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The Effect of Leachate Recirculation on the Slope Stability of Bioreactor Landfills

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Abstract:

Leachate recirculation in bioreactor landfills provides appropriate conditions for rapid decomposition of waste. On the other hand, this operation increases the pore water pressure and consequently increases risk of bioreactor failure, especially on the side slopes. In the present study, according to the waste conditions, a two-dimensional (2D) model was proposed through GeoStudio software for investigating the effects of leachate recirculation (by considering vertical injection pipes in two areas A1 and A2 at distances of 20 and 40 m from the side slope of the landfill, respectively) in a bioreactor landfill with a slope of 3:1 H: V at a height of 20m from the base and at two injection pressures (150 and 200 kPa) on stability of bioreactor. Also, six different waste layers with various charecteriastics (including different cohesion, internal friction angle, specific gravity, and hydraulic conductivity were considered. The results revealed that Factor of Safety (FS) values were lower when the leachate injection was located at the area A1 in comparison to the area A2. This could be due to the higher pore water pressure generated when leachate injection was located at A1. Moreover, the higher values of injection pressure (200 kPa) and greater distance from the side slope (A2) cause more areas to be affected by the leachate recirculation and provide stable conditions for bioreactor landfills in a shorter time. The findings of the current research help to better understand the influence of leachate recirculation on the FS value and enhance the design of biorector landfills.

1. Introduction

Population growth and lifestyle changes today have led to an increasing amount of waste generation. Landfilling has the lowest priority among available waste disposal methods, and it is still the primary approach to waste management in most areas. Therefore, the amount of waste entering the landfill is relatively high and this amount is sometimes more than the designed capacity of the landfill, which significantly increases the risk of landfill rupture and instability [1–6]. Therefore, the duration of waste decomposition can be shortened using leachate recirculation in landfills and the landfill extraction can accelerate the process of waste decomposition.

A bioreactor landfill is known as a sanitary landfill which applies advanced microbiological processes for rapid transformation of biodegradable waste.

There have been several bioreactor failures in recent years [7-9] that seems to have increased over the past years. Hence, the integrity and stability of bioreactors are of great importance for the design, construction, and maintenance of any modern bioreactor. Moreover, the failure of bioreactors may have multiple negative social, environmental and economic effects, that make it essential to evaluate the integrity and stability of bioreactors (especially on the side slopes) [10-12]. Feng et al. [13] investigated the influence of coupling hydro-mechanical–biodegradation process on the slope stability of bioreactor landfill through a complete two dimensional (2D) coupled hydro-mechanical-biodegradation model and a solver that was implemented on OpenFOAM platform based on finite volume method

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(FVM). It was found that leachate recirculation could accelerate the mechanical biodegradation resulting in increased leachate and gas pressures and consequently enhanced slope instability. It should be noted that, in the mentioned research, the effects of leachate injection site have been ignored on slope stability. Giri and Reddy [14] investigated the recirculation of leachate via horizontal trenches in the bioreactor landfills and used FLAC-2D software to develop a model with strength reduction. In another study by Feng et al. [15], a coupled hydro-mechanical-biodegradation (HM-B) model was developed to evaluate the effects of biodegradation on mechanical properties of the waste, which could ultimately affect the stability of the bioreactor. A developed solver applied the FVM technique based on the OpenFOAM platform. The proposed model was also validated by available data in the literature. The changes in void ratio significantly affected hydraulic conductivity, and decrease in void ratio caused reduction of hydraulic conductivity. It should be noted that the initial density and compressibility index have significant influence on recirculation of leachate.

As mentioned, the influence of leachate recirculation on the mechanical characteristics of waste in bioreactors has been studied in the literature. However, there are limited studies on the influence of leachate injection/recirculation on the bioreactor stability. In this paper, a two-dimensional (2D) numerical model of a bioreactor landfill was proposed to evaluate the effects of recirculation of leachate and increased pore water pressure on the stability of the bioreactor landfill in case of using vertical injection pipes. For this purpose, different injection pressures were imposed on the body of the bioreactor landfill at different locations, and finally, the best location and the most suitable injection pressure were identified. The findings of this study can improve interpretation of the influence of leachate recirculation on bioreactor stability, and can provide recommendations for design, construction, and maintenance of bioreactor landfill.

