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Research Paper

# Analytical solution for infiltration and deep percolation of rainwater into a monolithic cover subjected to different patterns of rainfall

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ABSTRACT

Monolithic cover is increasingly considered for use at landfills of solid wastes in arid and semi-arid areas. The evaluation of the deep percolation of rainwater through the monolithic cover is required for the cover design. An analytical solution is developed in this study for evaluating the infiltration and deep percolation of rainwater into a monolithic cover, subject to different patterns of rainfall events. The analytical solution is derived from the simplified one-dimensional governing equation of unsaturated flow for an infinitely long monolithic cover by taking the exponential forms of the soil–water characteristic curve and the hydraulic conductivity curve into account. A unit gradient boundary (UG) is considered at the bottom boundary of the monolithic cover. The patterns of rainfall considered include uniform type (U), advanced type (A1 and A2), central-peaked type (C), and delayed type (D1 and D2). The delayed percolation after the completion of a rainfall event can be captured by the analytical solution. Numerical simulation is conducted to compare the results with the analytical solution and to demonstrate that the analytical solution is acceptable for describing a silty soil, which is commonly used as the material for a monolithic cover. The analytical solution is used to investigate the influence of the rainfall pattern on the infiltration process and the occurrence of deep percolation. The analytical solution is used to evaluate the total percolation of a monolithic cover subjected to a sequence of non-continuous rainfall events within a wet season. The evaluation accounts for the influence of the initial water storage in the cover on the percolation by using the antecedent rainfall method proposed by Crozier and Eyles in 1980. A case study is performed to demonstrate the evaluation approach by using the water balance monitoring data of a model test on a silty soil cover reported in the literature. The case study indicated that the total percolation from the analytical solution is 34% greater than the measurement, which was on the conservative side for practical application.

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## 1. Introduction

As a form of earthen final cover, the monolithic cover is increasingly considered for use at some landfills in arid and semi-arid regions. Unlike conventional covers (e.g., compacted clay layers, geomembranes, and geosynthetic clay liners) that use materials with low hydraulic permeability to minimize the downward migration of rainwater from the cover to the waste (i.e., deep percolation), a monolithic cover uses a single layer of fine-grained soil to retain water until it is either transpired through vegetation or evaporated from the soil surface, so that the production of the percolation is minimized [1,2]. Compared to the conventional covers, the monolithic cover is expected to be less costly to construct and maintain [3]. Laboratory and field experiments have been conducted to evaluate the percolations of monolithic covers in different climate areas [4–6]. The research results show that the monolithic covers are effective in some arid and semi-arid areas [6–8]. In addition, numerical simulations have been conducted using many codes (e.g., UNSAT-H, VADOSE/W and HYDRUS) to evaluate the deep percolation of rainwater through monolithic covers [5,9–11]. In these simulations, the upper boundary was set as an atmospheric boundary condition consisting of evaporation or infiltration, the bottom boundary was often set as a unit gradient boundary (UG) or a seepage face boundary (SF), and the initial water content distribution was set as uniform or non-uniform, according to the actual situation. Experimental and numerical approaches have been widely used to evaluate the deep percolation of rainwater through the monolithic covers. However,

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such numerical studies are time consuming, and such experiments are costly. The analytical method requires some assumptions to derive closed-form solutions. If the assumptions are reasonable, then the analytical solution becomes a simple and practical tool for calculating the deep percolation of rainwater through monolithic covers [12].

To date, some analytical solutions for rainfall infiltration into horizontal or sloping ground have been studied by many researchers [12–17]. In 1991, Srivastava and Yeh [14] derived analytical solutions for simulating one-dimensional rainfall infiltration into homogeneous and two-layered soils using Laplace transformation. In 2010 and 2012, Zhan et al. [12,13] developed analytical solutions for simulating two-dimensional rainfall infiltration into infinite homogeneous soil and two-layered soils slopes. In 2012, Huang and Wu [15] presented analytical solutions to one-dimensional horizontal and vertical water infiltration in saturated/unsaturated soils. In 2009 and 2012, Wu et al. [16,17] developed analytical solutions for one-dimensional coupled seepage and deformation in homogeneous and two-layer unsaturated soils. However, the bottom boundary conditions used in the above analytical solutions were all the fixed pore water pressure boundary, which differs from the real conditions at the bottom of monolithic covers. The unit gradient boundary (UG) or the seepage face boundary (SF) is commonly used for the numerical computation of deep percolation through monolithic covers. In addition, the upper boundary condition used in the above analytical solutions was generally constant flow flux, which cannot be used to simulate non-uniformly distributed rainfall.

