

Effect of variation of water retention characteristics due to leachate circulation in municipal solid waste on landfill stability

M. Sina Mousavi¹, Yuan Feng¹, Jongwan Eun*¹ and Boo Hyun Nam²

¹Department of Civil and Environmental Engineering, University of Nebraska-Lincoln, Nebraska, USA

²Department of Civil Engineering, Kyung Hee University, Seoul, South Korea

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Abstract. This study investigated the effect of water retention characteristics between aged and fresh Municipal Solid Waste (MSW) on the stability of the landfill. A series of transient numerical modeling for the slope of an MSW landfill was performed considering the variation of water retention characteristics due to leachate circulation. Four different scenarios were considered in this analysis depending on how to obtain hydraulic conductivity and the aging degree of materials. Unsaturated hydraulic properties of the MSW used for the modeling were evaluated through modified hanging column tests. Different water retention properties and various landfill conditions, such as subgrade stiffness, leachate injection frequency, and gas and leachate collection system, were considered to investigate the pore water distribution and slope stability. The stability analyses related to the factor of safety showed that unsaturated properties under those varied conditions significantly impacted the slope stability, where the factor of safety decreased, ranging between 9.4 and 22%. The aged materials resulted in a higher factor of safety than fresh materials; however, after 1000 days, the factor of safety decreased by around 10.6% due to pore pressure buildup. The analysis results indicated that using fresh materials yielded higher factor of safety values. The landfill subgrade was found to have a significant impact on the factor of safety, which resulted in an average of 34% lower factor of safety in soft subgrades. The results also revealed that a failed leachate collection system (e.g., clogging) could result in landfill failure (factor of safety < 1) after around 298 days, while the leachate recirculation frequency has no critical impact on stability. In addition, the accumulation of gas pressure within the waste body resulted in factor of safety reductions as high as 24%. It is essential to consider factors related to the unsaturated hydraulic properties in designing a landfill to prevent landfill instability.

Keywords: coupled analysis; municipal solid waste; numerical modeling; slope; unsaturated hydraulic properties

1. Introduction

The leachate collected from the Leachate Collection and Removal System (LCRS) becomes commonly recirculated in Municipal Solid Waste (MSW) landfills to accelerate the biodegradation process in landfills and increase its airspace. Therefore, the long-term maintenance costs can be reduced while biogas production can increase (Reinhart and Townsend 1997, Reinhart *et al.* 2002, Sharma and Reddy 2004, Jain *et al.* 2010). However, the addition of moisture develops extra pore pressures within the landfill body resulting in decreased effective stresses and shear strength, which are among the main factors in analyzing slope stability. There are many reports of landfill slope failures caused by excess pore pressure development either caused by leachate recirculation or heavy rainfall events, which highlights the importance of understanding hydraulic processes in landfills and subsequently, these effects have been studied (Koerner and Soong 2000, Merry *et al.* 2005, Roy *et al.* 2009, Jafari *et al.* 2013, Zhai *et al.* 2022, Li *et al.* 2022). The pore pressure distribution is highly controlled by the injection pressure, injection pipe locations, and the

unsaturated hydraulic properties of MSW (Stoltz *et al.* 2012, Xu *et al.* 2014, Byun *et al.* 2019).

There are many examples of loss of landfill stability or function caused by excess pore pressure from leachate recirculation, including Kettleman Hills in California (Mitchell *et al.* 1990), Dona Juana landfill in Colombia (Hendron *et al.* 1999), Rumpke landfill in Cincinnati, Ohio (Eid *et al.* 2000, Stark *et al.* 2000), Payatas landfill in the Philippines (Merry *et al.* 2005) and Xerolakka landfill in Greece (Athanasopoulos *et al.* 2013), Greentree landfill failure of 2017 in Pennsylvania (The Courier Express, 2020), and many more. Gaillard and Cadag (2009) report that the Payatas landfill slope failure killed at least 330 people in 2000, and many had to leave their homes because of the proximity to the landfill site (Jafari *et al.* 2000). Due to the confidentiality of the landfill operation and the contract with the landfill owners, there might be more failure cases of landfills that are not recorded (Bonaparte *et al.* 2020), whether serviceability or total loss failures in landfills would be a human and economic forfeiture for states or countries. Therefore, the stability of landfills in terms of slope stability and significant settlement issues are in the interest of engineers.

The stability of landfill slopes has been monitored more closely after introducing leachate recirculation practices (Giri *et al.* 2013, Xu *et al.* 2012). The main factors that affect the static stability of landfills include the shear

*Corresponding author, Associate Professor
E-mail: jeun2@unl.edu

properties of MSW and subgrade, unit weight, slope geometry, MSW hydraulic conditions, and waste-liner friction (Alidoust *et al.* 2021). Previous studies have studied how to improve the design and operating considerations in a landfill. Hossain and Haque analyzed the stability of landfill slopes with decomposition by using the numerical modeling program PLAXIS and STABL (Hossain and Haque 2009). Their results showed that the factor of safety (FS) decreases as the biodegradation process advances over time due to a loss in shear strength. Therefore, they recommended considering the changing MSW parameters with decomposition in the analysis of landfill slopes. Zekkos *et al.* (2010) investigated the failed landfill in southern Greece in 2010 by limit-equilibrium and finite element analysis. They concluded that many factors included slope inclination, poor compaction practices, lack of daily cover soil and surface water management, and increased leachate and gas pore pressures due to the absence of a gas collection system triggering the instability of that landfill. Giri and Reddy (2014a) studied the effect of unsaturated hydraulic properties of MSW on the slope stability of landfills. Their study showed that the unsaturated condition of MSW affects the leachate distribution, pore water pressure, and slope stability in a transient condition. However, their findings are based on very limited and uncertain MSW unsaturated properties that were available. In another study, Giri and Reddy (2014b) evaluated heterogeneity and anisotropic influence on slope safety. They showed that the heterogeneous and anisotropic nature of MSW is recommended to be considered in slope analysis. Byun *et al.* (2019) reviewed the effect of leachate injection configuration and material condition in a landfill in South Korea. Their study showed that the FS decreased when leachate recirculation was applied and even more when higher injection pressures were considered. Using this analysis, they determined the optimum location of injection pipes to be at heights above $Y/H=0.33$ (Y is the height of the injection pipe, and H is the total height). This study was based on material properties obtained from Wu *et al.* (2012), where the unsaturated parameters seem unreliable due to the ratio of a sample size to cell diameters, while the effect of the uncertainty of the unsaturated parameters on landfill stability was not studied. Previous studies performed stability evaluations based on material properties measured by unrepresentative materials (heterogeneous material due to small cell dimensions or a large sample-to-cell diameter ratio). The effect of the degree of compaction in unsaturated soil has also been the subject of study (Rasool 2022). Furthermore, the effect of a functioning LCRS and gas collection system on the FS of a landfill slope was not evaluated. Also, the role of unsaturated hydraulic conductivity which determines how the leachate recirculation changes the pore distributions in a landfill is not fully investigated.