2. Methods

2.1. Characteristics of landfill leachate

After adding leachate (or other liquids) into the landfill, it is essential to study the flow equation and model the leachate flow according to the transient conditions (transient flow). In this regard, we can use the equation of water flow in soils (Laplace's equation), in general as Equation 1:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=0 \tag{1}$$

Given that the medium considered in the present study was not uniform and continuous, i.e., $K_x \neq K_y$, Equation 1 was rewritten as Equation 2 [11]:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+Q=\frac{\partial \theta}{\partial t} \tag{2}$$

Where, $\partial h/\partial x$ and $\partial h/\partial y$ represents hydraulic gradient in the x and y directions, respectively, and Kx and K_y are hydraulic conductivity in the x and y directions, respectively, Q is flow rate, and $\partial\theta/\partial t$ represents the rate of change in volumetric humidity in the considered period. Since the leachate flow inside the landfill is unsaturated, it is possible to determine the values of unsaturated hydraulic conductivity of the waste using water-soil characteristic curve (SWCC). Different empirical equations have been introduced for this purpose, among which Van-Genuchten model is one of the most valid equations:

$$S_e(\psi)=\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)=\frac{1}{(1+|\alpha\psi|^n)^m} \tag{3}$$

Where, $S_e(\psi)$ is defined as the effective degree of saturation based on the matric suction head, ψ represents matric suction in kPa, and θ_s, $\theta_{(r)}$, θ are initial, residual, and saturated volumetric moisture contents, respectively, α represents inverse of the air inlet pressure, n is the slope of the water retention curve, and m is obtained according to Equation 4:

$$m=1-\frac{1}{n} \tag{4}$$

To calculate the parameters in Equation 3, a retention curve computer program (RETC) based on the nonlinear least-squares method is used.

2.2. Material Properties

The condition of the waste inside the landfill and the percentage of waste decomposition depends on many factors such as the duration of the presence of waste at the landfill, the percentage of organic matter, the rate of waste compaction, the content of moisture and temperature. The amount of organic matter in the waste has the greatest impact on the decomposition process [16–18]. To investigate the specific gravity of the waste according to the depth of its location in the landfill, Zekkos et al. [19] proposed Equation 5.

$$\gamma=\gamma_i+\frac{Z}{\alpha+\beta z} \tag{5}$$

Where, γ_i is the specific gravity near the surface, z is the targeted depth, α and β are the model coefficients, whose values for various compactions are presented in Table 1.

Table 1: Values of α and β coefficients for different compaction conditions

Coefficient	Low compaction	Normal compaction	High compaction
α	2	3	6
β	0.1	0.2	0.9

The shear strength of the waste can be calculated by the Mohr-Coulomb criterion expressed in Equation 6. According to this criterion, the shear strength of the waste is determined by vertical stress, cohesion and internal friction angle. Several field studies and laboratory tests have been conducted on the waste in landfills with different amounts of decomposition and decay, in which the cohesion values varied from 0.5 to 71 kPa and the values of internal friction angle varied 15 to 53 degrees [20–24]:

$$\tau = \sigma_n . \tan(\emptyset) + c \tag{6}$$

Where, σ_n is the normal stress on the rupture plane, τ represents the shear stress, c is the cohesion, and $\emptyset$ is the internal friction angle.

