system. But, in practice, bioreactor landfill operators employ different configurations of HT system (depending upon the spacing and layout) for uniform and rapid moisture distribution. This condition, in particular, can have negative impact on the stability of landfill slopes due to generation of excessive pore fluid pressures near side slope. Giri and Reddy (2013a) investigated the effects of different geometric configurations (i.e., varied spacing and layouts) of HT system on leachate distribution and resulting influence on the stability of bioreactor landfill slope. In their study, a typical setback distance of 30 m was considered for all modeling simulations. However, in practice, setback distance of HT system could vary between 15-30 m, as recommended by USEPA (2007).

This study examines the effects of variation in setback distance of HT system, with known horizontal and vertical spacing between the successive HTs (Giri and Reddy 2013a), on the moisture distribution, generation and distribution of pore pressures, and the stability of bioreactor landfill slope. The validations of numerical two-phase flow modeling, selection of MSW heterogeneity and anisotropy, unsaturated hydraulic properties, and effects of geometric configuration of HT systems have been presented elsewhere (Giri and Reddy 2013a-d).

MODELING METHODOLOGY

Numerical Two-Phase Flow and Slope Stability Model

The numerical two-phase flow model assumes landfill leachate and gas as two immiscible phases existing simultaneously in the pores of unsaturated MSW. Leachate is considered as wetting fluid, while landfill gas is assumed as non-wetting fluid. The fluid flow is influenced by degree of saturation, capillary pressure, and relative hydraulic conductivity. The capillary pressure is a function of leachate degree of saturation, and can be represented by the van Genutchen (1980) model. The flow of leachate and non-wetting landfill gas is described by Darcy's law, whereas relative permeability of each fluid is based on wetting leachate saturation by the empirical laws of the van Genuchten function (ICGI 2011). The governing equations for the two-phase flow model consist of momentum balance and the fluid balance laws:

$$\rho = \rho_d + n(S_L \rho_L + S_G \rho_G) \tag{1}$$

$$n\left[\frac{S_L}{K_L}\frac{\partial P_L}{\partial t} + \frac{\partial S_L}{\partial t}\right] = -\left[\frac{\partial q_i^L}{\partial x_i}\right] \tag{2}$$

$$n\left[\frac{S_G}{K_G}\frac{\partial P_G}{\partial t} + \frac{\partial S_G}{\partial t}\right] = -\left[\frac{\partial q_i^G}{\partial x_i}\right] \tag{3}$$

where: n = porosity, S_L and S_G = leachate and gas saturation, ρ_L, ρ_G = fluid densities, ρ_d = matrix dry density, P_L and P_G = pore liquid and gas pressure, K_L and K_G= liquid and gas bulk modulus, q_i^L, q_i^G = flow rate of liquid and gas, respectively. The governing Eqs. (1), (2), and (3) are solved numerically with the Fast Lagrangian Analysis of Continua (FLAC) program using the finite difference method. The detailed information regarding the numerical formulations of the two-phase flow model is reported elsewhere (IGCI 2011).

Simultaneously, stability analyses are performed using FLAC, wherein strength reduction technique is adopted to determine slope stability in terms of factor-of-safety. Mohr-Coulomb failure criterion is combined together with strength reduction approach for stability analyses. In this approach, factor-of-safety (FOS) calculation is performed by successively reducing the shear strength parameters of MSW until the slope reaches on the verge of failure. More information on this and its application are presented elsewhere (Giri and Reddy 2013a-d).

Landfill Configuration

A simplified two-dimensional bioreactor landfill model, 175 m wide and 50 m deep with a side slope of 3H: 1V was created in FLAC using graphical interface (Fig. 1). The landfill model configuration and the overall modeling approach is similar to that reported by Xu et al. (2012) who used the single-phase flow model SEEP/W and SLOPE/W, respectively, to evaluate pore water pressures and their resulting impact on slope stability analysis. A 0.3 m thick leachate collection and removal system (LCRS), consists of free draining granular soil, is assumed to be located at the bottom of the 50 m deep landfill. To simulate the interface between the MSW and underlying LCRS, a cohesion and friction angle of 0 and 22 degrees, respectively, were considered (Xu et al.). A staggered configuration of 5 horizontal trenches (1 m x 1 m each) with known horizontal spacing (30 m) and vertical spacing (15 m) were selected for the modeling simulations. These spacing and layout have been discussed in Giri and Reddy (2013a) and are representative of typical field designs that are currently implemented at bioreactor landfills in the United States. For the modeling purpose, only the setback distance (SD) is varied, whereas the staggered pattern of HT system remains the same (Table 1).