The objective of this study is to evaluate the unsaturated properties of MSW material under field conditions, obtained from an operating landfill, and to analyze the effect of the variation of the unsaturated properties (including unsaturated properties from literature) on the pore-water pressure distribution and slope stability in the

landfill with LCRS and gas collection system. A series of numerical modeling and simulations were employed. Based on the results, changes in the FS were assessed for the variation of unsaturated hydraulic properties associated with subgrade stiffness, leachate injection frequency, and gas collection system as well as leachate circulation. For this purpose, representative fresh MSW samples were tested to obtain unsaturated properties at two different compaction levels. Additionally, the results of the unsaturated experiments, along with those reported in the literature (including measured unsaturated hydraulic conductivity), which were obtained for different compaction and age of MSW, were used as the input data in the numerical model to determine the hydraulics of the engineered structure as well as the FS for stability. Considering the impact of the factors, the analysis results are helpful for a more accurate and effective geotechnical design of MSW landfills and to prevent slope instability events.

2. Materials and methods

2.1 Butler county landfill slope

The Butler County Landfill is an operating landfill located approximately 90 km east of Omaha, NE. The site under our investigation is located at the southwest corner of the landfill. In Dec 2018, a team from the University of Nebraska- Lincoln installed impermeable geomembranes to monitor field gas emissions through intermediate membranes before a soil cover layer made from low plasticity clayey silt was placed on top of the landfill (Feng *et al.* 2020, 2023). The height of the slope is approximately 35 m, and the length at the bottom liner is 150 m. Butler County Landfill's Operation Manager provided basic geometry, layering, and leachate reinjection information. Butler County follows all Nebraska Department of Environment and Energy (NDEE) regulations. Waste layers of around 9.14 m thickness are compacted as being placed.

There is a 0.46 m intermediate layer of compacted native soil layers placed after each waste layer. However, due to the large settlement and subsequent cracks, the intermediate layers are neglected in analysing hydraulic procedures.

2.2 Unsaturated hydraulic properties of municipal solid waste

Unsaturated flow models use input parameters from water retention characteristic (WRC) fitting models and the hydraulic conductivity values of MSW. The saturated hydraulic conductivity of MSW is highly dependent on void ratio changes, dry density, and decomposition (Breitmeyer and Benson 2011, Breitmeyer *et al.* 2020). While it is difficult to formulate saturated hydraulic conductivity because of the cancelling effect of some of the factors, the relationship between void ratio and saturated hydraulic conductivity was proposed by Breitmeyer *et al.* (2019). Subsequently, it is necessary to find the change of void ratio in a vertical profile of a landfill due to the self-weight of the

Table 1 Estimated hydraulic and mechanical properties of each MSW layer

Layers Thickness (m)	Average Depth (m)	Void Ratio	Saturated Hydraulic Conductivity (m/s)	Vertical Stress (kPa)	Dry Unit Weight (kN/m ³)	Cohesion (kPa)	Friction Angle (°)
0.00-11.58	5.84	1.83	8.30×10^{-3}	64.90	6.50	0.88	26
11.58-22.55	17.37	0.48	2.37×10^{-7}	214.27	8.77	0.88	26
22.5-35.96	29.56	0.48	2.37×10^{-7}	383.68	9.86	0.88	26

MSW layers. Hartwell *et al.* (2021, 2022) analyzed the geotechnical properties of MSW in a landfill in Nebraska (with similar constituents to the disposed of waste in Butler County landfill) in relation to the vertical depth using a large-diameter borehole method. The equation which correlated the void ratio with the depth was suggested as follows

$$e = 0.693 \ln(d) + 2.93 \quad (1)$$

where d is the depth in meter and e is the void ratio ($e_{\min} = 0.48$). The mid-depth of each layer was chosen to represent an average of the void ratio in that layer. Breitmeyer *et al.* (2019) suggested the best-fit parameters of $\lambda = 1.5 \times 10^{-4} \text{ m/s}$ and $\beta = 8.36$ for the saturated hydraulic conductivity equation that was suggested by Samarasinghe *et al.* (1982) for consolidated clays

$$K_s = \lambda \left(\frac{e^\beta}{1+e} \right) \quad (2)$$

where K_s is the saturated hydraulic conductivity in m/s. The results of estimated average void ratio and hydraulic conductivity of each layer are shown in Table 1.

A hanging column apparatus, including a 3-meter manometer, fixed column, and moving column, was used following the instructions in ASTM D6826-02. Similar to the modifications from Breitmeyer and Benson (2014), a large testing cell with an inner diameter of 279.4 mm, an inner height of 100 mm, and a large outflow column was used in this test because of MSW large particles compared to most soil samples, however, an inner pipe cell was not used in this large cell to allow for larger representative samples (Fig. 1). The maximum theoretical suction that can be applied by the hanging column apparatus using water was 29 kPa, however, for higher suctions, an air aspirator with a capacity of applying vacuum pressure as high as 80 kPa was used. The outflow column made from a graduated transparent cylinder (38 mm inner diameter and 500 mm long) was used to measure the liquid volume changes with an accuracy of 2 mL. A ceramic disc with 280 mm diameter, 13 mm thickness, air-entry suction of 100 kPa and $K_s = 8.6 \times 10^{-6} \text{ m/s}$ was sealed on the base plate with the aid of a rubber seal (Soilmoisture Corp. #060D11-B01M3). Representative fresh samples collected from Bluff Road Landfill, Lincoln, NE were used in low compacted and medium compacted conditions to obtain the water retention properties of the samples.

The hydraulic conductivity functions in unsaturated soil mechanics are typically followed by estimations proposed by van Genuchten-Mualem (VGM) (Mualem 1976). The unsaturated hydraulic conductivity can be estimated through

Eq. (3) to (5). In the VGM model, (Eq. (4)) the hydraulic conductivity (K) is dependent on the saturated hydraulic conductivity (K_s) and relative permeability (K_r) as

$$K = K_s \cdot K_r \quad (3)$$

$$K_r = S_e^l \left[1 - \left(1 - S_e^{\frac{1}{m}} \right)^{m-2} \right] \quad (4)$$

$$S_e = \left[\frac{1}{1 + (\alpha\psi)^n} \right]^m \quad (5)$$

where, S_e is the effective saturation, ψ is the matric suction, α is a fitting parameter approximately related to the inverse of air entry suction, m and n are fitting parameters related to the slope of water retention curve (WRC) and $m=1-1/n$, all determined by fitting the van Genuchten equation to the experimental data, and parameter l is the pore interaction parameter commonly assumed as 0.5. However, Breitmeyer and Benson (2014) conducted a series of WRC tests to directly obtain the unsaturated hydraulic conductivity functions for MSW. To estimate the unsaturated hydraulic conductivity, K shown in Eq. (3), the values of Eqs. (4) and (5) were used. They used a multistep outflow (MSO) method on the compacted specimen. Using regression methods for K functions they suggested a pore interaction parameter of -0.37, -0.54, and -3.59 for low compacted, medium compacted, and high compacted fresh MSW, respectively.

