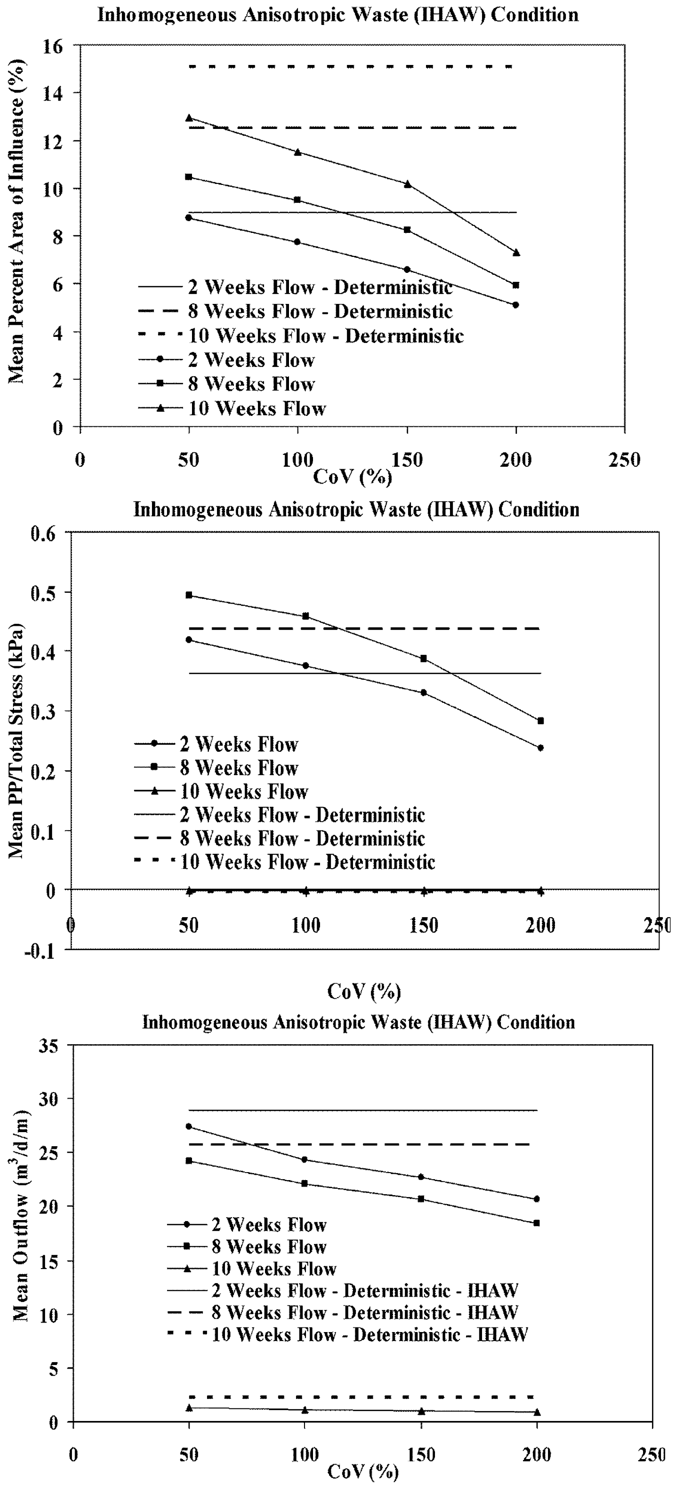

Fig. 2. Variation of the mean percentage area of influence, ratio of mean pore-water pressure to total stress, and mean outflow with the COV percentage of hydraulic conductivity of municipal solid waste for 2, 8, and 10 weeks of flow

