Intermittent leachate injection in bio-reactor landfills with bonded whole waste tyres

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Abstract. In bioreactor landfills, pressured leachate re-circulation can significantly influence the process of stabilization and the slope stability. To accelerate the leachate re-circulation and avoid slope failure, in this study, construction of a spatial reinforcement net is proposed, which consists of bonded whole waste tyres during municipal waste landfill. A coupled dual-permeability model and equilibrium equation were used to examine the enhanced leachate distribution and the local factor of safety of slope stability for a simplified bioreactor landfill. The simulation results demonstrated that for similar injection efficiency, the waste tyres net can help to decrease the amount of horizontal trenches and allows higher injection pressure under conditions of intermittent re-circulation. By virtue of waste tyres, the slope stability was considerably improved even when being exposed to a higher injection pressure.

1. Introduction
Bio-reactor landfills have emerged as a latest trend in solid waste management practices. In bio-reactor landfills, fluid including but not limited to leachate [1] is injected back into the MSW to accelerate the bio-degradation of MSW or increase the bio-gas production [2].

Horizontal trench systems (HTs) are extensively used to re-circulation leachate to landfill MSW [3]. The mission is to distribute the leachate or other fluid uniformly in the MSW as quickly as possible. Therefore, high injection pressures are commonly employed. However, it can result in excess pore fluid (i.e. water and gas) pressures which may cause landfill slope failure [4].

Waste tyre stockpiles have posed a serious problem in many industrialized countries [5]. The properties of waste tyres such as durability, strength, resiliency, and high frictional resistance are of significant values to improve soil shear strength [6]. However, the use of pure tyre shreds in civil engineering was reduced in the 1990s, when several tyre fills in the US were reported to develop self-heating reactions [7].

Disperse of whole tyres in waste could be more advantageous for the sake of avoiding internal hot spots. In the previous study [8], a spatial whole tyres net is proposed to be constructed during the filling of municipal waste. The waste tyres are bonded and filled together with waste, and a spatial interconnected net is knitted. For a simplified landfill with a single HT, the simulation results demonstrated that the tyres lead to a more rapid and uniform moisture distribution as well as a better mechanical stability of slope. The aim of this study is to examine the effects of intermittent injection for a landfill with single or multiple horizontal trenches, and to explore the possibility of a more efficient and cost-effective re-circulation injection strategy.
2. Theoretical models

2.1. Leachate flow model

The dual-permeability model adopts the pressure heads, $h$, as the primary variables, to describe the preferential flow in the vicinity of tyres surface and that within the waste [9]:

$$
(C_t + S_{ef} S_s) \frac{\partial h_f}{\partial t} = \nabla [K_f (\nabla h_f + 1)] - \frac{\Gamma_w}{w_f},
$$

(1)

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

(2)

where the subscripts of $f$ and $m$ designate the domains of preferential flow and waste matrix flow, respectively. The differential water capacity $\frac{\partial h}{\partial h}$ is indicated by $C$, followed by $S_e$, the effective saturation, $K$, the hydraulic conductivity and $S_s$, the specific storage. $\Gamma_w$ represents the water exchange rate between two overlapped and interacted flow domains, and its values is referred to [8]. The hydraulic properties of both flow domains are described by the van-Genuchten function, and the details are listed in table 1.

2.2. Slope stability analysis method

The slope-stability analysis of this study is based on the local safety factor approach. The local safety factor (LSF) is a stress ratio as $\tau^*/\tau$, where $\tau^*$ denotes the potential failure state stress under the Mohr-Coulomb criterion, and $\tau$ is the current Coulomb stress. LSF is written as:

$$
LSF = \frac{2 \cos \phi}{\sigma_1 - \sigma_3} \left( c' + \frac{\sigma_1' + \sigma_3'}{2} \tan \phi \right)
$$

(3)

where $\sigma_1'$ and $\sigma_3'$ are the first and third principal effective stress, $c'$ is the effective cohesion and $\phi$ indicates the friction angle.

Along with two Richards equations, the total stress is computed by a momentum balance equation for the calculation of the local factor of safety [10]. The coupled model is solved by COMSOL.

3. Modelling results

3.1. Landfill profile

The landfill illustrated in figure 1, which is similar to that reported by [11] and [4], is used in this study. For the hydraulic boundary conditions, the leachate is injected through a horizontal trench (1 m×1 m) into the waste in both continuous and intermittent pattern. The LCRS consists of free draining granular soil such as gravel. The excess pore-water pressure is specified to zero at the bottom where the drainage layer locates, and the remaining sides are no-flux boundaries.

For the stress equilibrium boundary conditions, there is no constraint at the side slope and the bottom is fixed in both horizontal and vertical directions. The lateral deformation on the left side boundary of the landfill is restrained but the top boundary and left-side boundary are free to move only in the vertical direction.
Figure 1. Conceptual sketch for a landfill using HTs for leachate re-circulation.