Table 2 shows the van Genuchten parameters (Van Genuchten 1980) of the water retention model from the unsaturated experiment as well as the materials from literature used in the slope stability evaluation. Four different unsaturated properties (3 from available literature and 1 from current study) were used to evaluate the effect of testing method, material property, and hydraulic conductivity estimation methods on pore-water distribution and slope stability analysis in landfills. Note that the biodegradation of material (change from fresh to age) The four different properties are defined as scenarios depending on how to obtain hydraulic conductivity and the aging degree of materials shown in Table 2:

Scenario 1 (This study): The van Genuchten parameters α and n were chosen based on the obtained WRC from fresh material in this study. The top layer used the parameters obtained for low compaction and the medium compacted material properties was assigned to the bottom layer. All materials were considered as fresh or non-biodegraded material. The unsaturated hydraulic conductivity was only estimated using Eq. (4) with a pore interaction parameter of 0.5.

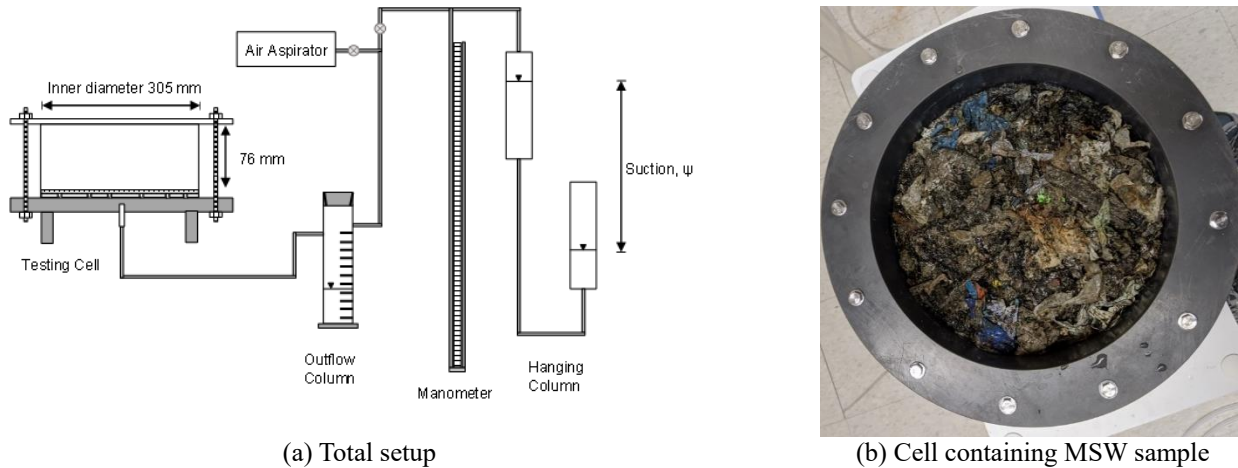


Fig. 1 Modified hanging column test setup

Table 2 Experimental hydraulic properties used for each scenario in SEEP/W analysis

Scenario	K Func.	Sample Condition	α (kPa-1)	n	θ_s	θ_r	γ_d (kN/m ³)	Source
Scenario 1	Calculated	Fresh	1.4	1.54	0.69	0.21	4.9	This Study
		Fresh	0.53	1.61	0.62	0.09	6.0	
Scenario 2	Calculated	Medium Degraded	0.92	1.95	0.57	0.28	7.8	Breitmeyer <i>et al.</i> (2020)
		High Degraded	5.35	1.21	0.58	0.00	7.8	
Scenario 3	Calculated	Fresh	2.76	2.23	0.58	0.21	5.5	Breitmeyer and Benson (2014)
		Fresh	2.92	1.58	0.53	0.22	6.2	
Scenario 4	Measured	Fresh	1.18	1.28	0.41	0.01	7.8	Breitmeyer and Benson (2014)
		Fresh	2.72	2.01	0.58	0.21	5.5	
Scenario 4	Measured	Fresh	2.06	1.95	0.53	0.25	6.2	Breitmeyer and Benson (2014)
		Fresh	1.18	1.33	0.41	0.03	7.8	

Scenario 2 (Aged Material – Calculated K Func.):

The van Genuchten parameters α and n were obtained from the study of Breitmeyer *et al.* (2020). For the top layer, the parameters of the low compacted and fresh material were used. For the middle and bottom layers, parameters of the medium degraded and high degraded compacted material were used. This scenario considered the WRC parameters of a material that was affected by biodegradation. The unsaturated hydraulic conductivity was only estimated using Eq. (4) with a pore interaction parameter of 0.5.

Scenario 3 (Fresh Material – Calculated K Func.):

The van Genuchten parameters α and n were obtained from the study of Breitmeyer and Benson (2014). All materials were fresh non-biodegraded materials with different compactions being assigned to the three different layers. The unsaturated hydraulic conductivity in this scenario was obtained using the fitted pore interaction parameters reported by Breitmeyer and Benson (2014).

Scenario 4 (Fresh Material – Measured K Func.):

The difference between scenario 4 and 3 is in using the fitted pore interaction parameters to evaluate the effect of measuring unsaturated hydraulic conductivities in MSW on landfill stability rather than using conventional pore interaction parameters in unsaturated soils. All 4 scenarios

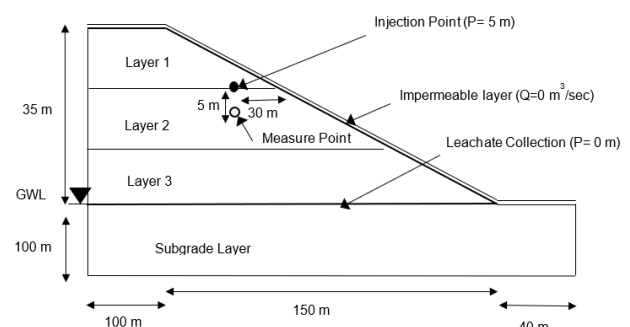


Fig. 2 schematic draw of the subject slope with applied hydraulic boundaries (not to scale)

used similar estimated properties (void ratio, saturated hydraulic conductivity, cohesion, and friction angle) for the three layers shown in Fig. 2.

2.3 Mechanical properties of municipal solid waste

The dry unit weight of MSW increases in lower depths of a landfill because of overburden pressure from top layers as well as advancement in biodegradation. Previous

researchers have used a proposed equation by Zekkos *et al.* (2006) to estimate changes of dry unit weight with depth. Recently, Hartwell *et al.* (2021) proposed a model using a First Order Rate Equation (FORE) analysis from the large diameter borehole assessment in Nebraska. The methodology allows estimating geotechnical properties by segregating waste and soil material as well as considering radial compression of the borehole. The suggested equation used in this study uses predicted vertical stress in finding the dry unit weight as follow

$$\sigma_v = 0.053 \times d^{1.096} \quad (6)$$

where σ_v is vertical stress and d is depth in m.

$$\gamma_{MSWd} = -(0.157 \times 10^{-0.0024 \times \sigma_v + 1.567} - 10.59) \quad (7)$$

where σ_v is the vertical stress in kPa and γ_{MSWd} is the dry unit weight of MSW in kN/m³. Similar to saturated hydraulic conductivity, average dry unit weights were estimated from the mid-depth of each layer.