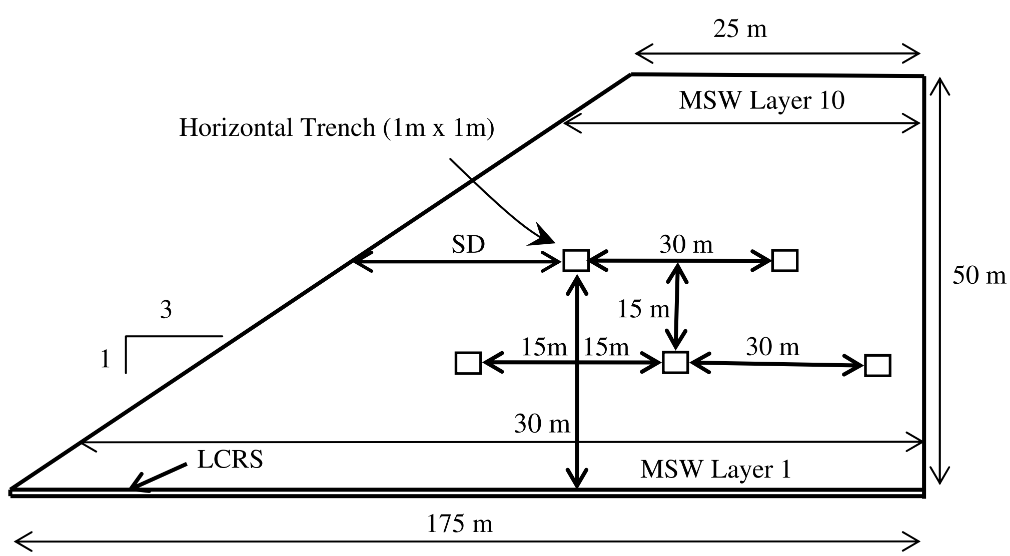

Fig. 1 Simplified bioreactor landfill configuration, depicting a horizontal trench system

Table 1. Different horizontal trench systems considered for model simulations

Configuration	Setback from the side slope, SD (m)	Number of HT Layers	Total Number of HTs	Vertical Spacing between HT Layers, (m)	Horizontal Spacing between HT Layers, (m)
HT-S1	15	2	5	15	30
HT-S2	20	2	5	15	30
HT-S3	25	2	5	15	30
HT-S4	30	2	5	15	30

Initial and Boundary Conditions

Mechanical boundary conditions are applied by fixing the base in both directions for zero lateral and vertical deformations at the base. The lateral deformation is restrained on the right side boundary of the model, while the side slope is free to move in both directions. The top surface can move only in the vertical direction. Pore gas pressure and seepage were fixed to zero at the top boundary and at the side slope to simulate hydraulic condition. The right-side boundary and the bottom of the landfill model are considered to be impermeable (i.e., free pore pressures and free saturation). All grid points were initially free to vary based on the net inflow and outflow from the neighboring zones. Pore water pressure was fixed to zero for the grid points at the LCRS to represent the drainage layer. The pore gas pressures were fixed to be zero initially at all grid points in order to establish initial mechanical equilibrium. Based on the established initial mechanical equilibrium conditions, baseline (mechanical) factor of safety of the slope was calculated. The initial volumetric moisture content of 15% (v/v, by volume) at all grid points and an initial porosity of 40% at all zones were considered.

