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Effects of Leachate Recirculation using Drainage Blanket and Horizontal Trenches on Slope Stability of Bioreactor Landfills

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ABSTRACT

In this study, a numerical analysis was carried out using the finite element method to investigate the effects of leachate injection using drainage blanket and horizontal trenches on the slope stability of landfills. The numerical model was validated and the results were compared with the previously published literature. The effects of leachate injection using drainage blanket and horizontal trenches on pore water pressure, moisture distribution, and stability of slope were investigated for heterogeneous anisotropic waste conditions for different slope configurations, injection pressures, and height of landfill. The performance of drainage blanket and multiple horizontal trenches with horizontal spacing varying between 10 - 100 m was compared for different injection pressures, and their effects on the degree of saturation and landfill slope stability were evaluated. It was observed that the pore water pressure developed in landfill using a drainage blanket was less as compared to horizontal trenches. Based on the results of factor of safety and the required degree of saturation, the optimum horizontal spacing for trenches was found to be 50 - 70 m for various injection pressures of 49 kPa, 98 kPa, and 147 kPa. The results showed that more than 60% degree of saturation was achieved for both cases, i.e. drainage blanket and multiple horizontal trenches at an optimum spacing of 60 m for leachate injection pressure of 98 kPa. Therefore, the use of multiple horizontal trenches instead of a drainage blanket system would be beneficial in saving the cost of materials, construction, and long-term maintenance, without compromising on the performance of the bioreactor landfills.

Keywords: Bioreactor landfill, Leachate recirculation, Horizontal trench, Drainage blanket, Slope stability, Factor of safety.

1 INTRODUCTION

Bioreactor landfills have earned considerable attention worldwide because of their vast benefits and are considered to be a sustainable waste management solution. Leachate recirculation has been practiced in bioreactor landfills to accelerate biodegradation and significantly enhance the rate of municipal solid waste (MSW) stabilization by operating in a controlled environment (Haydar & Khire, 2005; Khire & Haydar, 2007; Reddy et al., 2017). Various moisture sources such as stormwater, wastewater, or leachate may be used as moisture supplements for recirculation to provide favourable conditions for microorganism activity. The leachate recirculation is carried through various techniques, such as surface spraying, drip irrigation, surface ponds, horizontal trenches, vertical wells, and drainage blankets. Horizontal trenches and drainage blankets are the most commonly used techniques in leachate recirculation since these are constructed in active landfill conditions and do not interfere with landfill operations (Khire & Mukherjee, 2007; Reddy et al., 2013; Townsend et al., 2015; Reddy et al., 2020; Avinash et al., 2023).

The injection of leachate through leachate supplementation systems increases the pore water pressure and decreases effective stress. This, in turn, reduces the shear strength of waste and may affect the landfill slope stability (Koerner & Soong, 2000; Byun et al., 2019). Few researchers have investigated the impact of leachate injection on moisture distribution and its effect on landfill slope stability (Xu et al., 2012; Giri & Reddy, 2014c; Feng et al., 2018). Haydar & Khire (2007) conducted numerical modelling using HYDRUS 2D on leachate recirculation using drainage blankets to investigate the migration of injected liquid within the drainage blanket. They concluded that high permeable materials of thinner blankets are preferred to use as backfill and also suggested maintaining a distance greater than 15 m from the side slope to the edge of the blanket to reduce the potential of injected liquid breakouts. Reddy et al. (2020) compared the performance of three individual leachate recirculation systems by considering the effect of injection rate, waste characteristics, and mode of leachate injection. The results concluded that the drainage blanket system effectively increases the moisture by uniformly distributing the leachate across the landfill than horizontal trench and vertical well systems. The pore water pressure developed in the landfill is lesser for drainage blankets than horizontal trench systems. Based on the literature, it is clear that very few studies are available to investigate the effects of the horizontal spacing between the trenches on landfill slope stability. Furthermore, based on saturation levels and developed pore water pressures, limited research has been conducted to investigate the slope stability of landfills with different leachate recirculation systems for different landfill configurations.

In the present study, a numerical analysis was carried out using the finite element method to investigate the effects of leachate injection on different configurations of the landfill using a drainage blanket and multiple horizontal trenches. This study differs from previous studies because it focuses on the responses of moisture distribution and pore water pressure to examine the slope stability of landfills. This study also includes the variation in landfill geometry, such as slope and height, heterogeneous and anisotropic waste conditions with varied unit weight, and saturated hydraulic conductivity with depth and injection pressures. The optimum horizontal spacing of multiple horizontal trenches was proposed based on the observations of the degree of saturation and its impact on landfill stability.

