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RESEARCH ARTICLE

Effects of Bonded Tyres on Leachate Recirculation of Bioreactor Landfills

Huijie Zhang[1,*], Jie Heng[1], Dongsheng Jeng[2] and Haixia Xu[1]

[1]*Faculty of Civil Engineering and Mechanics, Jiangsu University, Zhenjiang, Jiangsu, 212013, China*
[2]*Griffith School of Engineering, Griffith University Gold Coast Campus, Nathan, Queensland, 4222, Australia*

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Abstract:

Introduction:

In bioreactor landfills, leachate recirculation significantly influences the process of stabilization and the stability of slope.

Method:

To speed up the leachate recirculation and reduce its adverse impact on slope stability, this paper proposes a new method which constructs a spatial net consisted of bonded whole tyres in the municipal waste during landfilling.

Results and Conclusion:

In this study, a numerical two-permeability flow model was used to investigate the effects of tyres embedding on the outflow rate of leachate injection. Furthermore, it was coupled with momentum balance equations to determine the local factor of safety of slope stability. The established model was applied to a simplified bioreactor landfill. The simulation results demonstrated that the tyre net can accelerate the rate of leachate injection and contribute to distribute the liquid more uniformly. Meanwhile, the slope stability was improved due to the enforcement of waste in the presence of tyres.

Keywords: Bioreactor landfill, Leachate recirculation, Bonded tyres, Moisture distribution, Slope stability.

1. INTRODUCTION

Recently, bioreactor landfills have been used for the safe disposal of municipal solid waste (MSW) as a new and effective method [1,2]. In bioreactor landfills, the collected leachate is recirculated into the MSW to increase the moisture and accelerate the biodegradation of the MSW [3 - 8] eventually. There exist many leachate recirculation systems in bioreactor landfills, including vertical wells (VWs) [9 - 12], horizontal trenches (HTs) [13 - 17] and drainage blankets (DBs) [18, 19]. Both whole and shredded tyres are commonly employed to form leachate drainage layers, but it remains an controversial issue regarding whether the self-ignition can occur for the scrape tyres in a leachate trench [20]. However, it is clear that reduction in tyre-filled layer thickness and creation of firebreaks are beneficial to avoid a potential combustion of tyres.

To distribute the liquids within a landfill in a desired time period, leachate is usually operated with pressure [21]. However, high injection pressures in leachate recirculation systems near the side slopes can cause excess pore water pressures. The positive pore liquid pressure is prone to reduce the shear strength of the MSW because of the decreasing effective stress, which poses a concern of slope instability.

In this study, a spatial net consisted of bonded whole tyres is proposed to be embedded in the municipal waste

* Address correspondence to this author at the Faculty of Civil Engineering and Mechanics, Jiangsu University, Zhenjiang, Jiangsu, 212013, China; Tel: +0086 0511-88797036; E-mail: frank071@163.com

during landfilling. The inter-connection between tyres is expected to provide additional flow paths for the leachate and enhance the slope stability due to the effect of enforcement. Meanwhile, the new pattern of disperse tyres leads to thinner drainage layers compared with traditional scrape tyre trenches and consequently reduces the risk of subsurface fires. To reexamine the new concept of drainage system, a two-permeability mathematical model was coupled with momentum balance equations and was used to numerically simulate the leachate flow within a bioreactor landfill subjected to a pressured leachate injection. The simulation results demonstrated that the spatial tyres net significantly enhanced the distribution of leachate and improved the slope stability as well.