Material Properties

The 50 m deep landfill was divided into ten different layers, each of 5 m thick, to simulate the heterogeneous and anisotropic MSW (HTAW) with varied unit weight and saturated hydraulic conductivity. The variation in unit weight with depth was estimated based on the relationship proposed by Zekkos et al. (2006), while the saturated hydraulic conductivity with depth was calculated using Reddy et al. (2009). The values of anisotropy (10 = horizontal hydraulic conductivity/vertical hydraulic conductivity), cohesion (15 kPa) and friction angle (35˚) were kept constant and were directly adopted from a single-phase flow study (Xu et al., 2012). Table 2 shows the properties of HTAW conditions. The unsaturated hydraulic properties of MSW were taken from the experimental study carried out by Breitmeyer and Benson (2011). The unsaturated hydraulic parameters of MSW considered for this study were as follows: Inverse of air-entry pressure, α (1.18 1/kPa); saturated moisture content, θs (0.41); residual moisture content, θr (0.03); the van Genuchten steepness parameter, n (1.33); and the van Genuchten parameter, m (0.248). The selection of unsaturated properties of MSW has been explained elsewhere (Giri and Reddy 2013c).

Table 2. MSW Properties for Heterogeneous Anisotropic Waste (HTAW)

Layer	Depth (m)	Depth to mid layer (m)	Unit Weight (kN/m^3)	Vertical Hydraulic Conductivity (cm/s)
10 (Topmost)	0-5	2.5	12.6	2.4×10^{-3}
9	5-10	7.5	13.5	2.5×10^{-4}
8	10-15	12.5	14.1	4.7×10^{-5}
7	15-20	17.5	14.6	1.3×10^{-5}
6	20-25	22.5	14.9	4.4×10^{-6}
5	25-30	27.5	15.1	1.8×10^{-6}
4	30-35	32.5	15.3	8.2×10^{-7}
3	35-40	37.5	15.4	4.1×10^{-7}
2	40-45	42.5	15.6	2.3×10^{-7}
1 (Bottom)	45-50	47.5	15.7	1.3×10^{-7}

MODEL SIMULATIONS

Effect of Horizontal Trench System

To investigate the influence of location of HT system, four different HT system configurations (i.e., HT-S1, HT-S2, HT-S3, and HT-S4) based on varied setback distance from side slope were modeled. And, the obtained results were compared in terms of moisture distribution (i.e., saturation contours), pore water and capillary pressures, and factor of safety with injection time.

Slope stability analyses were carried out using continuous as well as intermittent mode of leachate injection. In this study, all simulations were carried out with an injection pressure of 196 kPa for a steady-state flow condition or FOS $\geq$ 1.5, whichever occurred first. An injection pressure of 196 kPa was selected based on the maximum water column head of 20 m (i.e., vertical distance from the top boundary surface to the HT = 20 m).

RESULTS AND DISCUSSION

Fig. 2 shows the contours of leachate degree of saturation and evolution of pore water pressure for different horizontal trench systems just before the landfill slope failure (FOS $\geq$ 1.5). The results are presented for continuous leachate injection mode with an injection pressure of 196 kPa. As shown in Fig. 2, the injection duration needed to bring the landfill slope to verge of failure varied for different HT system configurations based on setback distance. Steady-state flow condition is not achieved for any of the modeled HT systems, since the MSW is heterogeneous and anisotropic in nature and the injected leachate migrated more in the lateral direction than in vertical downward direction. For each HT system, the spread of leachate was greater in shallow layers due to high saturated hydraulic conductivity than in deep layers, wherein low hydraulic conductivity resulted in small leachate migration.