2 METHODOLOGY

2.1 Configuration of landfill

A numerical analysis was carried out by modelling a two-dimensional bioreactor landfill with side slopes of 1V:4H and 1V:3H. Two different landfilled waste heights of 50 m and 30 m were selected in each landfill configuration. The landfill cell geometry was assumed to be symmetric at the centre and the MSW was placed in ten different layers, with a thickness of each layer of 5 m and 3 m for two different landfill heights of 50 m and 30 m, respectively. The width of the bioreactor cell for the landfill slope configuration of 1V:4H is 450 m and 370 m for a total landfill depth of 50 m and 30 m, respectively. Similarly, for the 1V:3H slope configuration, the landfill widths were 400 m and 340 m, respectively. A leachate collection and removal system (LCRS) consists of free-draining granular material of 0.3 m thickness placed at the bottom of the landfill cell. A drainage blanket (DB) consists of high permeable material that is spread over a large area in the landfill. The horizontal trenches (HT) are constructed by backfilling with high permeable materials such as gravel, and are generally square in cross-section with sides varying from 0.6 m to 1 m. Figures 1 and 2 show the landfill configuration of 50 m height with a side slope of 1V:3H for multiple HT and DB. In this study, a drainage blanket of thickness of 0.3 m and multiple horizontal trenches of 1m×1m were considered and installed at 33% of the total landfill height measured from the top surface (Reddy et al., 2020; Avinash & Mishra, 2023). The multiple horizontal trenches were installed by maintaining the horizontal spacing between 10 - 100 m. The setback distance of 30 m was considered based on the recommendations of USEPA (2007) for leachate injection from the landfill side slope for all the configurations.

2.2 Numerical model

The leachate infiltration and slope stability analysis were performed using the finite element analysis based on GeoStudio. SEEP/W and SLOPE/W analysis were used for modelling the bioreactor landfill to obtain the changes in pore pressure, moisture distribution, and slope stability with leachate injection. The injection infiltration was performed using the transient flow analysis in SEEP/W with a run time of 5 years. The slope stability analysis using SLOPE/W was followed using the reduced effective stress and strength obtained from the infiltration analysis. The SLOPE/W uses the computed SEEP/W stress and pore pressures to calculate the factor of safety (FOS). The Morgenstern-Price method was used in this study to calculate the slope stability of the landfill model because it satisfies both the force and moment equilibrium of the assumed slip surface. The landfill was modelled using hydraulic boundary conditions. The water pressure head boundary condition was used to apply the leachate injection pressure. To simulate the collection and removal of leachate from the bottom of the landfill, a zero-pressure head was assigned along the top surface of LCRS. An impermeable condition was assigned using the zero-boundary flux along the top, bottom, and side slope to simulate free pore pressure and free saturation.

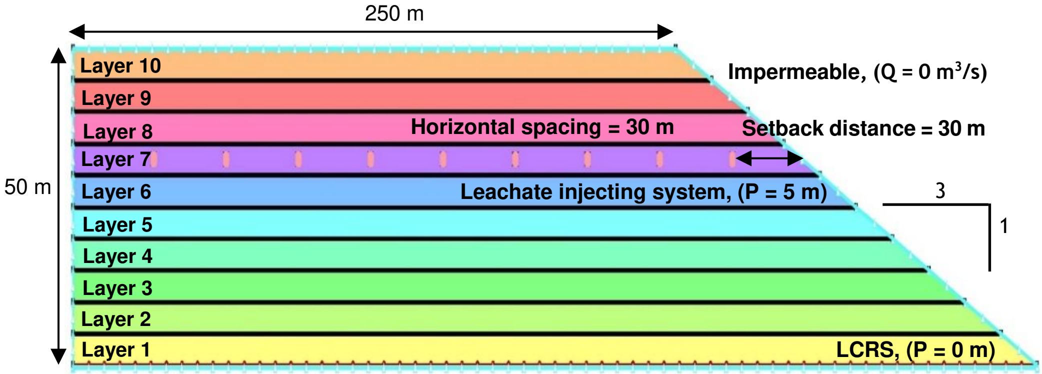

Figure 1. *Landfill model with heterogeneous anisotropic waste (HTAW) for multiple HT system*