Much research has been done on the hydraulic conductivity in various conditions, and a relatively wide range (1×10^{-2} to 3.8×10^{-8} cm/s) has been considered for landfills and the wastes contained in them [22-25]. Giri et al. [25] investigated various data on landfill permeability and finally proposed the following equation that defines relationship between effective stress and hydraulic conductivity:

$$K_v = K_{v_0} \left(1 + \frac{\sigma'}{P_a}\right)^{-5.3} \tag{7}$$

Where K_v represents the vertical hydraulic conductivity, K_{v_0} is the initial hydraulic conductivity of the landfills before decomposition, σ' is the effective stress, and P_a is equal to 101 kPa (atmospheric pressure). The anisotropy ratio of the waste has been calculated and reported by both laboratory experiments and field studies [26]. This property is mainly determined by the way waste accumulates in landfills (layer-by-layer accumulation of waste with different properties over time), high-density induced stress in the vertical direction, and the properties of dominant wastes (including plastic and paper). Thus, waste that is compacted in different parts and layers of the landfill has different hydraulic conductivity in vertical and horizontal directions. It should be noted that the hydraulic conductivity of the waste in the horizontal direction is commonly more than that of the vertical one. In fact, because of the higher hydraulic conductivity of the waste in the horizontal direction, related effects are more significant on the side slopes of landfills, which are mainly prone to leachate leakage. Therefore, to consider various conditions with different ratios of hydraulic conductivity, the anisotropy ratio (A) can be estimated using Equation 8.

$$A = \frac{K_h}{K_v} \tag{8}$$

Where, K_h and K_v are the horizontal and vertical hydraulic conductivity, respectively.

3. Results and Discussion

3.1 Landfill Configuration

Making changes in horizontal hydraulic conductivity and specific gravity, calculated by Equations 4 and 5, and taking into account the anisotropy ratio of 2 (K_x=2K_y), the waste decomposition and the formation of different layers of waste were modeled in the present research. The length and height of the landfill were assumed to be 200 and 30 meters, respectively. Additionally, assuming symmetrical conditions on the two sides of the landfill, only one side of the landfill was modeled with a slope of 1:3 (vertical: horizontal). Six layers of the waste with a thickness of 5 m and the specifications presented in Table 2 were also considered.

Table 2: Material properties of bioreactor layers' model

Layers	γ (kN/m^3)	K_v (m/s)	φ (°)	c (kPa)
6 (Top)	12.28	3.76×10^{-6}	20	10
5	13	1.19×10^{-6}	21	11
4	13.55	4.46×10^{-7}	22	12
3	14	1.9×10^{-7}	23	13
2	14.36	8.96×10^{-8}	24	14
1 (Bottom)	14.66	4.57×10^{-8}	25	15
Cover	15.5	10-6	25	15
Subgrade	16.45	10-9	30	20

To prevent the infiltration of leachate into groundwater, the soil of the site was considered to be compacted clay/compacted clay was considered for the soil of the site. Figure 1 shows an overview of the developed model.

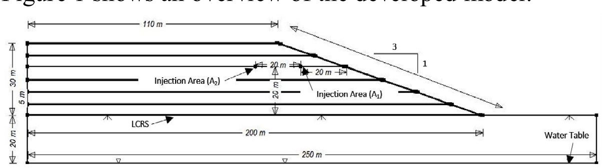


Fig. 1: The geometric design of conceptual bioreactor landfill.

3.2 Model Validation

To evaluate the validity of the model presented in the current research, the stability of the landfill slope was analyzed in order to assess the Factor of Safety (FS), and samples of modeling of leachate recirculation by other studies. The FS values were investigated according to the study of Feng et al. [10] who developed a three-dimensional model using FLAC-3D software to determine the effect of recirculation of leachate (vertical injection pipes) on landfill stability.