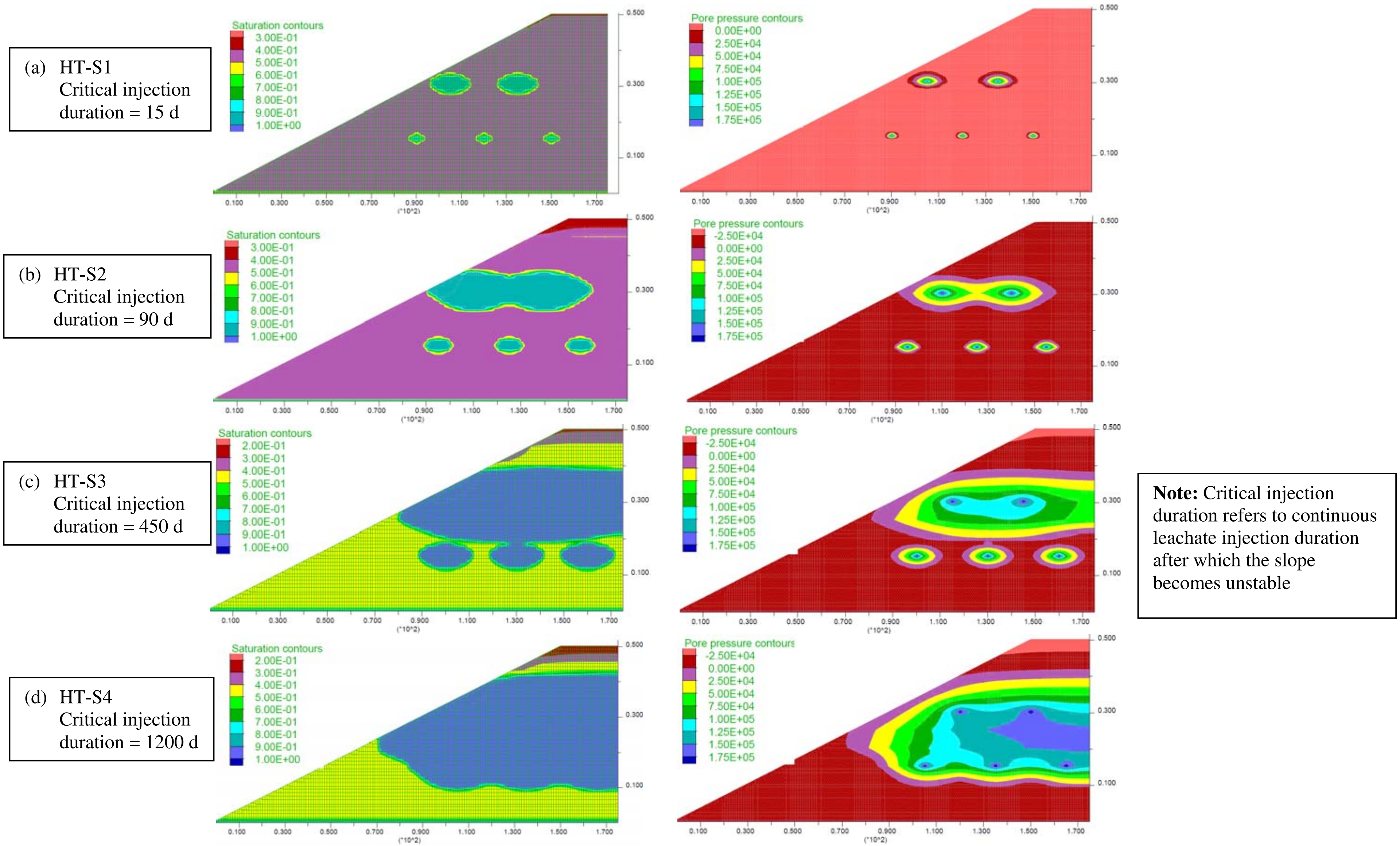

Fig. 2. Contours of saturation and pore water pressures for (a) HT-S1, (b) HT-S2, (c) HT-S3, and (d) HT-S4 configurations during continuous leachate injection with an injection pressure of 196 kPa

The wetted area of MSW (defined as the area corresponding to leachate saturation ≥ 60%) were estimated to be 2.5%, 4.7%, 21%, and 43% of the total landfill area, respectively, for HT-S1, HT-S2, HT-S3 and HT-S4 configurations, just before the landfill failure, during continuous leachate injection. This implies that the staggered HT system located relatively far away from side slope (i.e., SD = 30 m) would distribute the leachate more effectively as compared to HT system placed relatively closer to side slope (SD = 15 m). Similarly, the developed excess pore water pressures were significantly higher during a short leachate injection of 15 days in the case of HT-S1 than the rest of HT systems due to its close proximity to side slope. Hence, a staggered HT system must not be placed very close to side slope, during continuous leachate injection with high injection pressure, as it fails to provide uniform moisture distribution without generating excess pressures.

During continuous injection, different HT systems resulted in varied pore water and capillary pressures within the first two weeks as well as just before the landfill slope failure (Fig. 3). High initial capillary pressures (~5-40 kPa) were observed during the first two weeks, as a result of unsaturated MSW, which implies the need to consider pore gas pressures during slope stability analyses. However, as the degree of saturation increases, capillary pressure reduces while pore water pressure increases. Pore water pressure was highest in HT-S1 (~80 kPa) and lowest in HT-S4 (~20 kPa) after first two weeks. However, just before the failure, maximum pore water pressure was observed to be in the case of HT-S4 (116 kPa).