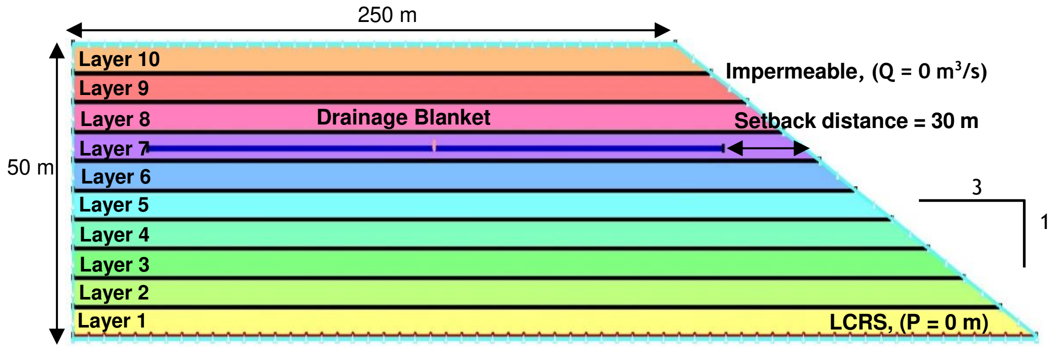

Figure 2. *Landfill model with heterogeneous anisotropic waste (HTAW) for DB system*

2.3 Material properties

The landfilled MSW is considered anisotropic and heterogeneous with varied saturated hydraulic conductivity and unit weight along landfill depth to simulate the realistic field conditions. For incorporating the HTAW condition, the variation in unit weight with depth is modelled based on the relationship proposed by Zekkos et al. (2006). The variation in saturated hydraulic conductivity with depth due to an increase in normal effective stress by overlying waste layers is modelled based on the relationship proposed by Reddy et al. (2009). The shear strength properties are kept constant throughout the entire landfill due to the unavailability of a specific correlation for variation of shear strength. The anisotropy of 10 and shear strength parameters, cohesion, and friction angle were taken as 15 kPa, and 35°, respectively (Xu et al., 2012). The material properties of HTAW are shown in Table 1 (Giri & Reddy, 2014a; Giri & Reddy, 2014b). The unsaturated properties of MSW defined by van Genuchten (1980) model considered in this study were taken from the experimental studies of Breitmeyer & Benson (2011). A 0.3 m thick LCRS consisting of free-draining granular material, was used (Xu et al., 2012). This study considers four different leachate injection pressures to investigate the influence of these pressures on stability and moisture distribution for two different leachate injection systems, i.e. multiple HT and DB. These injection pressures are simulated based on pressure heads of 5 m, 10 m, 15 m, and 20 m. Table 2 shows the configuration of the landfill cell and the type of parameters considered in the analysis.

3 RESULTS AND DISCUSSION

3.1 Model validation

The numerical model for slope stability was validated for the homogeneous anisotropic waste (HAW) and heterogeneous anisotropic waste (HTAW) conditions. The landfill slope was validated with the previously reported results of Xu et al. (2012) and Feng et al. (2018) for continuous leachate recirculation for ten years by using a horizontal trench with an injecting pressure of 49 kPa. Xu et al. (2012) used the finite element method-based software GeoStudio and Feng et al. (2018) used the finite difference method-based software FLAC.

Table 1. *Properties of MSW for different landfill heights considered for FE model simulation*

Layer	Height of landfill = 50 m			Height of landfill = 30 m		
	Depth (m)	Unit weight (kN/m^3)	Vertical saturated hydraulic conductivity (m/s)	Depth (m)	Unit weight (kN/m^3)	Vertical saturated hydraulic conductivity (m/s)
10	0-5	12.6	2.4×10^{-5}	0-3	13.0	3.9×10^{-5}
9	5-10	13.5	2.5×10^{-6}	3-6	13.7	8.6×10^{-6}
8	10-15	14.1	4.7×10^{-7}	6-9	14.2	2.5×10^{-6}
7	15-20	14.6	1.3×10^{-7}	9-12	14.6	9.1×10^{-7}
6	20-25	14.9	4.4×10^{-8}	12-15	14.9	3.8×10^{-7}
5	25-30	15.1	1.8×10^{-8}	15-18	15.1	1.8×10^{-7}
4	30-35	15.3	8.2×10^{-9}	18-21	15.3	9.0×10^{-8}
3	35-40	15.4	4.1×10^{-9}	21-24	15.5	4.9×10^{-8}
2	40-45	15.6	2.3×10^{-9}	24-27	15.6	2.8×10^{-8}
1	45-50	15.7	1.3×10^{-9}	27-30	15.8	1.7×10^{-8}

Table 2. *Summary of different landfill configurations for the numerical simulation program*

Height of landfill (m)	Landfill width (m) for multiple HT and DB		Location of multiple HT	Leachate injection	Number of simulations for multiple HT		Number of simulations for DB	
	1V:4H	1V:3H	Horizontal spacing between trenches	Injection pressure (kPa)	1V:4H	1V:3H	1V:4H	1V:3H
50	450	400	10-100 m with an interval of 10 m	49, 98, 147 and 196	40	40	1	1
30	370	340	10-100 m with an interval of 10 m	49, 98, 147 and 196	40	40	1	1