Additionally, the research of Xu et al. [27] was followed for further investigation, in which a 2D model was developed through SEEP/W and SLOPE/W software to examine the landfill slope stability during leachate recirculation. For both landfills, a height of 50 m and a slope of 1:3 (vertical: horizontal) were considered to investigate the stability in both models. The injection site was located at a height of 30 m from the base of the landfill. The general shape and dimensions of the given models were determined using the method adopted in the present study. Due to the relatively low injection pressure (49 kPa), the leachate recirculation was assumed to be continuous for 10 years to ensure a constant flow. Seven different internal friction angles of the waste were considered, the minimum one was 20 degrees and the maximum one was 35 degrees, and the values between mentioned limits increased by 2.5 degrees in each step. The properties considered have been presented in Table 3.

Table 3: Properties used for numerical simulation

Parameter	Value
$\gamma\ (kN/m^3)$	15
$c\ (kPa)$	15
$K_v\ (cm/s)$	10^{-5}
A	10
Injection Pressure	49
Height (m)	30-50
Inclination	1:3

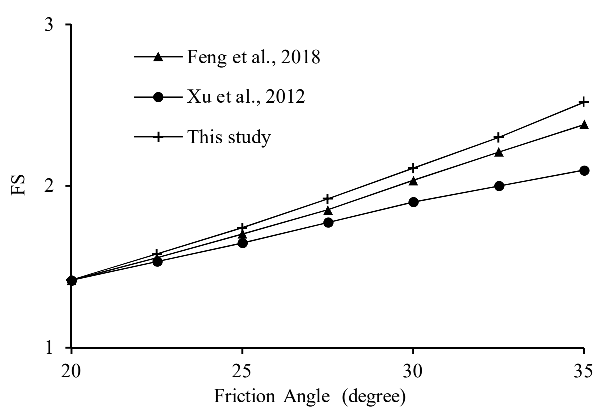


Fig. 2: Model validation by comparing studies by Feng et al. [10] and Xu et al. [27], and the present study

Finally, an acceptable agreement between the reported results by Feng et al. [10] and Xu et al. [27] and those from the model developed in the present research was recognized in view of the fact that the values of FS increased with the increase in the internal friction angle, as shown in Figure 2.

3.3 Effect of Leachate Injection on Landfill Stability

A special feature of the GeoStudio software suite is that the SEEP/W can model semi-saturated conditions that affect permeability. The philosophy of this feature in GeoStudio software theoretically is that the permeability of soil under the semi-saturated conditions is less than the saturated conditions because the air bubbles in the soil prevent the smooth flow of water in the soil. Consequently, the analysis of leakage and flow in semi-saturated soils leads to unrealistic outcomes. In the present study, the effect of leachate recirculation was investigated using finite element analysis and SEEP/W software. The parameters of unsaturated hydraulic conditions were selected according to the research by Wu et al. [28], presented in Table 4.

Table 4: Unsaturated condition parameters

Parameter	value
θ_r (-)	0.25
θ_s (-)	0.61
$\alpha\ (kPa^{-1})$	0.98
n (-)	1.51
m (-)	0.339