2. METHOD

2.1. Leachate Flow Model

The Richards' equation is employed to describe leachate flows in waste without tyres. The dual-permeability model couples two Richards' equations to describe the flow within waste matrix and the preferential flow at the tyre-waste interfaces respectively. The two flow domains are considered to be overlapped and interacted. Composite bulk soil properties are composed of domain-specific matrix and fracture pore system properties as [22]:

$$n = w_f n_f + w_m n_m \tag{1}$$

$$\theta = w_f \theta_f + w_m \theta_m \tag{2}$$

$$q = w_f q_f + w_m q_m \tag{3}$$

$$K_s = w_f K_{sf} + w_m K_{sm} \tag{4}$$

$$w_f + w_m = 1 \tag{5}$$

where the subscript "f" indicates the preferential flow domain and the subscript "m" indicates the matrix domain, n is porosity(L^3L^{-3}), θ is the water content (L^3L^{-3}), q is the fluid flux density(LT^{-1}), K_s is the total saturated hydraulic conductivity, and w is the volumetric ratio of the preferential flow domain or the matrix domain over the total soil volume (-). Flow of water in the dual-permeability medium is described by means of two coupled Richards' equations as follows:

$$\left[C_f + S_{ef} S_s\right] \frac{\partial h_f}{\partial t} = \nabla\left[K_f \left(\nabla h_f + 1\right)\right] - \frac{\Gamma_w}{w_f} \tag{6}$$

$$\left[C_m + S_{em} S_s\right] \frac{\partial h_m}{\partial t} = \nabla\left[K_m \left(\nabla h_m + 1\right)\right] + \frac{\Gamma_w}{w_m} \tag{7}$$

Where, C is the differential water capacity (dθ/dh) (L^{-1}), S_e is the effective saturation, h is the pressure head (L), t is time (T), K is the hydraulic conductivity (LT^{-1}), S_s is the specific storage (L^{-1}), Γ_w is the water exchange term (T^{-1}) between the two domains.

The van-Genuchten function is used to describe the hydraulic properties of both the matrix and preferential flow domains [23]:

$$\theta = \begin{cases} \theta_r + S_e(\theta_s - \theta_r) & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{8}$$

$$S_e = \begin{cases} \dfrac{1}{\left[1+\left|\alpha h\right|^n\right]^m} & h<0 \\ 1 & h\geq 0 \end{cases} \quad (9)$$

$$C = \begin{cases} \dfrac{\alpha m}{1-m}(\theta_s-\theta_r)S_e^{\frac{1}{m}}\left(1-S_e^{\frac{1}{m}}\right)^m & h<0 \\ 0 & h\geq 0 \end{cases} \quad (10)$$

$$K = \begin{cases} S_e^{\,l}\left[1-\left(1-S_e^{\frac{1}{m}}\right)^m\right]^2 & h<0 \\ 1 & h\geq 0 \end{cases} \quad (11)$$

Where, θ is the water content ($L^3\ L^{-3}$), θ_r is the residual liquid volume fraction, θ_s is the saturated liquid volume fraction, K is the relative permeability, α, l, m, n are fitting parameters.

Exchange of water between the matrix and the fracture pore systems is assumed to be proportional to the pressure head difference between both pore systems [24]:

$$\Gamma_w = \alpha_w(h_f - h_m) \quad (12)$$

in which, α_w is a first-order mass transfer coefficient ($L^{-1}T^{-1}$) for water defined as:

$$\alpha_w = \gamma_w \frac{\beta}{a^2} K_a \quad (13)$$

Where, β is a dimensionless geometry coefficient for describing the shape of the matrix structures, *a* is the characteristic length of the matrix structure (L), γ_w is a dimensionless scaling coefficient for water absorption, K_a is the relative hydraulic conductivity. A single average value of 0.4 for γ_w was found to be applicable for different hydraulic properties and initial conditions [25]. The geometry coefficient β equals 3 [26]. The relative hydraulic conductivity K_a is calculated by averaging the hydraulic conductivities of the two pore domains [27, 28]:

$$K_a = \frac{K_f + K_m}{2} \quad (14)$$

2.2. Slope Stability Analysis Method

The limit-equilibrium methods are commonly used for slope-stability analyses because of their proven effectiveness and reliability [29 - 35]. The slope-stability analyses of this study are based on the local factor of safety approach [36, 37]. The total stresses in the linear elasticity model are calculated by a momentum balance equation:

$$\nabla(\sigma)+\gamma(\theta)b=0 \tag{15}$$

Where, σ is a stress tensor ($ML^{-1}T^{-2}$) with three independent stress variables in two-dimensional space, and γ is the bulk unit weight ($ML^{-2}\ T^{-2}$), which is a function of water content θ. b is the unit vector of body forces with two components.