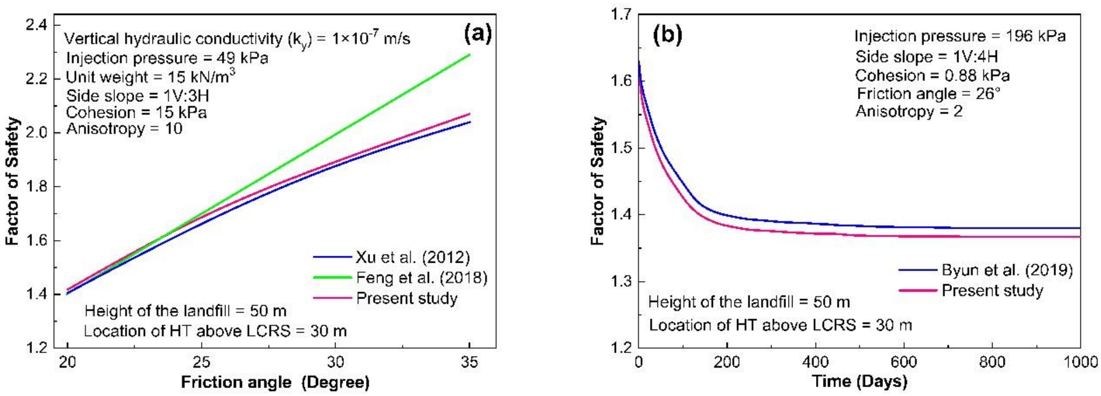

Figure 3. *Comparison of factors of safety (a) for different friction angles under HAW and (b) over time under HTAW*

The difference in the results of the computed factor of safety for different friction angles observed in Figure 3(a) is due to different methods adopted for calculating the slope stability. Feng et al. (2018) used the strength reduction method, while the limit equilibrium method is used in the present study and Xu et al. (2012). This concludes that the strength reduction method could obtain a slightly high factor of safety than the limit equilibrium method. Figure 3(b) shows the comparison of the factor of safety over time with injecting pressure of 196 kPa for HTAW conditions. The factor of safety at time t = 0 days without leachate injection is 1.63, and it decreases to 1.38 after 1000 days of leachate injection due to increased pore water pressure. The results are in good agreement, and the factor of safety becomes constant after about 200 days due to the high injecting pressure of 196 kPa.

In the present study, multiple HT and DB systems were used separately for leachate recirculation under different pressurized conditions. The numerical simulations were carried out to determine the distribution of pore pressures and moisture to investigate their influence on the landfill slope stability. The results observed in this study for leachate recirculation systems in landfills are applicable only when the slope design is within the acceptable limit (FOS≥1.5). This limit was suggested (Giri & Reddy, 2014c) to help landfill operators to maintain, create and perform safe landfill operations.

3.2 Pore water pressure

The leachate injection through leachate recirculation systems generates pore water pressure (PWP) in the landfill and could potentially affect the landfill slope. The monitoring of PWP is vital because high injection pressures may create lateral seepage. The observations were made at a location of 5 m from the injection system towards the landfill side slope. Figure 4 shows the PWP distribution over time for multiple HT (spacing of 30 m) and DB for landfill height of 50 m with a 1V:3H slope. The observations showed that the developed PWP is lesser for DB than the multiple HT systems with a difference in the range of 25-32%. The observations for the other landfill configurations with DB and multiple HT were found to be nearly the same.

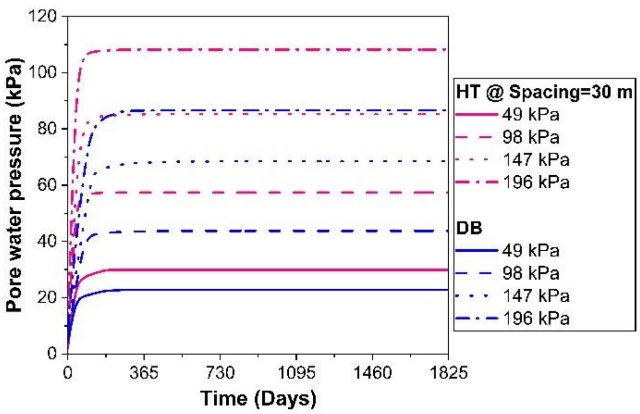

Figure 4. *Comparison of pore water pressure with the injection time for multiple HT and DB for different injection pressures*