Finally, assuming the two injection pressures of 150 and 200 kPa for areas A1 and A2, the effect of leachate recirculation after a period of five years (1825 days) was investigated. To create the injection pressure, a pressure head is used at the injection point. For example, to produce an injection pressure of 150 kPa, a pressure head of 16 m was used at the desired point. In terms of boundary conditions, the waste all around the landfill was assumed to be impermeable (Q = 0 m^3/s) to create the bioreactor landfill, and the pressure head was considered to be zero in the landfill bottom to model Leachate Collection and Removal System (LCRS). Figure 3 shows the values of the leachate movement over a period of five years for two cases, a (injection pressure of 150 and 200 kPa in area A1) and b (injection pressure of 150 and 200 kPa in area A2). It was also assumed that the anisotropy ratio in the x-direction was twice the ratio in the y-direction. As shown in Figure 4, the leachate injection into case (a) increased the risk of landfill rupture due to the proximity of this area to the landfill slope and the increased pore water pressure (pore water pressure ranged from 120 to 180 kPa in areas close to the critical slip surface). However, as the injection pressure increased from 150 to 200 kPa, the pore water pressure did not increase much. Additionally, the area moistened by the leachate also relatively expanded with the increase in the injection pressure. For example, the area affected by the leachate injection at a pressure of 150 kPa after 5 years was equal in volume to the area affected by the leachate injection at a pressure of 200 kPa at the end of the fourth year. Changing the injection site from A1 to A2 had two advantages for the bioreactor landfill. First, the area affected by the increase in pore water pressure (120 to 180 kPa) was away from the critical slip surface and the landfill slope, which reduced the risk of landfill instability. Second, by moving away from the side slope, the increase in the amount of pore water pressure became less. This resulted in a higher injection pressure for the leachate transfer and reached a stable state in a shorter time with the same surface covered as before. For instance, according to Figure 4 showing the amount of increase in pore water pressure at a distance of 15 m from the side slope of the landfill for different injection pressures, a stable condition was created in the area after about 200 days in A1. However, in the area A2, a stable condition was created after about 400 days with an injection pressure of 200 kPa and after 600 days with an injection pressure of 150 kPa. The values of pore water pressure nevertheless, were lower in the area A2 than in the area A1. This time difference between the two areas A1 and A2 was due to the greater distance (15 m) of the area A2 from the side slope. Effects of different injection pressures on FS for different locations are presented in Table 5.

Table 5: effect of different injection pressures on FS for different locations

Case	Slope 1:3 (Vertical: Horizontal)	
	FS under 150 kPa injection pressure	**FS under 200 kPa injection pressure**
Normal	2.49 (Without recirculation)	2.49 (Without recirculation)
A1	1.51	1.43
A2	1.61	1.57

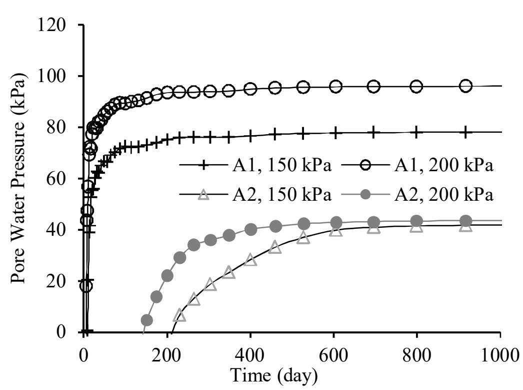


Fig. 3: Distribution of pore water pressure by time

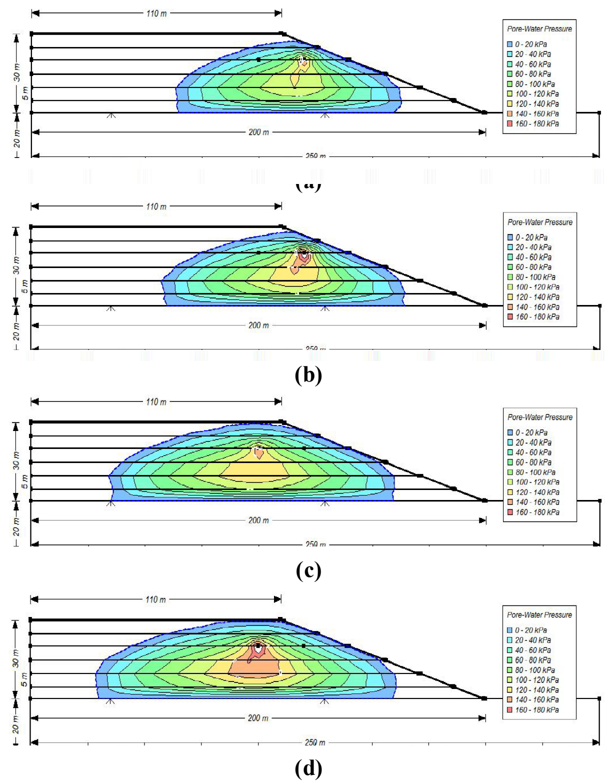
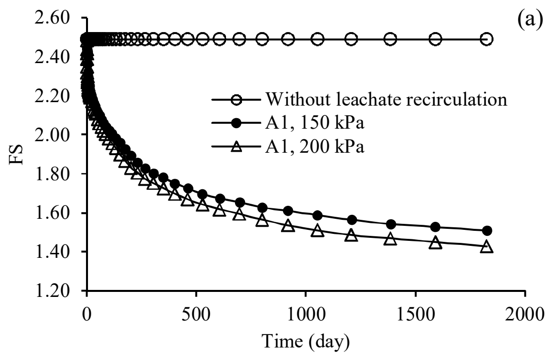