The shear strength properties of MSW can be described similarly to soils by following Mohr-Coulomb failure criteria. This paper used the shear strengths adapted in Byun *et al.* (2019) analysis which assumed a cohesion of $c = 0.88$ kPa and a friction angle of 26° for the MSW material. Therefore, allowing to investigate the possible effects of water retention properties on an assumed homogenous material with consistent strength parameters. The estimated values of stress, dry unit weight, and shear strength parameters used in the analysis are shown in Table 1. A subgrade made of saturated soft and strong clay was considered at the bottom of the landfill with a height of 100 m which to evaluate the effect to subgrade condition. The mechanical values were followed by Byun *et al.* (2019) where the unit weight for strong and soft subgrade was 18 and 15.7 kN/m³, respectively, cohesion was 0 and 25 kPa, and the friction angles were 35 and 15° , respectively.

2.4 Numerical modelling of unsaturated flow

Increased pore pressures from the leachate recirculation practice can lead to internal slope failure. Therefore, to analyze the stability of a landfill slope, the pore distribution needs to be analyzed before evaluating stability. For this analysis, finite element (FE) based SEEP/W was used, which employs the following constitutive time-dependent transient flow equation (Fredlund and Rahardio 1993)

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial H}{\partial y} \right) + Q = m_v \gamma_w \frac{\partial H}{\partial t} \quad (8)$$

where H is total head, k_x and k_y are hydraulic conductivity in x and y directions, Q is the boundary flux, m_v is the coefficient of compressibility, γ_w is the water unit weight and t is time. Since landfills are known to function in an unsaturated condition, the hydraulic conductivity functions are obtained using VGM model discussed in MSW hydraulic properties section. The simulation is a one-way coupling to engage hydraulic and mechanical processes simultaneously. Unsaturated soil conditions related hydraulic process would change the internal friction angle and soil weight related to mechanical process and failure.

As illustrated in Fig. 2, a leachate injection point having a pressure head of 5.0 and 2.5 m (equal to 49 and 24.5 kPa) was placed at 30 m from the landfill slope per recommendation by USEPA (2007) at top of the second layer at 22 m. A measuring point was chosen 5 m below the injection pipe to monitor the changes of pore pressure and saturation with different simulation configurations. An impermeable boundary condition of zero boundary flux ($Q = 0$ m³/s) was assigned to the top cover of the slope simulating the impervious geomembrane cover on top and a pressure head of zero ($P = 0$ m) was assigned to the LCRS at the bottom to represent the leachate collection practice.

The groundwater level was assumed to be beneath the LCRS, a worst-case scenario in mechanical stability. The flow was analysed for 1000 days which was supposed enough time for the landfill to reach a steady state.

2.5 Slope stability analysis

The FS analysis of the slope is performed after the pore water distribution analysis is completed on the subject slope. The failure model used in SLOPE/W analysis is the unsaturated shear strength of Mohr-Coulomb as (Hilf 1948, Wilson 1998, Oh and Lu 2015)

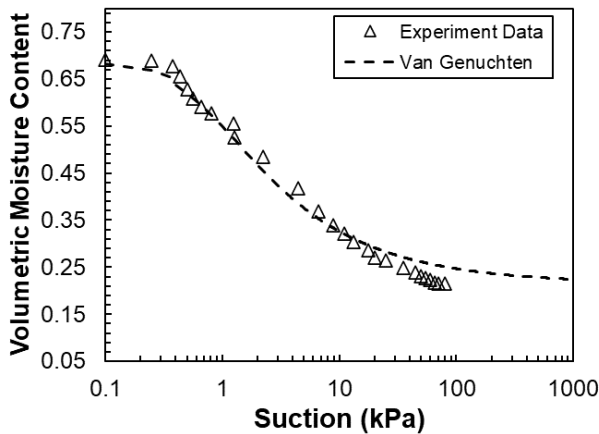
$$s = c' + (\sigma_n + u_a) \tan(\phi') + (u_a - u_w) \left[\frac{(\theta_w - \theta_r)}{(\theta_s - \theta_r)} \tan(\phi') \right] \quad (9)$$

where s is the shear strength, c' is the effective cohesion, σ_n is the normal stress, u_a and u_w are the pore gas and pore water pressures, ϕ' is the effective friction angle, θ_w , θ_s and θ_r are the volumetric, saturated, and residual water content, respectively. The stability analysis uses reduced effective stress and strength following the pore water distribution analysis. Therefore, the effect of water retention properties on the FS is reflected both by the variations in pore-water distributions as well as affecting the effective stress and strength described in Eq. (9).

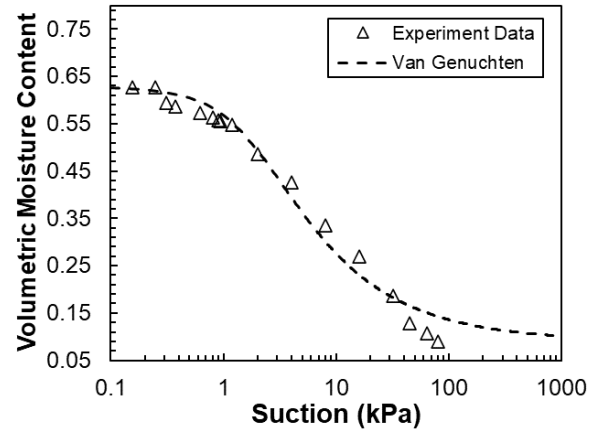
In this study, the effect of excess pore gas pressure was also considered assuming a lack or failure of a gas collection system. According to Eq. (9), an increase in pore gas pressure decreases the effective stress and raises the suction strength where the suction strength depends on the volumetric water content function. Noted that SLOPE/W does not consider the pressure balance between the two phases (i.e., gas and water) in the material (Geoslope.com, 2020). Furthermore, the limit equilibrium technique of bishop's method, where horizontal forces are neglected at each slice (Punmia and Jain 2005), was used to find the most critical slip surface and FS of the subject slope.

3. Results and discussion

Simulations were carried out considering different reported material properties and MSW landfill configurations to find out the potential critical factors (such as subgrade condition, unsaturated property estimation, and leachate collection system) determining the stability of landfills. The results will help with considerations during the design of landfills starting from subgrade condition to a proper installation of a LCRS and biogas collection systems.