3.3 Slope stability

Figure 5 shows the FOS over time for multiple HTs with different horizontal spacing for different landfill slope configurations with heights of 50 m and 30 m under different leachate injection pressures. Table 3a and Table 3b show the influence of leachate injection on the stability based on changing the landfill configuration. High values of FOS were observed for landfill configurations with a landfill slope of 1V:4H as compared to a slope of 1V:3H. In addition, as the landfill height reduces from 50 m to 30 m, the subsequent results of FOS increase and lead to a more stable scenario due to the reduction in overburden stresses. It was also observed that high injecting pressure could adversely affect slope stability because under injecting pressure of 196 kPa, the computed FOS is less than 1.5 for all the landfill configurations. The spacing of 50 - 100 m is observed to be favourable in terms of landfill slope stability for all landfill configurations with all injecting pressures, except 196 kPa. In addition, for a landfill height of 50 m with slope 1V:3H, both 147 and 196 kPa injection pressures were not suitable for spacing of 50 - 100 m. The variation of FOS over time for DB and multiple HT systems is due to the changes in the PWP distribution observed in Figure 4, which significantly increases the slope stability for DB compared to multiple HT systems shown in Figure 6.

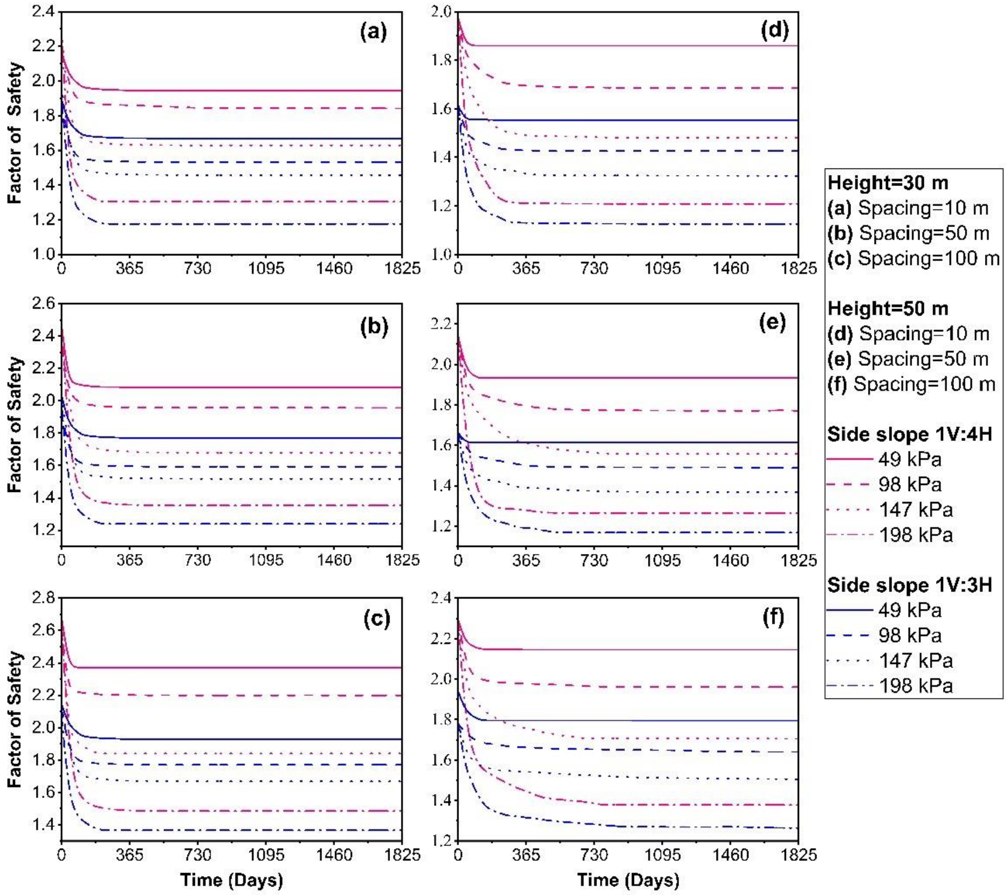

Figure 5. *Factor of safety for multiple HT systems under different injection pressures for different landfill configurations*