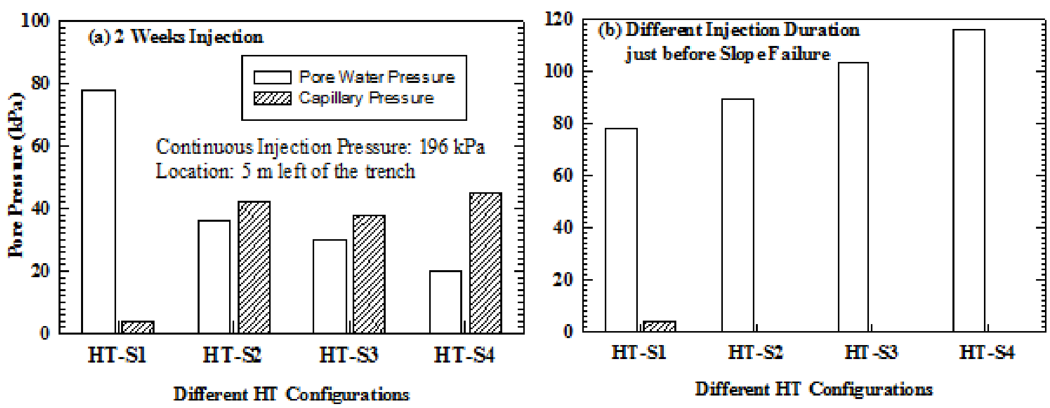

Fig. 3. Pore water and capillary pressures for different HT configurations using continuous leachate injection modes with injection pressure of 196 kPa

Landfill slope stability analyses were performed for all HT systems by taking into consideration of transient varying pore fluid pressures during leachate recirculation. Fig. 4 presents the critical slip surface of the landfill slope, wherein the leachate is continuously injected using different HT systems until the slope reaches on the verge of failure. The initial baseline FOS (no leachate injection) was computed to be 2.11 for all HTs. However, once the leachate is continuously recirculated in landfilled MSW using above mentioned HT systems with varied setback distances, the failure of landfill slope occurred (FOS < 1.5) depending upon the developed excess fluid pressures near side slope. This is evident from the fact that the failure surface(s) of each HT system was observed to be shallow and passed through the side slope.

(a) HT-S1
Critical injection
duration = 15 d

(b) HT-S2
Critical injection
duration = 90 d

(c) HT-S3
Critical injection
duration = 450 d

(d) HT-S4
Critical injection
duration = 1200 d

Note: Critical injection duration refers to continuous leachate injection duration after which the slope becomes