The effective stress can be expressed as [38]:

$$\sigma^{'}=(\sigma-u_a)-\sigma^s \tag{16}$$

Where, u_a is the pore air pressure, σ′ is the effective stress, and σ_s is defined as the suction stress characteristic curve of the soil with a general functional form of

$$\begin{aligned}\sigma^s &= -(u_a-u_w) && u_a-u_w\le 0\\ \sigma^s &= -\frac{(u_a-u_w)}{(1+[\alpha(u_a-u_w)]^n)^{(n-1)/n}} && u_a-u_w\ge 0\end{aligned} \tag{17}$$

Where, u_w is the pore water pressure,α and n are unsaturated soil parameters identical to those in van Genuchten's soil-water characteristic curve model.

The local factor of safety (LFS) is defined as the "ratio of the Coulomb stress of the potential failure state under the Mohr–Coulomb criterion to the Coulomb stress at the current state of stress" [36, 37]:

$$LFS=\frac{\tau^*}{\tau} \tag{18}$$

Where, τ* is the potential Coulomb stress and τ is the current state of Coulomb stress ($ML^{-1}T^{-2}$). Application of the Mohr–Coulomb failure criterion gives the local factor of safety at every point in the landfill slope:

$$LFS=\frac{2\cos\varphi}{\sigma_1^{'}-\sigma_3^{'}}\left[c^{'}+\frac{\sigma_1^{'}+\sigma_3^{'}}{2}\tan\varphi\right] \tag{19}$$

Where, c′ is the effective cohesion ($ML^{-1}T^{-2}$), φ is the friction angle, and σ_1' and σ_3' are the spatially varying first and third principal effective stress for the variably saturated soil ($ML^{-1}T^{-2}$).

2.3. Coupled Dual-Permeability and Soil Mechanics Model

In this study, the Subsurface Flow Module and Solid Mechanics Module in the commercial finite element software COMSOL were used to couple hydrological and soil mechanical system. The two-permeability model is defined as two coupled Richards' equations and the coupling can be expressed by the water exchange term, which is imported as Mass Source term in the Richards' Equation Interface. Then, the software solver recognizes the system of coupled equations during the computation. The coupling between the dual-permeability model and soil mechanics model is represented from two aspects. First, the Body Load Term of the Solid Mechanics Module varies with the moisture content; second, the effective stress for Solid Mechanics Module depends on the pore pressure output by the hydraulic module. In this study, there is no experimental data to show the development of slope failure. Therefore, the pore water pressure of the preferential flow domain is used to calculate the effective stress. The framework of coupled dual-permeability model and soil mechanics model is shown below (Fig. **1**):