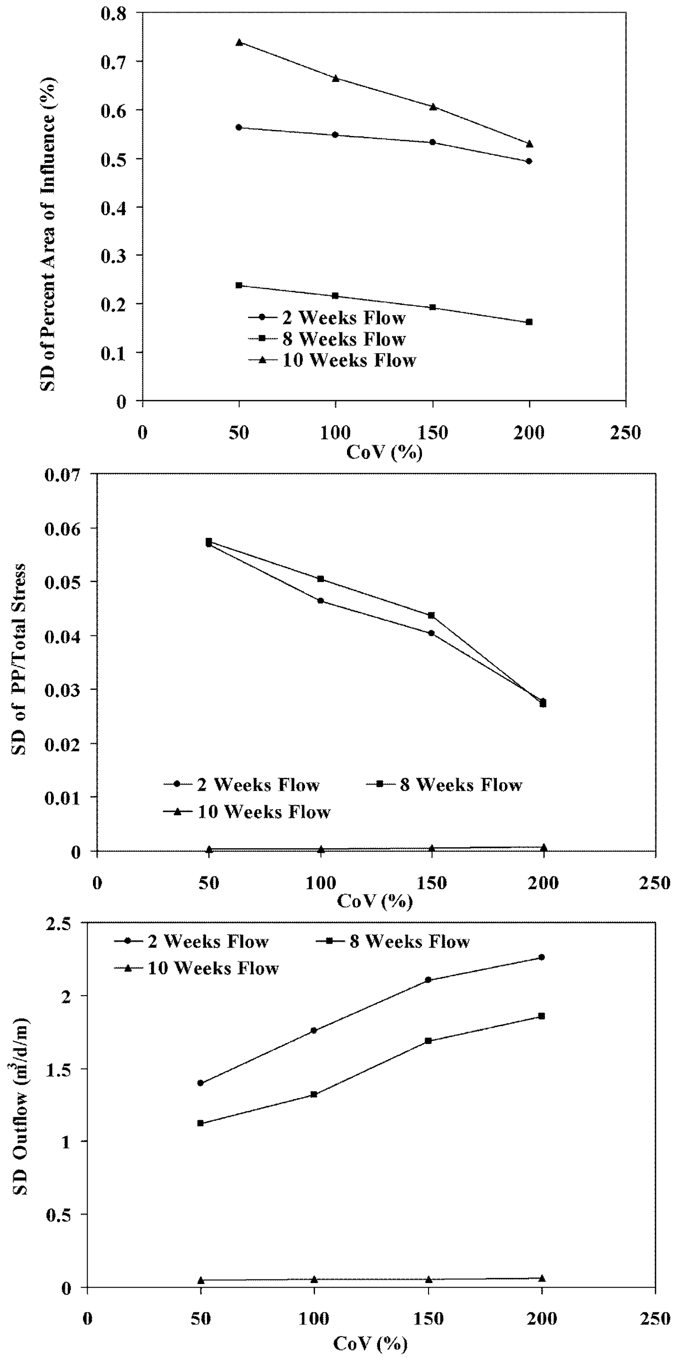

Fig. 3. Variation of the SD of the percentage area of influence, ratio of pore-water pressure to total stress, and outflow with the COV percentage of hydraulic conductivity of municipal solid waste for 2, 8, and 10 weeks of flow

Table 4 shows the reliability index (β) values evaluated for the ratio of PP:total stress at the location of the leachate injection with different COV values. Here, the reliability index values decrease with the increase in the PP:total stress ratio and with an increase in COV (%) in the PP:total stress values. The results of the reliability analysis suggest that the injection rate should be such that, in a worst case scenario (highly heterogeneous MSW giving 30% COV), the ratio of PP:total stress is not more than 0.4, to ensure excellent performance level, but it can be tolerated up to 0.52 for above-average performance.

The results of the analysis suggest guidelines for improving the overall efficiency of bioreactor landfills by keeping the configuration of the LRS to improve the percentage area of influence up to 60% and increasing the leachate recirculation injection rate up to the extent that PP:total stress ratio is 0.52, which will ensure proper conditions for biodegradation of MSW.

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Table 3. Variation of Reliability Index Values with Percentage Area of Influence and Its COV

COV (%)	Percentage area of influence of recirculation system						
	10	20	30	40	50	60	70
	Capacity (C) = 100% area of municipal solid waste						
	Percentage area of municipal solid waste left (demand, D)						
	90	80	70	60	50	40	30
	Reliability index (β) values						
5	2.22	5.00	8.57	13.33	20.00	30.00	46.67
10	1.11	2.50	4.29	6.67	10.00	15.00	23.33
15	0.74	1.67	2.86	4.44	6.67	10.00	15.56
20	0.56	1.25	2.14	3.33	5.00	7.50	11.67
25	0.44	1.00	1.71	2.67	4.00	6.00	9.33
30	0.37	0.83	1.43	2.22	3.33	5.00[a]	7.78

[a]Recommended for excellent performance.

Table 4. Variation of Reliability Index Values with Maximum Ratio of Pore Pressure:Total Stress and Its COV

COV (%)	Capacity (C) = 1.0 (maximum ratio of pore pressure:total stress)						
	Demand (D) = ratio of pore pressure:total stress achieved						
	0.2	0.3	0.4	0.5	0.6	0.7	0.8
	Reliability index (β) values						
5	80.00	46.67	30.00	20.00	13.33	8.57	5.00
10	40.00	23.33	15.00	10.00	6.67	4.29	2.50
15	26.67	15.56	10.00	6.67	4.44	2.86	1.67
20	20.00	11.67	7.50	5.00	3.33	2.14	1.25
25	16.00	9.33	6.00	4.00	2.67	1.71	1.00
30	13.33	7.78	5.00[a]	3.33	2.22	1.43	0.83

[a]Recommended for excellent performance.

Conclusion

The study identifies the two influencing parameters defining the efficiency of the LRS, that is, the percentage area of influence and the ratio of PP:total stress. The comparison of the results of the numerical analysis, which considers the anisotropic and inhomogeneous deterministic case and spatial variability modeling and Monte Carlo simulations, clearly indicates that the spatial variation property of hydraulic conductivity of MSW greatly influences the various output parameters, such as the wetted area of MSW, PP generation at the injection point, and leachate outflow, and requires consideration in assessing the performance of bioreactor landfills. The results of the reliability analysis provide guidelines for improving the performance of the bioreactor landfill. It is suggested that the percentage area of the influence of MSW should not be less than 60% and the ratio of PP:total stress can be taken as 0.52 for proper configuration of the LRS and deciding injection rate of leachate, respectively.

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