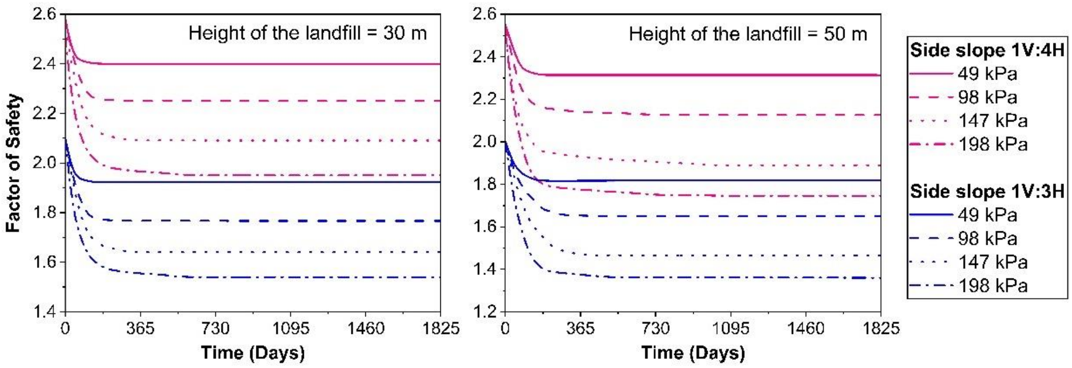

Figure 6. *Factor of safety for DB system under different injection pressures for different landfill configurations*

Low injecting pressures such as 49 and 98 kPa are sufficient in the case of the DB system to achieve a minimum degree of saturation and meet the stability requirement. Figure 7(a) shows the comparison of FOS over a change in horizontal spacing (10 - 100 m) for a landfill slope of 1V:4H with a height of 30 m under injection pressures. The results show a more significant change in FOS for low injecting pressures of 49 and 98 kPa, as the horizontal spacing increases. This is because the developed PWP inside the landfill with low injecting pressures is less, as shown in Figure 5. Similarly, a typical case shown in Figure 7(b) reveals that injecting pressure of 98 kPa is favourable beyond 50 m horizontal spacing for landfill configuration of 50 m height with 1V:3H slope. Therefore, the spacing of horizontal trenches for leachate injection plays an essential role in controlling the FOS. The cases with observed FOS less than 1.5 were not suitable for landfill operations.

Table 3a. *Comparison of FOS for different slope configurations with landfill height of 50 m for multiple HT injection system*

Spacing (m)	Height = 50 m							
	1V:4H				1V:3H			
	Injection pressure (kPa)				Injection pressure (kPa)			
	49	98	147	196	49	98	147	196
10	1.86	1.69	1.48	1.21	1.55	1.43	1.32	1.12
20	1.87	1.70	1.50	1.22	1.56	1.44	1.33	1.13
30	1.89	1.72	1.51	1.23	1.57	1.45	1.35	1.14
40	1.91	1.75	1.53	1.25	1.59	1.47	1.36	1.15
50	1.93	1.77	1.56	1.27	1.61	1.49	1.37	1.17
60	1.96	1.80	1.58	1.28	1.64	1.52	1.39	1.19
70	1.99	1.83	1.62	1.30	1.67	1.54	1.41	1.21
80	2.03	1.87	1.64	1.32	1.70	1.58	1.44	1.23
90	2.08	1.91	1.67	1.34	1.74	1.61	1.47	1.25
100	2.15	1.96	1.71	1.37	1.80	1.64	1.51	1.27

Table 3b. *Comparison of FOS for different slope configurations with landfill height of 30 m for multiple HT injection system*

Spacing (m)	Height = 30 m							
	1V:4H				1V:3H			
	Injection pressure (kPa)				Injection pressure (kPa)			
	49	98	147	196	49	98	147	196
10	1.95	1.84	1.63	1.30	1.67	1.53	1.46	1.17
20	1.97	1.86	1.64	1.31	1.70	1.54	1.47	1.18
30	2.00	1.89	1.65	1.32	1.73	1.55	1.48	1.19
40	2.04	1.92	1.66	1.34	1.75	1.57	1.50	1.21
50	2.08	1.95	1.68	1.36	1.77	1.59	1.52	1.24
60	2.13	1.99	1.71	1.38	1.80	1.62	1.54	1.26
70	2.19	2.03	1.74	1.40	1.83	1.66	1.57	1.29
80	2.26	2.08	1.77	1.430	1.86	1.69	1.60	1.32
90	2.31	2.14	1.80	1.46	1.89	1.73	1.63	1.35
100	2.37	2.20	1.84	1.49	1.93	1.77	1.67	1.38