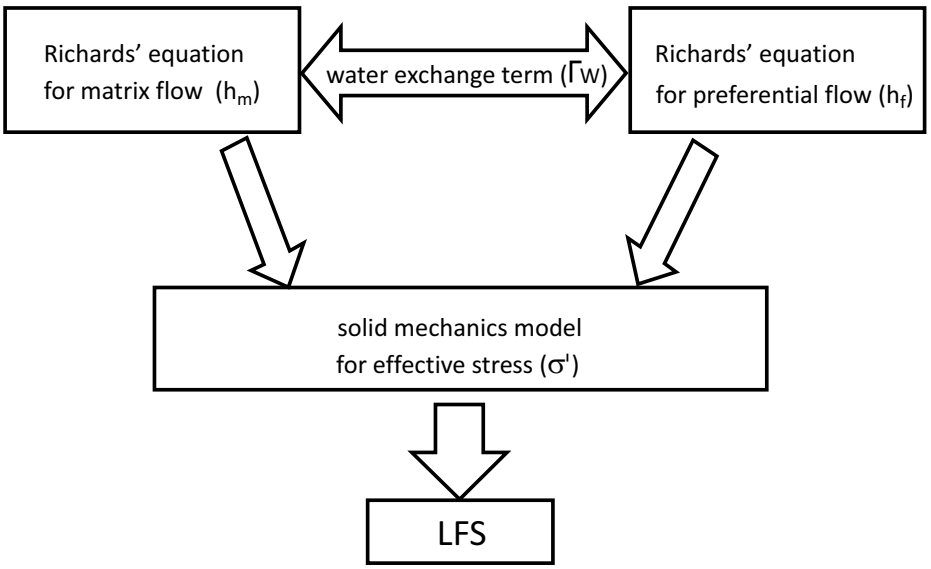

Fig. (1). Flowchart of coupling of dual-permeability model and soil mechanics model.

3. APPLICATION TO A LANDFILL PROFILE

The configuration of landfill is similar to that examined previously (Xu *et al.* (2012)) as illustrated in Fig. (**2**). The leachate is injected through a horizontal trench into the waste with a continual injection pressure. The leachate collection and removal system (LCRS) is located at the base of landfill with a thickness of 0.3 m and consists of granular material such as sand. The top boundary, left-hand side and side slope are no-flux boundaries. The pore-water pressure of the bottom sides for LCRS is fixed to zero due to the drainage layer. At the horizontal trench, a constant injection pressure is applied. For the solid mechanics model, the side slope is a free boundary, and the top and the left-hand side can move in laterally and vertically, respectively. The bottom boundary is fixed.

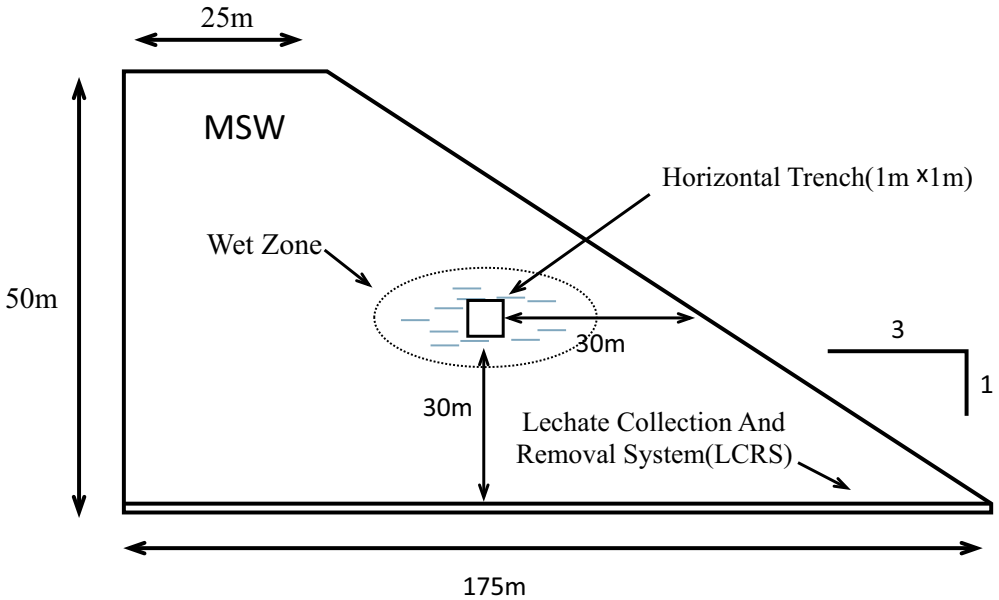

Fig. (2). Conceptual model for leachate recirculation using horizontal trench system.