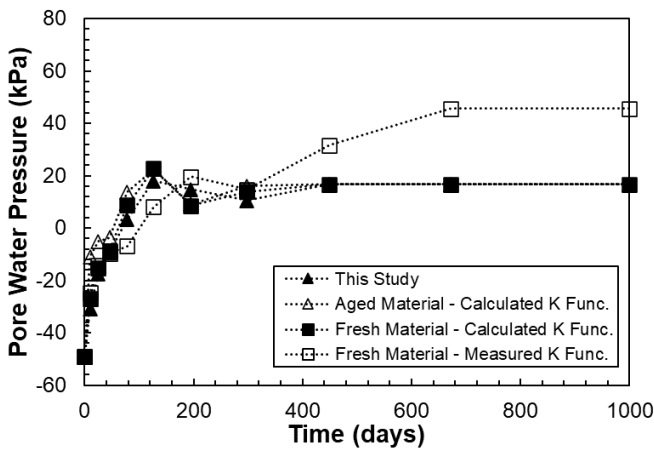


(a) 4.9 kN/m³ of dry unit weight specimen

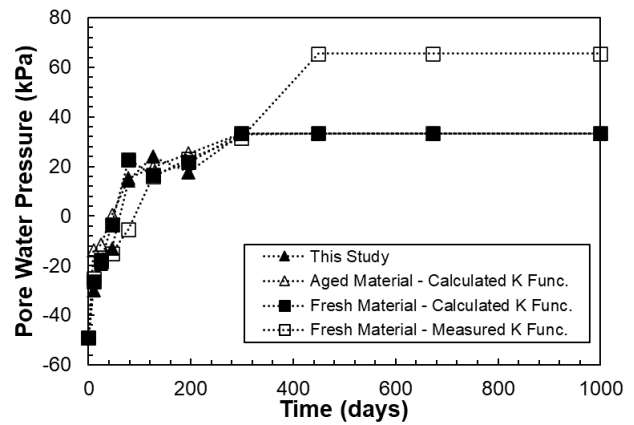


(b) 6 kN/m³ of dry unit weight specimen

Fig. 3 Typical van Genuchten fit to WRC data using minimization of mean squared error (MSE)



(a) 24.5 kPa injection pressure



(b) 49 kPa injection pressure

Fig. 4 Pore water pressure changes at the measuring point with time

3.1 Slope stability analysis

Two unsaturated properties tests were performed to plot WRCs of MSW sample with dry densities of 4.9 and 6.0 up to a suction pressure of 80 kPa. The sample with dry density of 6.0 kN/m³ shows to have a broader curve as compared with the less compacted, which is consistent with results obtained by Breitmeyer and Benson (2014). The obtained WRCs for MSW did not yield an evident air entry pressure. However, the results show that the more compacted sample produced higher air entry pressure, which is consistent with air entry pressure behavior in finer soils where the curve moves to the right compared to coarser material. Another reason for the widely broad curve of MSW compared to soils is the wide range of particle sizes where a range of fine particles (unidentifiable fine soils, 2% passing sieve #8) to particles larger than 25 mm (around 40%) existed in the samples. Furthermore, the finer portion of the MSW particles appear to have high plasticity, which, according to Zapata *et al.* (2006), shifts the air entry pressure to the right while showing less curvature. The saturated volumetric moisture content tended to decrease with higher compaction due to the decrease in void spaces available for liquid.

The obtained experimental data were fitted to van Genuchten using the MSE method presented in Fig. 3. The alpha parameter (α) in the van Genuchten model is related to the inverse of air entry pressure. According to Table 2, α decreases from 1.4 in the loose sample (4.9 kN/m³) to 0.53 in the densified sample (6 kN/m³), indicating an increase in air entry pressure.

3.2 Pore water pressure changes with unsaturated material properties

Pore water pressures were measured at a vertical distance of 5 m below the injection point. As shown in Figs. 4(a) and 4(b) injection pressures of 24.5 and 49 kPa result in a gradual increase of pore pressure from negative values indicating unsaturated condition up to 16.66 and 33.38, respectively, until around 300 days. All three material properties show a similar trend in pore pressure increase while different van Genuchten parameters and saturations are applied. The only exception in the infiltration analysis case is the measured K values which takes around 672 and 449 days for 24.5 and 49 kPa injection, respectively, to reach pressure stabilization. The results show that the

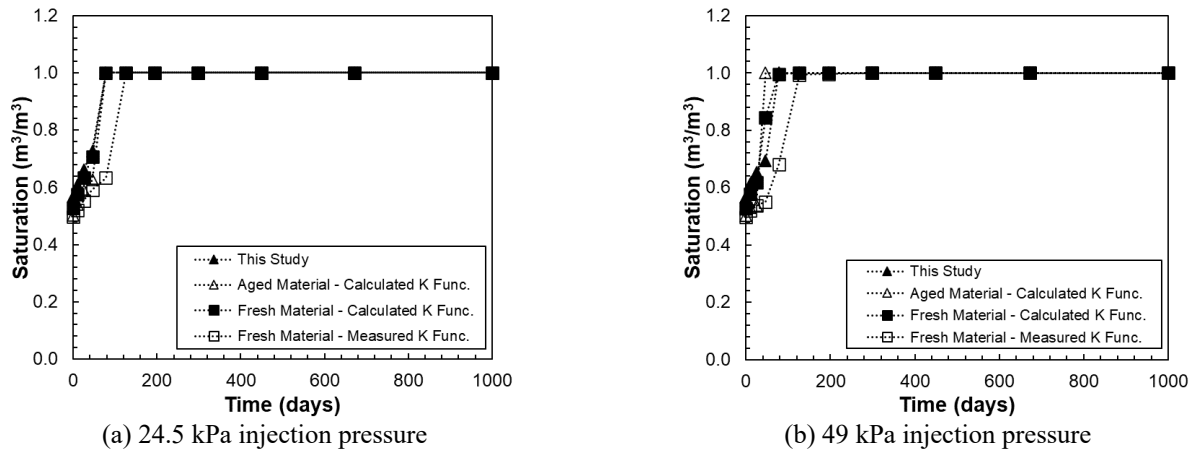


Fig. 5 Saturation changes at the measuring point with time

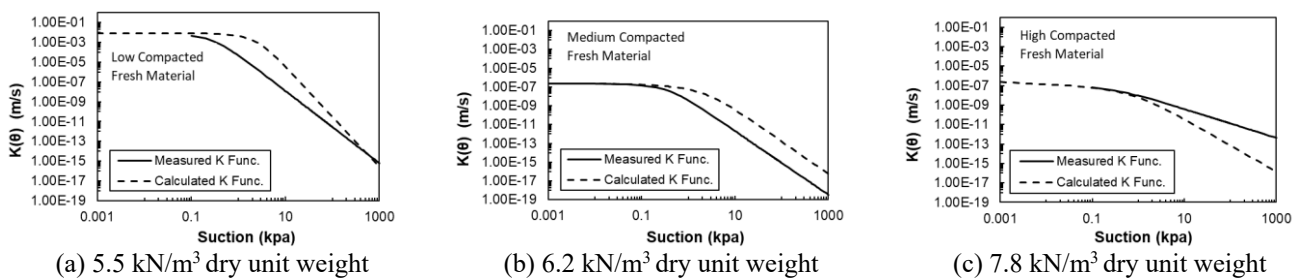


Fig. 6 Experimental hydraulic conductivity versus estimated hydraulic conductivity using pore interaction value of 0.5

hydraulic conductivity factor determines the pressure stabilization trend, while different van Genuchten parameters representing different waste age, compaction and testing method yield similar stabilization times. Figs. 5(a) and 5(b) show the saturation level at the same measuring point. The saturation levels show consistent trends among different material properties where the waste reaches saturated conditions around day 78.

The MSW layer becomes fully saturated after when positive pore-water pressures are reached according to Fig. 4. Therefore, in the case of measured K functions, the fully saturation condition is delayed as compared to calculated K functions because of the lower hydraulic conductivities in the second layer that was experimentally measured (shown in Fig. 6).

