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Slope stability of landfills considering leachate recirculation using vertical wells

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ABSTRACT

In bioreactor landfills, leachate recirculation system can significantly promote moisture distribution, thereby enhancing the biodegradation of municipal solid waste (MSW). However, it increases pore pressure inside landfills, which can greatly affect slope stability. In this study, a three-dimensional numerical model is established to study the landfill slope stability under leachate recirculation through Vertical Wells (VWs). A leachate flow model is adopted to describe the migration of leachate, and the distribution of pore pressure is then used to calculate the Factor of Safety (*FS*) using strength reduction method. A large number of simulations are conducted using the proposed model to investigate the influences of injection pressure, hydraulic and mechanical properties, slope gradient, VW location and group-well configuration on slope stability. Large injection pressure or anisotropy of MSW is adverse to the slope stability. *FS* changes almost linearly with the variation of friction angle and cohesion. The horizontal distance between the VWs and the slope surface (d) and well spacing (D) are two important factors for slope stability. Design charts of the minimum safe distance (d_s) and the minimum safe well spacing (D_s) are proposed considering various conditions. Finally, a design method of leachate recirculation system using VWs is proposed considering both recirculation efficiency and slope stability. The proposed model can well accommodate practical landfills with leachate recirculation system using VWs. The method and the results are promising to be used as a reference in engineering practice.

1. Introduction

Landfill is the main method for Municipal Solid Waste (MSW) disposal all around the world. In recent decades, bioreactor landfills have been developed by recirculating the leachate collected from Leachate Collection and Removal System (LCRS) back into the landfill, which reduces the amount of leachate needed to be disposed. By leachate recirculation, the moisture content of MSW can be increased, which accelerates MSW degradation and landfill stabilization processes (Allen, 2001; Reinhart et al., 2002). In engineering practice, Vertical Wells (VWs), which consist of spraying pipes and highly permeable filter materials surrounded, are the most widely used facility for leachate recirculation, compared with horizontal trenches and surface spraying (Reinhart and Townsend, 1997). On the other hand, the injection of leachate also increases pore pressure inside landfills, and it may cause slope failure. For example, the slope failure in Payatas landfill was caused by excess pore pressure (Merry et al., 2005). The failure of landfill slopes would pose a threat to the infrastructures and the socio-economic activities nearby (Marcato et al., 2012). Therefore, it is very important to investigate the effect of leachate recirculation on slope stability for rational design of landfills.

Numerous researches have studied leachate recirculation in landfills. Jain et al. (2010), Haydar and Khire (2005) and Feng et al. (2014, 2015) investigated leachate migration in bioreactor landfills with VWs, horizontal trenches and surface spraying, respectively. Kadambala et al. (2011) presented the impact of leachate recirculation using VWs on pore pressure at a full-scale landfill. Feng et al. (2017) employed a three-dimensional two-phase flow model based on OpenFOAM to study the leachate recirculation using VWs and the interactions between leachate and gas were evaluated. However, these studies did not consider the impact of recirculated leachate on slope stability in landfills, which is a very important concern when a landfill is designed.

Some researches further considered the influence of leachate recirculation on slope stability in landfills. Koerner and Soong (2000) presented a unified approach explaining the influence of leachate on landfill stability in a sequential manner, but the spatial-temporal

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characteristics of leachate recirculation were not considered. Thiel and Christie (2005) studied the potential long-term concern of slope stability caused by leachate recirculation, whereas the discussion was qualitative rather than quantitative. Xu et al. (2012) and Giri and Reddy (2014) developed two-dimensional (2D) single-phase (leachate) and two-phase (leachate and gas) flow models, respectively, to investigate the landfill slope stability under leachate recirculation condition using horizontal trenches. However, the geometries of landfills are always complex, which cannot be simulated by these 2D models. Moreover, in a landfill with leachate recirculation system using VWs, the transport of leachate and the distribution of pore pressure are spatially complicated and cannot be simulated with 2D models. To the best of our knowledge, few studies have focused on the slope stability of landfills with leachate recirculation using VWs.

This paper presents a three-dimensional (3D) model for analyzing slope stability in landfills when recirculating leachate using VWs. This model can reasonably reflect the landfill conditions and simulate both single-well and group-well recirculation systems. The effects of injection pressure, hydraulic-mechanical properties of MSW, and landfill geometric parameters (i.e., slope gradient, VW location) on slope stability are then investigated using the proposed model. A preliminary design method of VWs considering the slope stability of landfill is also proposed. Two key design parameters, including the minimum safe distance between VWs and landfill slope surface (d_s) and the minimum safe well spacing (D_s), are carefully investigated and recommended values are given. The established 3D model can well accommodate landfills with leachate recirculation system using VWs. The method and the results are promising to be used as a reference in engineering practice.