All the parameters used in the following examples are listed in Table **1**. In this study, the unsaturated hydraulic properties of the MSW were not varied with respect to the depth because: (1) very little published information is

available on the evolution of unsaturated hydraulic properties of MSW as a function of overburden pressure; and (2) unsaturated hydraulic properties have a relatively small impact on the key design parameters at steady-state conditions [39].

Table 1. Summary or parameters.

Symbol	*Parameter Name*	*Units*	*Value*
γ^a	Unit weight	(kN/m^3)	5.5
α	Inver of air-entry pressure	(1/kPa)	1.4
θ_r	Residual moisture content	(-)	0.14
θ_s	Saturated moisture content	(-)	0.58
n	Van Genuchten fitting parameter	(-)	1.6
a	Van Genuchten fitting parameter	(-)	0.37
b	Van Genuchten fitting parameter	(-)	0.5
c	Van Genuchten fitting parameter	(-)	0.5
K_v	Hydraulic conductivity	(m/s)	1×10^{-7}
K_h/K_v	Waste anisotropy	(-)	10
C’	Waste cohesion	(kPa)	15
C”[b]	Tire shred-sand mixtures cohesion	(kPa)	41
Φ’	Waste friction angle	(Degree)	35
Φ”	Tire shred-sand mixtures friction angle	(Degree)	35
p	Injection pressure	(kPa)	49

a.The van Genuchten model parameters of MSW based on Kazimogle (2006) [40]. b.The shred-sand mixtures cohesion based on Zornberg JG (2004) [41]

3.1. Comparison with Previous Work

Prior to being applied to landfills, the results obtained from the present computational model were compared with the published results. The evolution of outflow rate with time was determined and was found as satisfactorily close to that of Xu *et al.* (2012) Fig. (**3**). To reexamine the influences of preferential flow on slope stability, Shao *et al.* (2014) performed local factor of safety (LFS) analysis for a slope with rainfall infiltration. Fig. (**4**) shows the LFS distribution and the results of the model established in this study agree well with Shao *et al.* (2014).

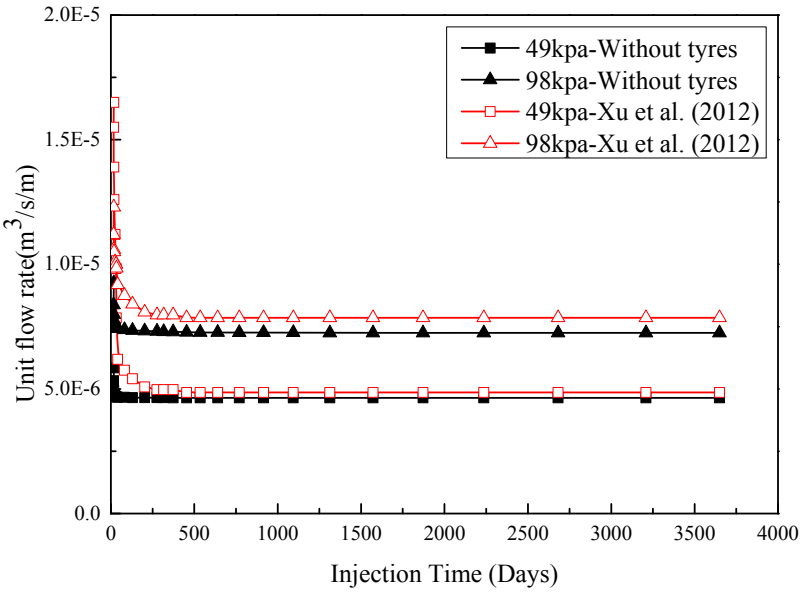

Fig. (3). Model validation: the flow rate for single-permeability model (without tyres).

3.2. Simulation Results and Discussion

3.2.1. The Flow Rate and Distribution of Leachate

A base scenario without tyre was simulated using single-permeability model to determine the influences of varying injection pressures on leachate outflow rate, the distribution of the degree of saturation of leachate and the local factor of slope safety. As for the landfill with spatial tyre net, the two-permeability model was utilized to represent the preferential flow paths created by tyre-waste interfaces.