Fig. 6 is plotted using the VGM model (Eq. (4)) where typical pore interaction parameter (l) of 0.5 was used for calculated hydraulic conductivity and fitted pore interaction parameters obtained by Breitmeyer and Benson 2014) were used for the measured hydraulic conductivity function. It is noted that Figs. 4 and 5 show the pore-water pressure and saturation levels at a single measuring point. Therefore, the distribution of water pressure throughout the landfill body is further presented in Fig. 7.

At day 10, the result from the experimental hydraulic conductivities yields higher suction pressures indicating that because of the lower hydraulic conductivities in unsaturated conditions above and below the injection point, it takes longer for the landfill to develop positive pore pressures. It can be seen that at 1000 days in the case of the use of measured hydraulic function, there is clear accumulation of

positive pore pressures throughout the waste body whereas in the other three cases there are relatively similar distribution of pressure with lower values. The results among the three calculated unsaturated hydraulic conductivity material property show no significant difference even with the properties used by Breitmeyer *et al* (2020) which represented biodegraded material in the bottom two layers. According to Fig. 6, there is a two-fold difference between the hydraulic conductivities in suctions ranging between 0.1 and 10 kPa and higher than 0.1 for the top layer and middle layer, respectively. The reason for a higher positive pressure accumulation in the experimental hydraulic conductivity is attributed to the fact that the hydraulic conductivities are lower than those of the predicted conductivities, therefore the flow will favour moving downward (with higher hydraulic conductivity in a saturated area) and building up hydrostatic pressure.

3.3 Pore water pressure changes with unsaturated material properties

The change of FS was evaluated when different scenarios were used for the three landfill layers. For this simulation, fixed injection pressures of 24.5 and 49 kPa were applied at the injection point with a working LCRS at the bottom. The subgrade material was chosen as a strong clay and the gas collection system was working in a way that no excess pore-gas is developed in the landfill. The material properties obtained from this study as well as Breitmeyer and Benson (2014) represent fresh material and therefore analyze the FS change with time with the

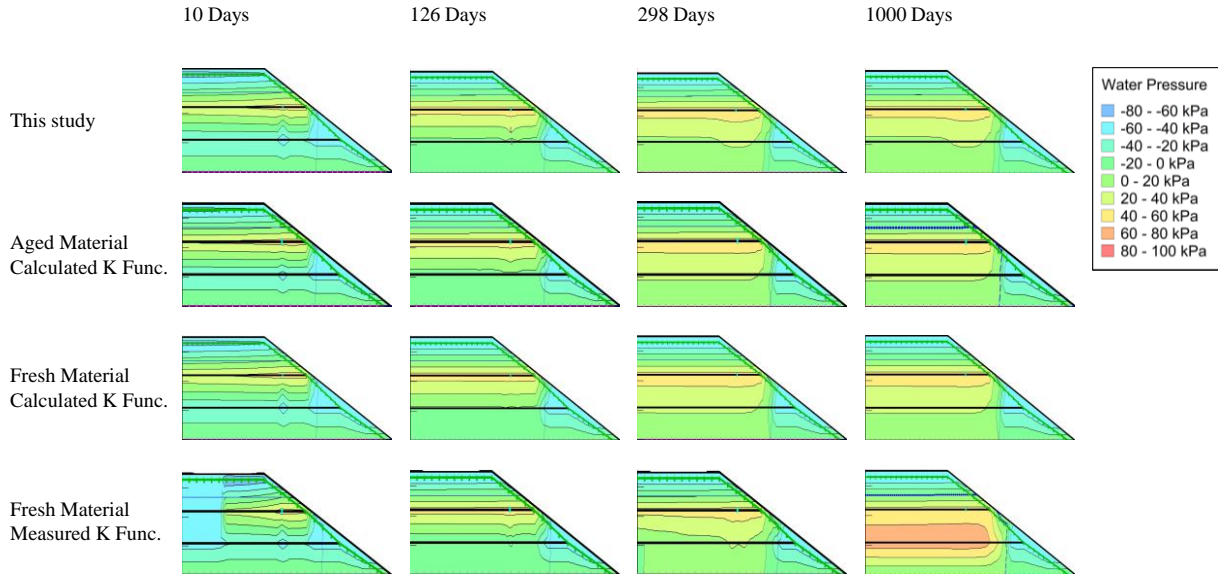


Fig. 7 Pore water distribution throughout the landfill body with an initial 49 kPa injection pressure

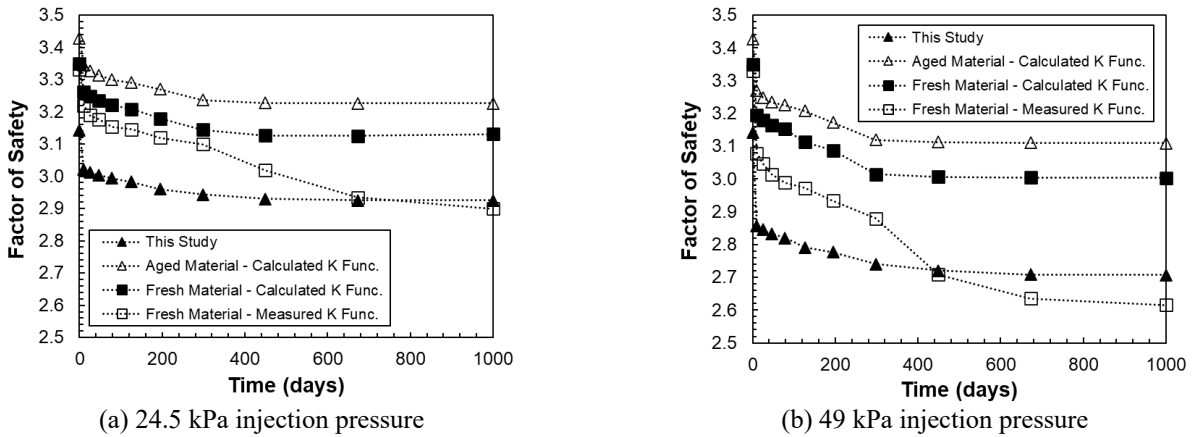


Fig. 8 FS changes of different material property

assumption that there are minimum biodegradation occurring during the first 1000 days. Findings of Hartwell *et al.* (2021) showed that a bioreactor landfill in Nebraska was operating in the primary phase of biodegradation throughout the whole profile meaning that the assumption is likely representing actual conditions. Breitmeyer *et al.* (2020) obtained water retention properties for fresh, medium biodegraded and high levels of biodegradation and therefore represent material that have been affected by biodegradation.

The results shown in Figs. 8(a) and 8(b) show that fresh material yielded lower factors of safety at day 1 and day 1000 compared to biodegraded MSW where FS for non-fresh material decreased from 3.48 to 3.11 (10.6% decrease). Fresh materials reported by Breitmeyer and Benson (2014), measured hydraulic functions of Breitmeyer and Benson (2014) and current study resulted in a FS of 3.35, 3.31, and 3.14, which decreased to 2.61, 3, and 2.70, respectively, showing 22, 9.4 and 14% decrease. The results show a sudden drop in value before around 10 days and continue to decrease until they reach stable pore pressures

around 300 days for estimated hydraulic conductivities and around 672 days for materials with experimentally obtained hydraulic functions where FS decreased between 10 and 22%. According to the results presented in Fig. 5, the pore pressures are consistent among the materials with estimated hydraulic functions. Therefore, by considering Eq. (9), the differences arise from the third term that represents the unsaturated effective strength. Based on Eq. (9), an increase in the third term has an opposing effect on the shear strength, which is determined by the effective saturation term, which is determined by the water retention characteristics. The FS changes trend is similar to those reported by Giri and Reddy (2013), Giri and Reddy (2014a), and Byun *et al.* 2019).