Table 1. Parameters used in the mathematical model.

| Symbol | Parameter                                      | Value | Unit   |
|--------|------------------------------------------------|-------|--------|
| γ      | Unit weight                                    | 5.5   | kN/m³  |
| α      | Inverse of air entry pressure                  | 1.4   | 1/kPa  |
| θᵣ     | Residual moisture content                      | 0.14  | -      |
| θₛ     | Saturated moisture content                     | 0.58  | -      |
| n      | VG unsaturation coefficient                    | 1.6   | -      |
| a      | -                                              | 0.37  | -      |
| b      | -                                              | 0.5   | -      |
| c      | -                                              | 0.5   | -      |
| kᵥ     | Hydraulic conductivity                         | 1×10⁻⁷ | m/s    |
| kₖ/kᵥ  | Hydraulic conductivity anisotropy of MSW       | 10    | -      |
| c'     | Cohesion of MSW                                | 15    | kPa    |
| c''    | Cohesion of the tyre-waste mixtures            | 41    | kPa    |
| Φ'     | Friction angle of MSW                          | 35    | °C     |
| Φ''    | Friction angle of the tyre-waste mixtures      | 35    | °C     |

Table 1 lists all the parameters used in the following simulations. Constant hydraulic properties of the MSW were used due to the lack of measure data and [12] has proved their influences on the key design parameters for the steady flow are relatively small.

3.2. The combined effect of tyres and intermittent injection on the injection pressure allowed

High injection pressure has been often used to add liquids to the municipal solid waste using buried horizontal trenches. However, the high pressure raises the concern of slope instability [3]. Both field and laboratory experiments have found that addition of tyre shred could effectively increase the soil shear strength [5]. The simulations in this study include this improvement by increasing the values of cohesion and the internal friction angle according to the findings in [5].

Figure 2 illustrates the LSF for two cases with a relatively high pressure (herein, it is 280 kPa). At the absence of tyres, even the case of intermittent injection causes danger of slope failure (figure 2 (a)) whilst its counterpart of case with tyres avoid the slope instability (figure 2 (b)). Therefore, operation of intermittent injection pattern with spatial tyres embedded should be adopted for a high injection pressure.
Figure 2. LSF at the end of one year with injection pressure equal to 280 kPa: (a) Continuous injection without tyres; (b) Intermittent injection with tyres.

3.3 The effect of tyres on quantity of the horizontal trench

In practice, the bioreactor landfill designers and operators usually employ various configurations of HTs (depending upon the spacing and layout) for more uniform and rapid distribution of leachate in the landfilled MSW. More horizontal trenches in the landfill obviously lead to higher injection efficiency. However, it is evident that the migration of leachate results in a decrease in effective stress, and in turn, a decrease in shear strength, which could endanger the physical stability of landfill slopes. In addition, the increase in the number of HTs also increases the installation cost. In this study, the embarrassment is resolved by virtue of the embedded tyres.

Figure 3 shows the variation of wet area with injection time for varying number of horizontal trenches. The wetted area is the landfill domain with a degree of liquid saturation greater than or equal to 60%. This level of liquid content provides the most appropriate situation for the biological decomposition in landfill waste. Although the temporal change of wetted area for the case of one trench with tyres is similar to that for case of two trenches without tyres, the slope stability results are totally different.
Figure 3. The variation of wet area with injection time for both continuous and intermittent injection (injection pressure: 196 kPa).

Figure 4 displays the slope stability situation for the landfill with two HTs subjected to one-week-on-off injection. Figure 4(b) indicates there is no instability for the former case whereas the LSF less than unity occurs for a large area in the latter case (figure 4(a)). Therefore, it demonstrates that the utility of spatial bonded tyres can reduce the number of horizontal trenches needed and the associated installation and maintenance cost without compromise of the injection efficiency. Meanwhile, the slope stability of landfill is significantly improved.

4. Conclusions
Pressured leachate injection can accelerate the distribution of liquid in MSW and create a favorable environment for bio-degradation. To avoid the occurrence of slope failure without sacrifice of leachate addition efficiency, this study proposed a drainage system of bonded whole-tyres-net for the bioreactor landfills which undergoing leachate re-circulation. The coupled flow and stress equilibrium model was employed to investigate the efficiency of re-circulation and the slope safety, and it was found that:
- Compared to the continuous injection, the intermittent recirculation at presence of tyres experiences the enhancement of leachate distribution due to the preferential flows path created by the tyre-waste interface.
- In addition, the intermittent pattern allows higher injection pressure without causing slope failure because of the combination benefits of longer dissipation of the excess pore pressure and the reinforcement of embedded tyres.
- Furthermore, for a drainage system consists of a multiple horizontal trenches, the intermittent injection with the use of bonded tyres could achieve excellent recirculation efficiency at a lower cost than a traditional practice.
Therefore, the results in this study demonstrate that the spatially bonded-waste tyre is a promising drainage system for a bio-reaction landfill and deserves more investigations to clear the possible hinders on the way to application in field.

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