Fig. 4: Pore water pressure distribution under different injection pressures (a): 150 kPa for A1; (b): 200 kPa for A1; (c): 150 kPa for A2; (d) 200 kPa for A2.

3.4 Effect of Leachate Injection on Landfill Stability

Finally, a model was developed using SLOPE/W software that received the conditions of groundwater, pressure injection, and pore water pressure from SEEP/W software to investigate the leachate recirculation at the landfill and its effect on the final FS of the side slope of the landfill. As shown in Table 5, the FS of the landfill slope was equal to 2.49 in the normal conditions, which is a reasonable and reliable value. By applying the injection pressure of 150 kPa to the area A1, the FS value changed from 2.49 to 1.51, which was 1.43 for an injection pressure of 200 kPa. In addition, as the injection pressure of 150 kPa was imposed on area A2, the FS value changed from 2.49 to 1.61, which was 1.57 for an injection pressure of 200 kPa. Figure 5 also shows the reduction of the FS values for the most critical slip surface in the two cases a (area A1) and b (area A2).



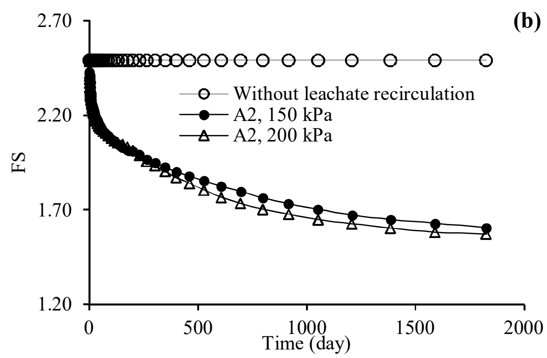


Fig. 5: Values of FS at different injection areas: (a) Area A_1; (b) Area A_2.

4. Conclusions

In all stages of design, construction, and maintenance of landfills, it should be taken into account that the properties of waste, especially Municipal Solid Waste (MSW), are very remarkably variable. Accordingly, the results presented in previous and current research may not apply to all landfills. Different waste compositions, different types of landfilling and waste management methods, and climatic conditions in different areas can affect the waste conditions. This difference may apply to not only different countries but also different parts of a city. For example, in Iran, the wastes of fruit and vegetable markets have a much higher content of water and organic matter than other areas, and the percentage of food waste in the uptown of a city is less than in other areas. Therefore, continuous and regular collection of data from landfills and the properties of waste generated can lead to a more accurate understanding of the different properties of waste and better methods for its decomposition.

Assuming the side slope of 1:3 for the landfill and imposing two different injection pressures (150 and 200 kPa) at a height of 20 m from the landfill base for the leachate recirculation, different values of FS were obtained for two different injection pressures. Thus, in addition to other conditions at the landfill and waste-related parameters, the geometry of the slopes was also of particular importance. Due to the anisotropy ratio of the waste and other conditions in the landfill, the area closest to the side slope of the landfill was not necessarily the most stable area. According to various simulations with different locations to apply injection pressures, the areas farther from the side slope of the landfill can be considered suitable. However, higher values of injection pressure (in the present study, the pressure of 200 kPa and the distance of 40 m from the side slope of the landfill) cause more areas to be affected by the leachate recirculation and provide stable conditions for bioreactor landfills in a shorter period of time.

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