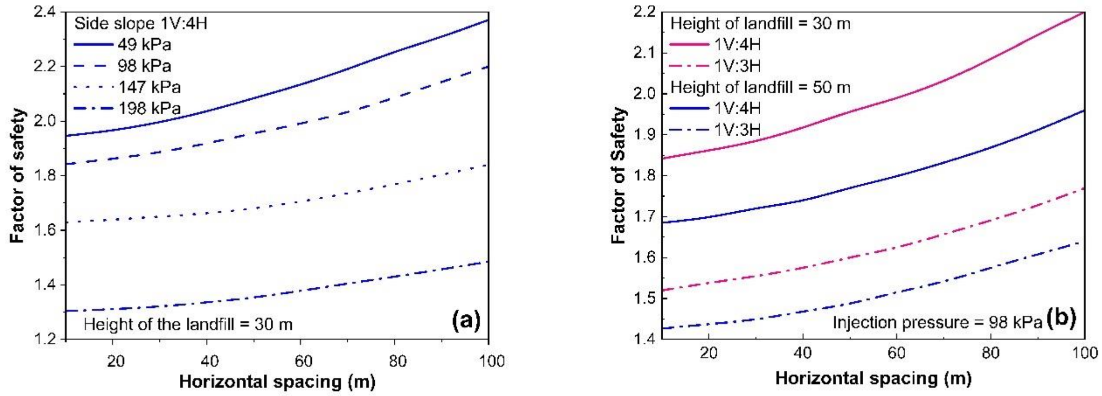

Figure 7. *Comparison of factors of safety over horizontal spacing for multiple HT (a) for different injection pressures and (b) for different landfill configurations*

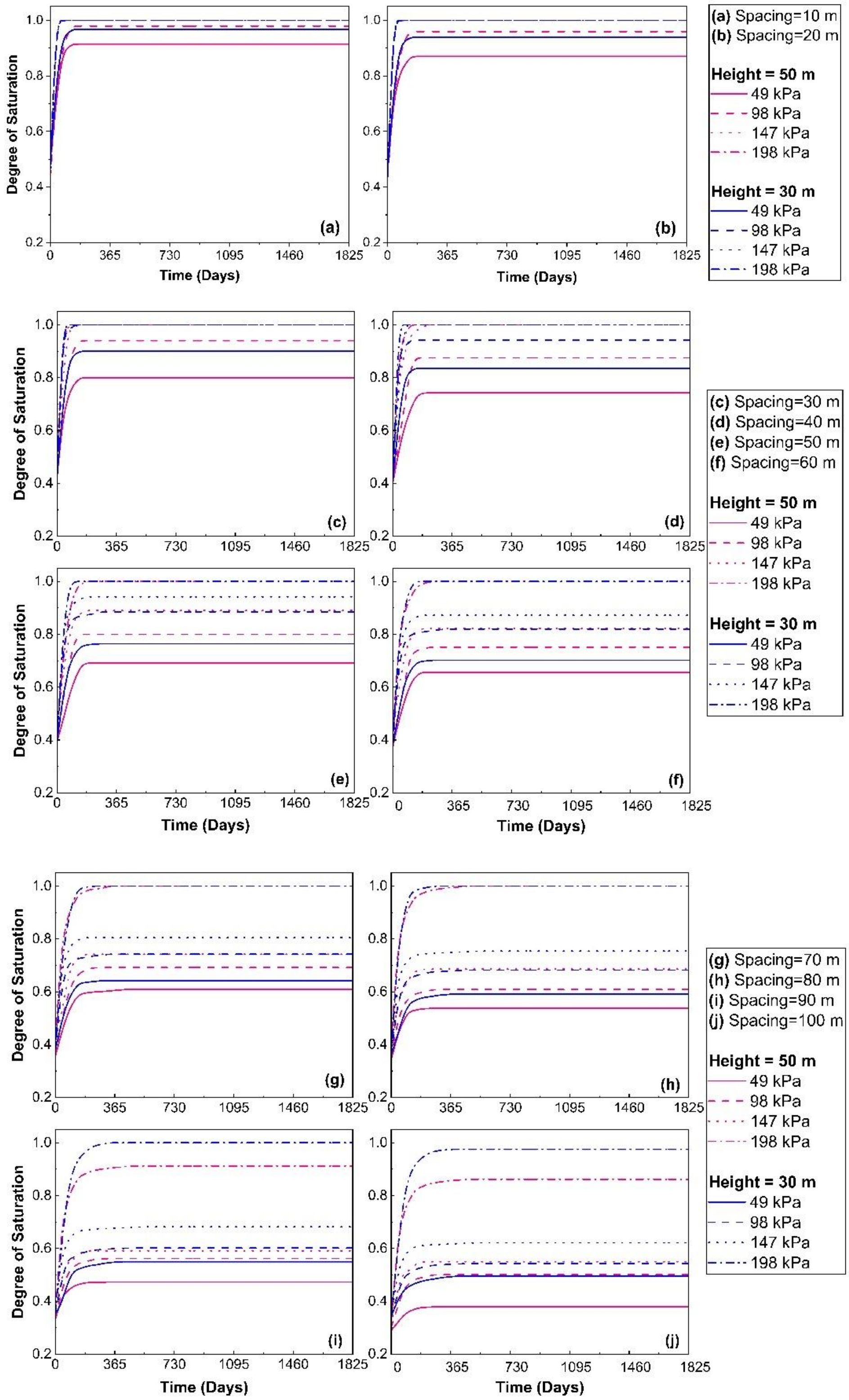

Figure 8. *Degree of saturation for multiple HT under different injection pressures for different landfill configurations*