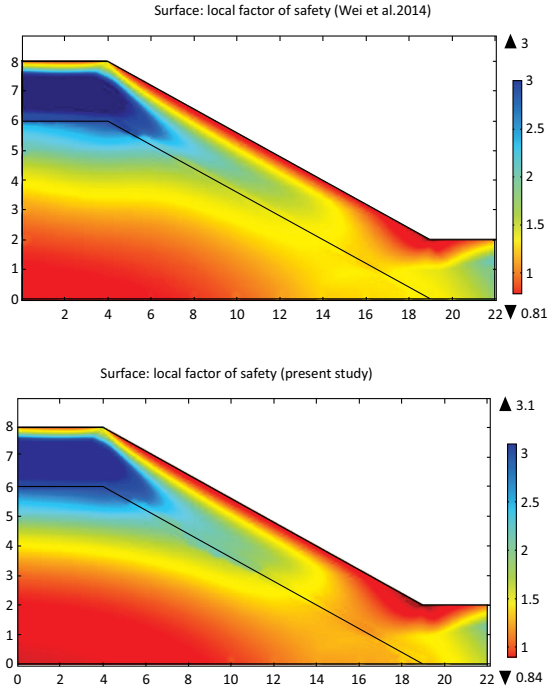

Fig. (4). Model validation:the local factor safety for dual-permeability model.

Fig. (**5**) illustrates the variation of outflow and the presence of tyre net significantly speeds up the leachate injection up to three times. The associated leachate distribution in Fig. (**6**) demonstrates that the two-permeability model leads to a larger wetted zone than the single-permeability model. Moreover, the wetting front of the landfill with tyre net spreads laterally further rather than going downward to the bottom drainage layer as for its counterpart, which indicates that the tyre net results in a more uniform distribution of leachate. For a bioreactor landfill, the accelerated distribution uniformly is a key desired feature.

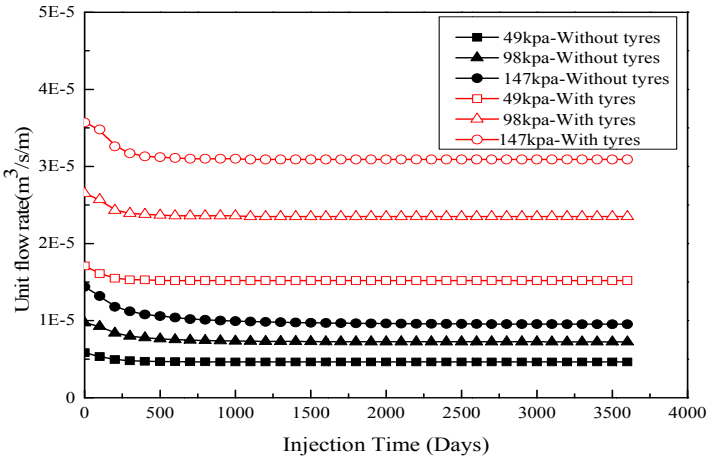

Fig. (5). Effect of tyre drainage net on the flow rate.