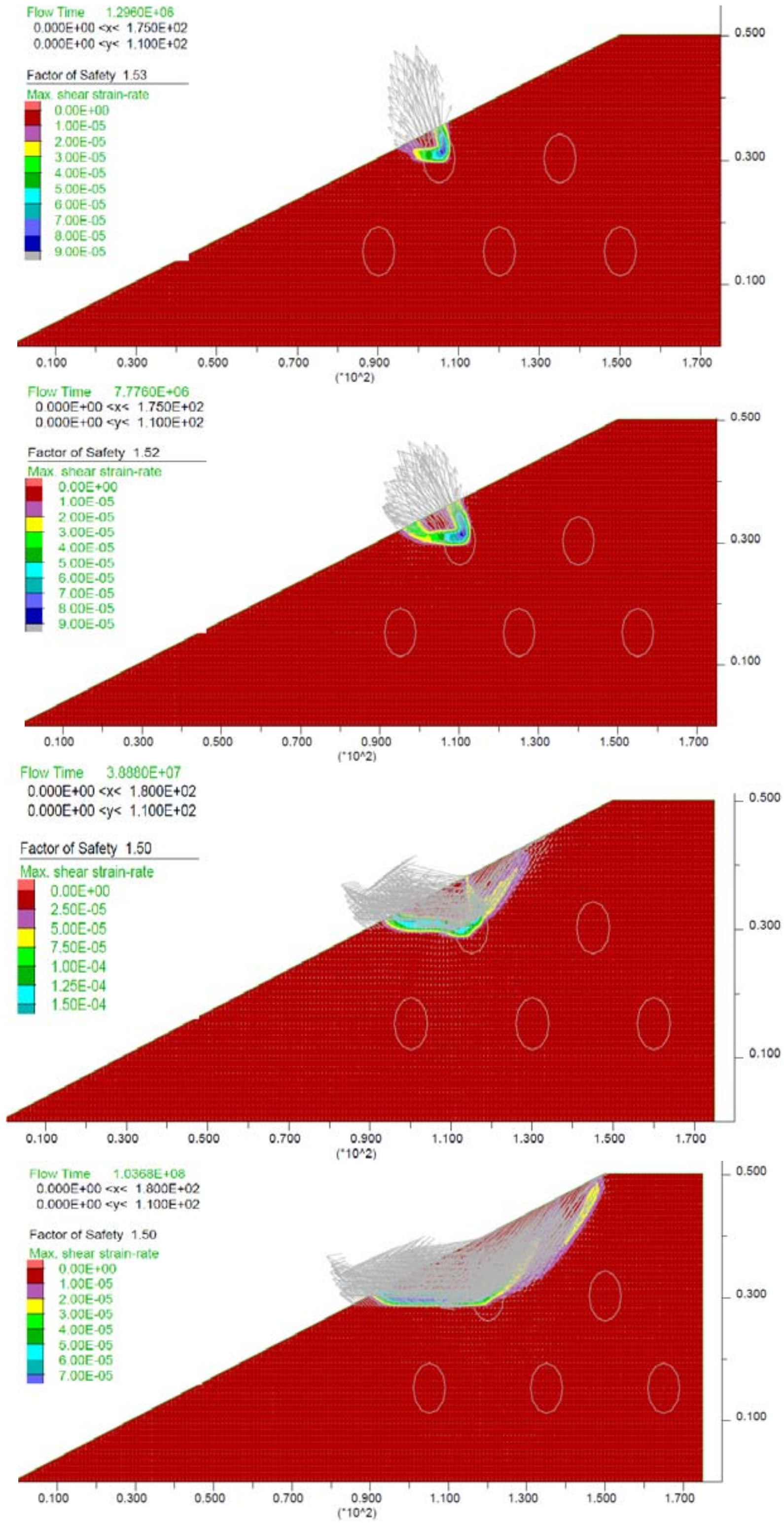

Fig. 4. Critical slip surface for (a) HT-S1, (b) HT-S2, (c) HT-S3, and (d) HT-S4 configurations during continuous leachate addition with injection pressure of 196 kPa

As mentioned before, HT-S1 produced considerably high pore pressures in relatively short injection duration, therefore, this scenario led to the failure of landfill slope within first 16 days. But, as the lateral distance(s) between HT system and side slope were increased (from 15 m to 30 m), the injection time required to bring the landfill slope failure extended subsequently. This is due to the fact that the HT systems placed farther away from side slope (i., HT-S4 and HT-S3) were able to distribute the leachate, both laterally and vertically downward, in a more effective manner than HT-S1. Hence, it provided sufficiently longer duration (450 days for HT-S3 and 1200 days for HT-S4) for these two HT systems to generate high enough pore fluid pressures that would bring about the slope failure.

Continuous leachate injection led to slope failure. Hence, One-Week-On-Off intermittent injection simulation was performed with the following scenarios: First week leachate injection in shallow HTs only; second week injection in deep HTs only, and repeated cycles until steady state conditions or slope failure occurs. As shown in Fig. 5, One-Week-On-Off injection mode would provide safer design and operations in bioreactor landfill than continuous leachate injection. This is because the gravity drainage during intermittent injection allows sufficient time for excess pore fluid pressure to dissipate. And, low pore fluid pressures near side slope yield in relatively stable bioreactor landfill for all HT systems in the specified injection duration