However, the results show a higher variation of FS with different unsaturated properties than those reported by Giri and Reddy (2014a).

3.4 FS Changes with subgrade condition

The FS of the stability of the MSW landfill was

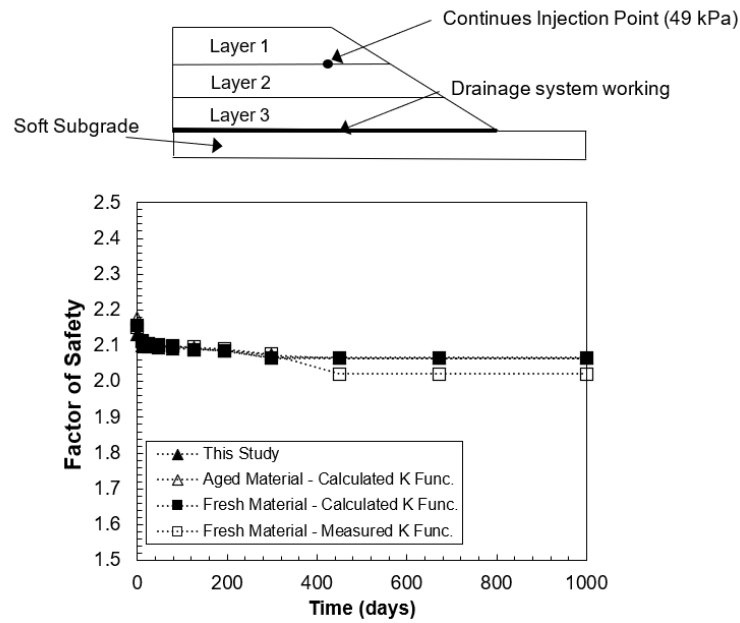


Fig. 9 FS changes with time when a soft subgrade (Unit weight of 15.7 kN/m^3 , cohesion of 0 and friction angle of 15°) is employed

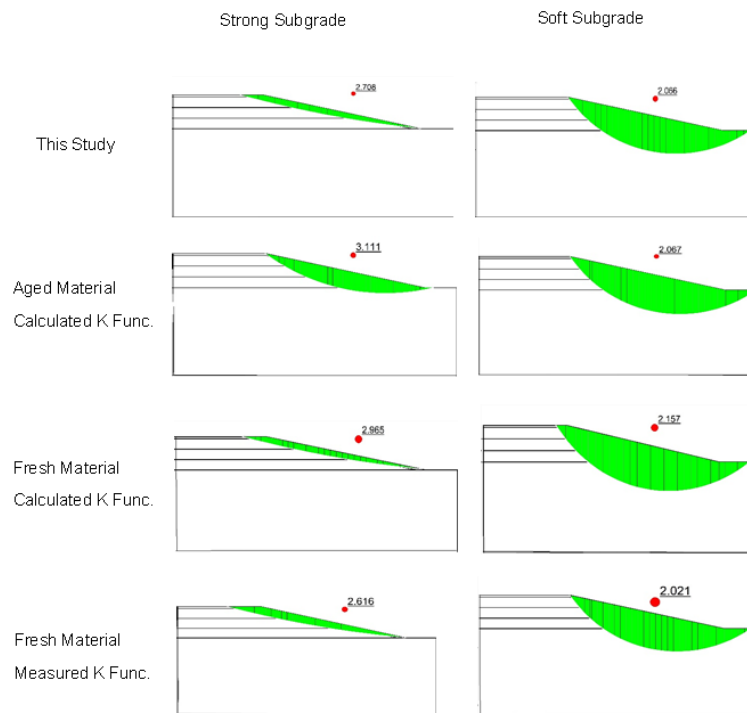


Fig. 10 Slip surfaces obtained with strong and soft subgrade material

analysed for the cases of soft (less compacted) and strong (highly compacted) subgrade. Fig. 9 shows the changes of FS with time when a soft subgrade is employed constructing the landfill. The results show the case where a continuous injection of leachate with a pressure of 49 kPa was assigned to the pipe and a working drainage and gas well collection system was configured. The results show that the factors of safety decrease by an average of 34.8% and the soft subgrade becomes the determining factor in

calculating the FS. As it can be seen from Fig. 9, all different material properties with an estimated hydraulic conductivity yield a similar FS while the material property with experimental K functions only shows 2% lower FS.

The results compared with Fig. 8(b) shows the importance of the subgrade condition in the long-term stability analysis of a landfill. Also, the results of the slip surface analysis in Fig. 10 shows that the slip surface formed with the soft subgrade is a deeper and longer slip

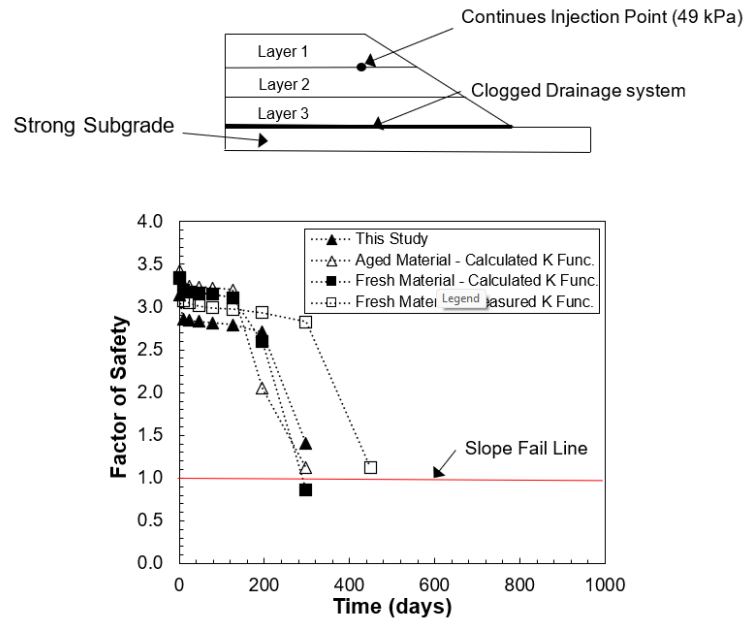


Fig. 11 FS changes with time when drainage system is clogged

surface that continues tens of meters below the drainage system. This deep slip surface could be an indication of potentially larger damage and cost in the case of a failure, considering the overall smaller factors of safety. The results are consistent with the findings of Byun *et al.* (2019). Also, Koerner and Soong (2000a, b, 2005) analyzed ten landfill failures and reported five landfill failures with a soft subgrade failing to meet regulatory compaction standards.