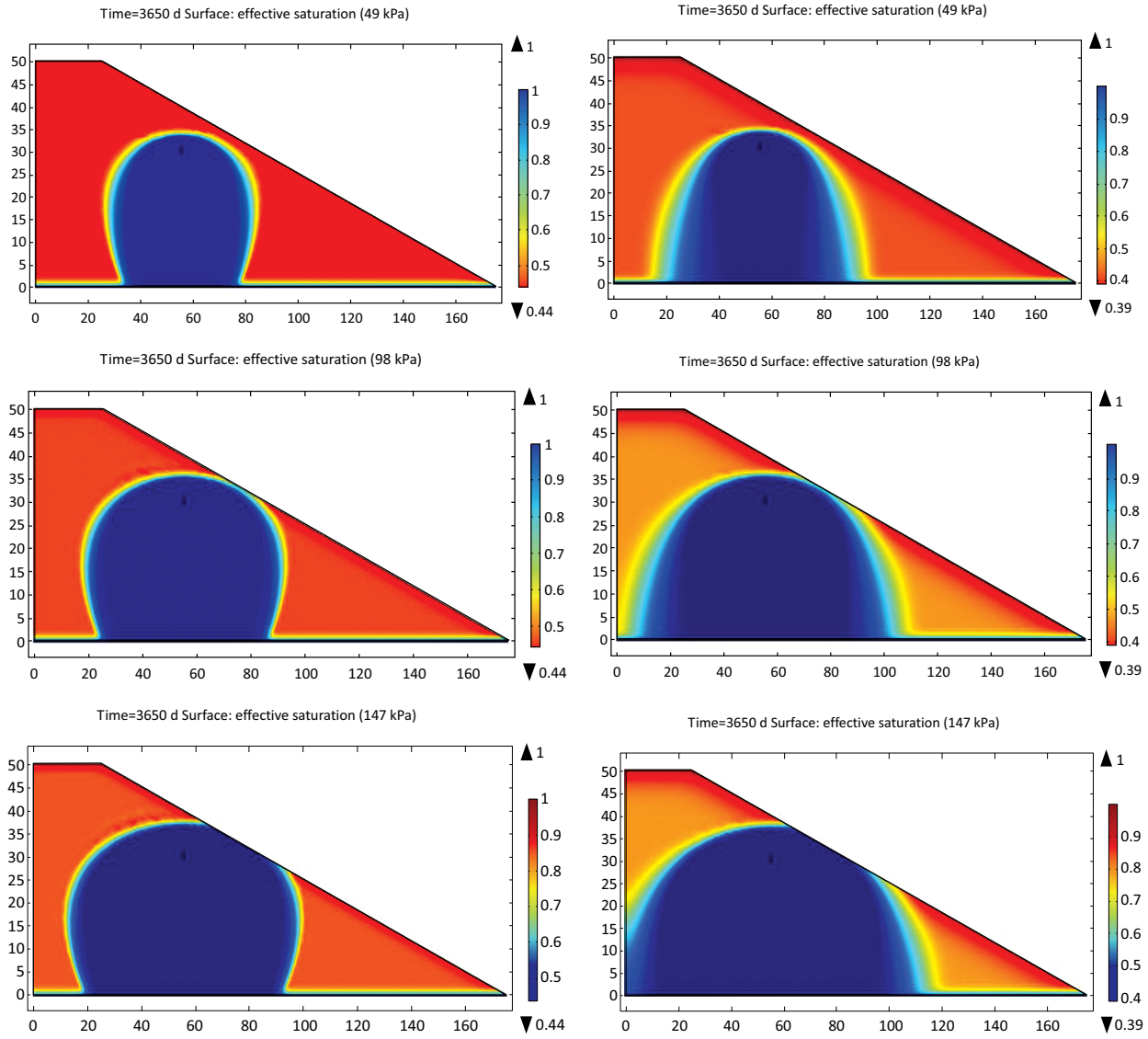

Fig. (6). Effect of tyre drainage net on the effective saturation (left panel show the results of landfill without tyres).

3.2.2. Slope Stability

Tyre has been proven to improve the shear strength of soil in both field and laboratory experiments [33]. It is reasonable to anticipate a similar enforcement for waste in a landfill with tyre. Since the data for enforcement of waste by the whole tyres is scarce, this study represents it by increasing the cohesion and angle of internal friction following the experiments in Zornberg *et al.* (2004).