2. Methodology

2.1. Conceptual model

There are numerous vertical wells working together in a leachate recirculation system of landfill (Fig. 1). In this section, a 3D bioreactor landfill is established with a cover system on the top and the slope surface, and a Leachate Collection and Removal System (LCRS) at the bottom (Fig. 1). FLAC^{3D} is employed to build the model and both brick and radial cylinder grid types are used. A sensitivity analysis is carried out first to estimate the grid size and it is found that when the grid size is smaller than 0.5 m, the simulation results are almost the same, so a grid size of 0.5 m is chosen. The cover system, including the top and the slope surface, is regarded as impermeable. The bottom LCRS is assumed as a free-drainage boundary to allow the leachate flowing out by fixing the pore pressure of grids at the bottom to zero. In a basic scenario, a VW is set near the slope (Fig. 1a). The height of the landfill is H and the elevation of the injection screen is h (Fig. 1b). d is the horizontal distance between the VW and slope surface at the elevation of the injection screen top. The injection screen at the bottom of the VW has a length of 2 m and a diameter of 0.3 m in this study. Leachate is recirculated into the landfill under controlled pressure. The mechanical boundary conditions are shown in Fig. 1a. The bottom surface is totally constrained and the displacements of two end faces are fixed in the y direction ($v = 0$), and the back face is constrained in the x direction with a u of 0. Leachate migrates in the landfill, which can increase the water content of MSW. The impact zone in Fig. 1 is defined as area with degree of saturation larger than 0.8, which can provide an optimal environment for biodegradation (ITRC, 2006). During leachate recirculation, leachate flows inside landfill and spreads widely before being collected by the LCRS, and thus the impact zone gets larger with time before reaching a steady state. The effective stress of MSW within the impact zone decreases with the increase of degree of saturation, resulting in a decrease of shear strength (Zhang et al., 2015). With the expansion of the impact zone, slope failure may occur (Fig. 1b).

The anisotropic structure of MSW has been reported in both field

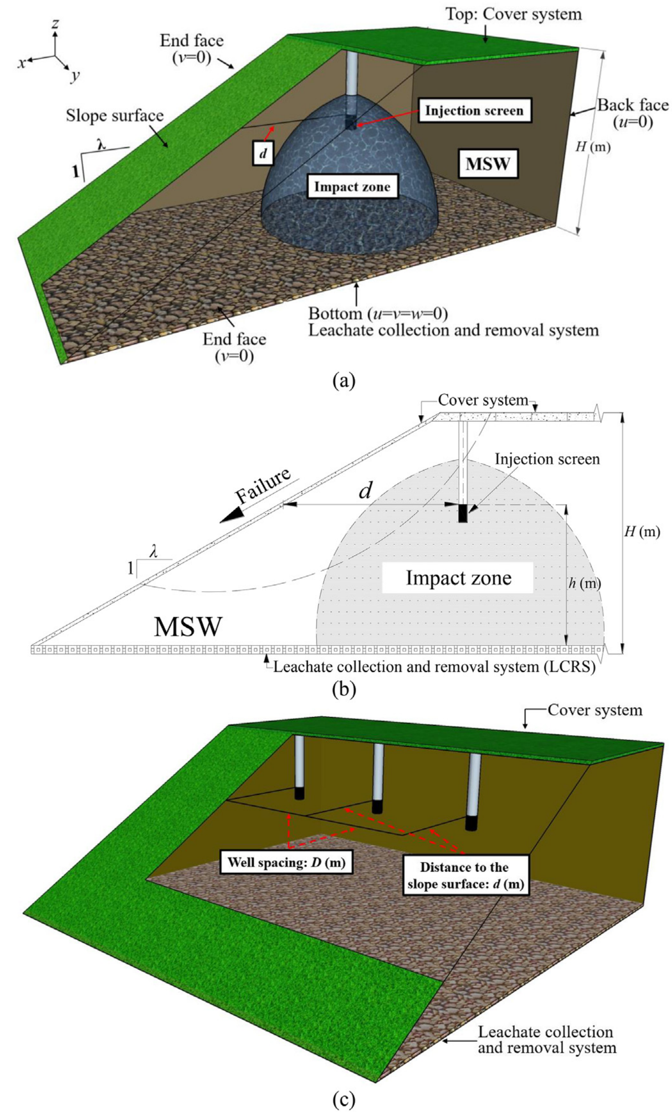

Fig. 1. Conceptual model of a landfill slope with vertical wells: (a) 3D view of single-well scenario; (b) cross-sectional view of single-well scenario; (c) 3D view of group-well scenario.

(Kadambala et al., 2011; Singh et al., 2014) and laboratory tests (Hudson, 2007; Stoltz et al., 2010). The anisotropy is mainly attributed to the anisotropic deposition of MSW (landfilling layer by layer), the high compression stress in the vertical direction, and the nature of some predominant waste components such as plastic and paper. Hence, MSW has different hydraulic conductivities in horizontal and vertical directions, and the anisotropic coefficient (A) is used to evaluate the difference, which can be expressed as

$$A = k_h/k_v \tag{1}$$

where k_h and k_v are the horizontal and vertical hydraulic conductivities, respectively. Reddy et al. (2009) reported that the hydraulic conductivity of MSW has a wide range of 3.7×10^{-8} to 1×10^{-2} cm/s. Landva et al. (1998) also reported that k_v could range from 2×10^{-6} to 2×10^{-3} cm/s and A from 4 to 10. An even larger range of A (1 to 100) was reported by Tchobanoglous et al. (1993). Thus, in this study, a range of 1×10^{-6} to 1×10^{-3} cm/s for hydraulic conductivity and a range of 1 to 20 for A are adopted for analysis. The initial saturation of MSW is 0.4 which is within the reported range in landfills and was also adopted in other studies (e.g., Reddy et al., 2014). Under the gravity load, the initial pore pressure can be solved automatically by the