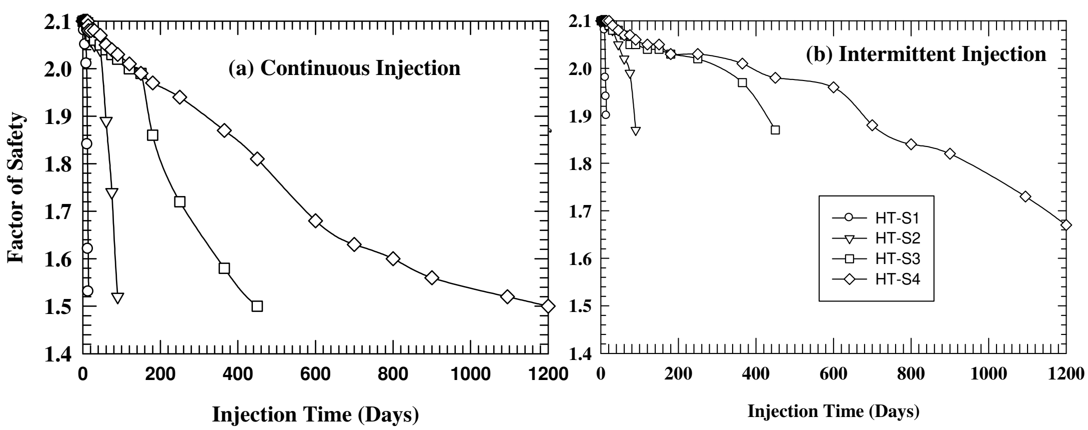

Fig. 5. Evolution of factor of safety with injection time for different horizontal trench systems using (a) continuous and (b) One-Week-On-Off injection mode

CONCLUSIONS

This study focused on evaluating the stability of a simplified bioreactor landfill slope during leachate recirculation using horizontal trench system. Numerical simulations were performed by varying the lateral distance(s) between a staggered HT system and nearby side slope. Based on the present study, following conclusions were drawn:

- Determination of location(s) of horizontal trench system with respect to the side slope of a bioreactor landfill is of most importance, for successful design and operations during leachate recirculation. As variation in lateral distance of a staggered HT system from side slope significantly influenced the degree of leachate saturation, moisture distributions, generation and distribution of pore fluid pressures and the stability of landfill slope.

- Staggered HT system with a typical horizontal and vertical spacing between successive HTs, located in a relatively close proximity of side slope, could greatly affect the slope stability and lead to landfill slope failure under continuous injection as a result of excessive pore fluid pressures when compared with the HT systems, located relatively far away from side slope. Intermittent leachate injection in alternate HT layers proved effective in maintaining stable slope without generating excess pressures, and resulting in an optimal environment for waste biodegradation.

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Undrained Response of Municipal Solid Waste Collected from a Waste Site in Delhi, India

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ABSTRACT: Consolidated undrained triaxial compression tests with pore water pressure measurement were carried out on 150 mm-diameter samples of municipal solid waste (MSW) recovered from a waste site in Delhi. While understanding of the mechanical response of municipal solid waste has evolved significantly in the recent years, most of the previous work has studied the behavior of MSW under drained conditions. However, there are several situations in which the undrained behavior of MSW may be important, particularly for uncontrolled dumps and bioreactor landfills where the MSW may be in a saturated or near-saturated condition. MSW samples were reconstituted at their in-situ composition and reconstituted with only the less than 20 mm fraction (the soil-sized fraction) for comparison. The stress strain response of specimens at the in-situ composition showed a strain hardening type behavior, with the mobilized shear strength continuing to increase without reaching peak strength at strains in excess of 20 percent. Specimens with only the soil sized fraction exhibited a peak response, clearly demonstrating the role/importance of fibrous waste constituents in the mechanical response of MSW. In both cases, shear strength parameters established based upon several different failure strain criterion indicated an effective friction angle in excess of 45 degrees.

INTRODUCTION

This paper present the results of and interpreted strength parameters from consolidated undrained triaxial compression tests with pore pressure measurements ($\overline{CU}$ tests) carried out on 150 mm-diameter samples of municipal solid waste recovered from a waste site in Delhi, India. Disposal of municipal solid waste (MSW) in landfills has been the most common and in many cases unavoidable component of MSW management systems. Rapid urbanization has led to an exponential increase in MSW generation which needs to be disposed in an environmental friendly manner. However, due to the difficulty in procuring suitable