The distribution of local factor of safety is illustrated in Fig. (**7**). The LFS becomes smaller when the wetting propagates because the effective stress becomes smaller due to the increasing liquid pressure. For the cases with a lower injection pressure (49 and 98 kPa in the considered scenario), the LFS is larger than unity and it indicates no slope failure. However, the LFS decreases to 0.83 around the horizontal trench for injection when the injection pressure changes to 147 kPa. In the presence of tyre net, the LFS increases especially along the slope face due to the improvement in shear strength, consequently avoiding the potential occurrence of slope slide.

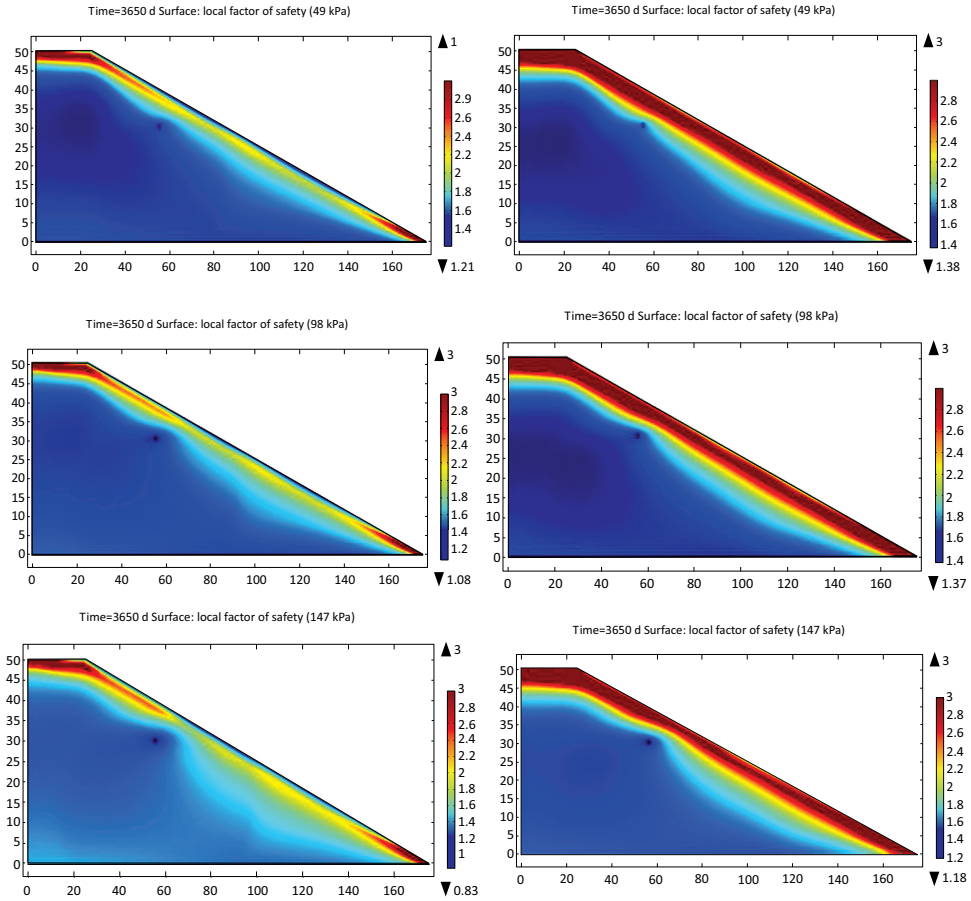

Fig. (7). Effect of tyre drainage net on the local factor of safety (left panel show the results of landfill without tyres).

CONCLUSION

This paper proposed to use a spatial bonded whole tyre net to accelerate the leachate recirculation in bioreactor landfills. A two-permeability flow model was employed to represent the preferential flow at tyre-waste interfaces and the flow within waste. Additionally, the flow model was coupled with solid mechanic model and by which the local factor of safety was determined. In this study, the established model was applied to a landfill and it demonstrated that the tyre net can significantly speed up the leachate injection and the liquid was distributed more uniformly. Furthermore, the slope stability was improved due to the enforcement of waste by virtue of tyres.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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