3.5 FS Changes with drainage condition

There have been reports of clogging in landfill drainage systems. Traditionally, coarse granular material has been used to construct MSW landfills drainage systems, although more recently a network of high-density polyethylene (HDPE) collection pipes is placed within a continuous graded granular material and in both cases, there have been reports of a decrease in void ratios and clogging of the leachate collection system with biomass and particles accumulation. Clogging of the drainage system could potentially result in the leakage of leachate, and increase of pore water pressure, and instability issues (Fleming *et al.* 1999, Koerner and Soong 2000b, Bouchez *et al.* 2003, Levine *et al.* 2005, McIsaac and Rowe 2007, Rowe and Yu 2012, Rowe and Yu 2013, Liu *et al.* 2018).

Therefore, an analysis of FS was performed in a worst-case scenario of an LCRS failure while a continuous injection of leachate and a strong subgrade was considered. A similar case can be assumed in landfills where there is a lack of water run off management on the top and heavy rainfalls occur which could simulate the accumulation of leachate within the body waste. The results as presented in Fig. 11 show that a failed LCRS with continued injection results in a rapid loss of failure (FS=1) after almost 300 days, except in the case of experimental K functions material which takes around 450 days to reach slope failure.

The results establish the importance of a well-designed LCRS not only for leachate management but also for the slope stability safety of the landfill.

3.6 FS Changes with pore gas pressure

MSW landfills often fail to install a gas collection system in time after finalizing the waste placed in a zone. Depending on the temperature and biodegradation process there could be excessive pore gas pressures built up in a landfill. The stability of landfills in elevated temperature and gas production has been the attention of landfill stability analysis (Koerner and Soong 2000b, Stark *et al.* 2010, Liu *et al.* 2020).

An equation has been suggested by Thiel (1998) to incorporate landfill gas pressure into calculating FS of an infinite slope as follows

$$FS = \frac{a' + (h\gamma \cos(\beta) - u_g)\tan(\phi')}{h\gamma \sin(\beta)} \quad (10)$$

where a' is the effective stress geomembrane-soil interface adhesion, β is the slope inclination from the horizon, h is the soil cover thickness, γ is the average unit weight of the material, and ϕ' is the effective stress geomembrane-soil interface friction angle. The equation shows that an increase in landfill gas pressure results in a decrease of the effective normal stress and subsequently the FS. Due to lack of information on the geomembrane-soil interface friction angle, the FS equation cannot be used in this study, however, the equation fails to consider unsaturated hydraulic properties which have been shown to have a significant impact on the pore water distribution and subsequently the FS. Therefore, the analysis of gas pressure has been performed using Eq. (9) described in the slope stability modelling section. Investigation on the excess landfill gas pressure have shown a maximum gas pressure

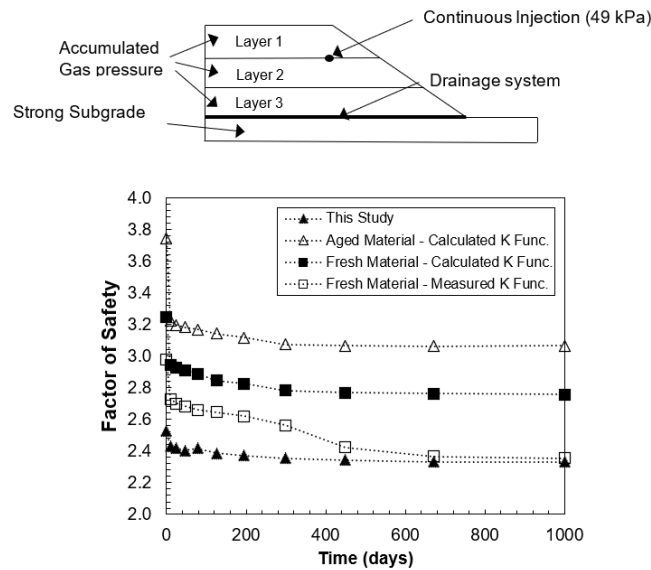


Fig. 12 FS change in accumulation of gas pressure in the absence of gas collection system

of 16 kPa in bioreactor landfills, although some extreme conditions of 50 kPa have also been reported (McBean 1995, Hettiarachchi *et al.* 2007, Wei 2007, Ng *et al.* 2015). In this study a constant gas pressure of 16 kPa was applied to the whole waste profile considering a worst-case scenario where no gas collection system is installed. The results shown in Fig. 12 represent a condition with a continuous leachate injection of 49 kPa and strong subgrade. The results show that the factors of safety decreased from 2.53, 3.75, 3.25, and 2.98 to 2.33, 3.06, 2.76, and 2.35 (8.10, 19.97, 16.28, and 23.35% reduction) for materials of current study, Breitmeyer *et al.* (2020), Breitmeyer and Benson (2014), and Breitmeyer and Benson (2014) experimental K functions, respectively. The results indicate that excess gas pressure is also a potential factor that needs to be considered in designing landfills. As reported by Athanasopoulos *et al.* (2013), the absence of a gas collection system was determined as one of the factors contributing to the slope failure of the Xerolakka landfill in Greece.

4. Conclusions

In this study, the slope stability of the in-service MSW landfill was evaluated, considering various unsaturated material properties and different landfill configurations, including leachate injection pressure, subgrade condition, failing drainage system, and excessive gas pressure in the case of an absence of a gas collection system. The analysis used SEEP/W and SLOPE/W programs to analyze the distribution of pore water and, subsequently, the factor of safety depending on the pore-water distributions.

- The analysis results indicated that the unsaturated material properties represented by α and n parameters in the van Genuchten model have an evident influence on the stability analysis of landfills, showing that the FS varies between 9.4 and 22%.

- The aged materials yield higher FS (3.48 compared to 3.35, 3.31, and 2.7); thus, using fresh material properties for the analysis yielded the lowest FS. This indicates that the most critical time for landfill stability is the initial state of the landfill. The hydraulic conductivity remarkably influenced the pore water distribution among the hydraulic material properties. The results indicate that estimating the hydraulic conductivity according to conventional soil mechanics values (pore value of 0.5) is unreliable.
- Furthermore, the analysis of landfills with different conditions showed that the subgrade material significantly determines the outcome of the stability analysis, where a soft subgrade leads to an average of 34% lower FS, meaning that the subgrade condition is a determinant factor in the geotechnical design of landfills.
- Moreover, the absence or failure of the leachate and gas collection system reduces the FS, whereas, in the case of the drainage system clogging, the landfill can fail in less than one year. The presence of gas pressure up to 16 kPa within the waste body showed an FS decrease as high as 24%.
- It should be noted that the study considered that the WRC characteristics of MSW landfills remained unchanged during the study period in the transient simulation. The changes in MSW water retention parameters resulting from the mechanically induced void ratio in the long term are currently not established in MSW studies.
- With most regulations specifying a minimum factor of safety of 1.5-2, it is essential to consider all factors in constructing an MSW landfill with proper LCRS and gas collection systems.

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Nebraska Collaboration Initiatives (ID 19521), and the finding and conclusions do not necessarily reflect the sponsor's perspectives. Also, thanks to the material support from Lancaster County Bluff Road Landfill.

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