3.4 Moisture distribution

Leachate recirculation is carried out by controlling the injection pressure to achieve the recommended degree of saturation of MSW≥ 0.60 for providing the optimal conditions for biodegradation activity (ITRC, 2006). In this study, the observations were taken below the top layer for all the landfill configurations with a setback distance of 100 m from the side slope. This location was taken to observe moisture distribution in the upper layers. It was observed to be the same for the specific landfill height, even with different slopes, due to the same MSW properties considered in the model. Figure 8 shows the variation in degree of saturation over time for multiple HT systems for different horizontal spacing under different leachate injection pressures for different landfill configurations. The results show that the close horizontal spacing of 10 - 40 m was not favourable due to the oversaturation (>0.7) of top layers, which may lead to seepage of injected liquid from the surface, creating problems for a landfill operation. Similarly, the horizontal spacing of 80 - 100 m was found to have a degree of saturation less than 0.6, which is also not favourable to achieve biodegradation in some cases. It was also observed that the required degree of saturation is achieved in case of DB systems with low injecting pressure of 98 kPa without affecting the slope stability. Therefore, for any landfill configuration presented in this study, a horizontal spacing of 50 - 70 m is found to be optimum with an injecting pressure of 49 kPa, 98 kPa, and 147 kPa based on the results of FOS and the required degree of saturation. In addition, the landfill height of 50 m with slope 1V:3H is not suitable for this optimum horizontal spacing with injecting pressure of 147 kPa.

3.5 Comparison of performance of multiple horizontal trenches and Drainage blanket

The leachate injection through the drainage blanket yields uniform moisture distribution even at low injecting pressures and does not impact the slope stability. The observations from Table 4 showed that a degree of saturation (>60%) was achieved for both the cases of leachate injection systems, i.e., DB and multiple HT at the optimum spacing of 60 m for leachate injection pressure of 98 kPa. This conclusion was drawn by analysing the results of a critical configuration of steep slope 1V:3H and waste thickness of 5 m. Therefore, the application of multiple HT systems is preferred for leachate recirculation than the DB system because these multiple HT systems also achieve the same performance. In addition, these multiple HT systems with optimum spacing will also save the material cost for construction and long-term maintenance of bioreactor operation.

Table 4. *Comparison of FOS and degree of saturation for a typical landfill with a height of 50 m and side slope 1V:3H under various injection pressures for different leachate injection systems*

Type of system	Factor of safety				Degree of saturation			
	Injection pressure (kPa)				Injection pressure (kPa)			
	49	98	147	196	49	98	147	196
Multiple HT with spacing 60 m	1.64	1.52	1.38	1.18	0.66	0.75	0.82	1.00
DB	1.82	1.65	1.465	1.360	0.46	0.62	1.00	1.00

4 CONCLUSIONS

In this study, a numerical analysis was carried out to evaluate the influence of PWP and moisture distribution on the stability of bioreactor landfill under different configurations. Several scenarios were considered, such as varying the type of leachate injecting system, horizontal spacing between the trenches, and leachate injecting pressures. The following conclusions were drawn:

The PWP developed in the landfill was lesser when the DB was used for leachate injection in comparison to the multiple HT systems. It was found that flat side slopes of landfills are typically more stable than steep ones. However, the degree of saturation reaching the top layers decreases with an increase in the thickness of MSW for all the landfill configurations. The close horizontal spacing causes the oversaturation of top layers in the landfill and increases the potential for slope failure. The spacing of 80 – 100 m is found to be more stable, but the prime objective of the required degree of saturation for biodegradation is not achieved. Therefore, a horizontal spacing of 50-70 m is found to be optimum with an injecting pressure of 49 kPa, 98 kPa, and 147 kPa based on the results of FOS and the required degree of saturation, except for the landfills with high MSW thickness and steep slopes. Low leachate injecting pressures are sufficient for DB systems to meet the stability requirement with a minimum degree of saturation. However, the required performance of more than 60% degree of saturation and FOS greater than 1.5 was achieved for both the cases of leachate injection systems, i.e. drainage blanket and multiple horizontal trenches at an optimum spacing of 60 m for leachate injection pressure of 98 kPa. Therefore, the leachate injection through multiple HT systems with optimum spacing is favourable and can replace the use of DB systems.

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