An analytical solution is proposed in this paper for describing rainfall infiltration into a monolithic cover and for calculating its percolation. The analytical solution is able to take six patterns of rainfall into account. The soil–water characteristic curve and hydraulic conductivity curve used in the analytical solution are expressed by exponential functions. A numerical simulation was conducted to verify the analytical solution and to determine the conditions under which the analytical solution is acceptable. The analytical solution was used to study the influence of the six patterns of rainfall on the infiltration and percolation in the monolithic covers. The analytical solution was further applied to evaluate the total percolation of a monolithic cover being subjected to a sequence of non-continuous rainfall events within a wet season. A case study was performed to demonstrate the evaluation approach by using the water balance monitoring data of a model test on a silty soil cover reported in the literature.

## 2. Infiltration model of the monolithic cover

The schematic diagram of a monolithic cover is shown in Fig. 1. The Cartesian rectangular space coordinates, $x$ and $z$, are used, with $x$ as a positive value in the horizontal downslope direction and $z$ as a positive value in the upward vertical direction. Another set of Cartesian coordinates are used as the rotated coordinates, namely, $x_*$ and $z_*$, as defined in Fig. 1. To obtain an analytical solution that can describe rainfall infiltration into the monolithic cover and calculate its percolation, the following five assumptions are made:

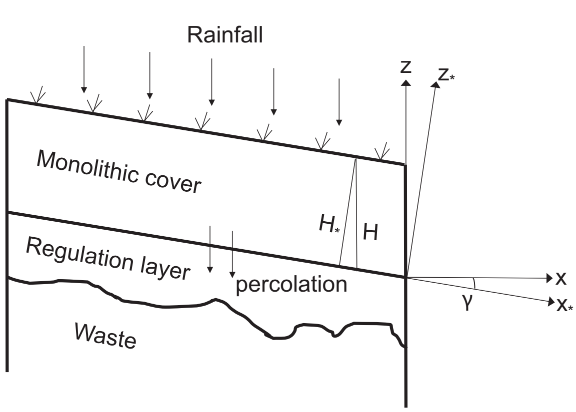


**Fig. 1.** Schematic diagram of a monolithic cover.

(1) The soil of the monolithic cover is homogeneous and does not exhibit a volume change during the wetting and drying process.
(2) The sloping length of the monolithic cover is assumed to be infinite, and the equipotential lines of pore water pressure are parallel to the surface of the slope [12,13]. Thus, the rainfall infiltration into the monolithic cover can be simplified as a one-dimensional problem.
(3) The pore air pressure in the soil, which remains constant and is equal to the atmospheric pressure, does not influence the water migration.
(4) The change of soil temperature has no influence on the water migration.
(5) The hysteresis associated with wetting/drying process is not considered in this paper.

According to the above assumptions, the two-dimensional unsaturated flow of the infinitely long monolithic cover can be simplified and expressed by a one-dimensional governing equation, as shown in Eq. (1). Its detailed derived process and description can be found in the previous literatures [12,13].

$$\frac{\partial}{\partial z_*}\left(k\frac{\partial \psi}{\partial z_*}\right)+\frac{\partial k}{\partial z_*}\cos\gamma=\frac{\partial \theta}{\partial t} \tag{1}$$

where $k$ is the unsaturated hydraulic conductivity, $\psi$ is the pore-water pressure head, $\gamma$ is the slope angle of the monolithic cover, $\theta$ is the volumetric water content, and $t$ is the time.

Eq. (1) is non-linear. To obtain its analytical solution, exponential functional forms are assumed to represent the hydraulic conductivity function and the soil–water characteristic curve (SWCC), as shown in Eqs. (2) and (3) [15,16].

$$k=\begin{cases}k_s e^{\alpha(\psi+\psi_{ae})} & \psi \leqslant -\psi_{ae}\\ k_s & \psi > -\psi_{ae}\end{cases} \tag{2}$$

$$\theta=\begin{cases}\theta_r+(\theta_s-\theta_r)e^{\alpha(\psi+\psi_{ae})} & \psi \leqslant -\psi_{ae}\\ \theta_s & \psi > -\psi_{ae}\end{cases} \tag{3}$$

where $k_s$ is the saturated hydraulic conductivity of the soil used for the monolithic cover, $\theta_r$ is the residual moisture content, $\theta_s$ is the saturated moisture content, $\alpha$ is a parameter representing the rate of reduction in hydraulic conductivity or moisture content as $\psi$ becomes more negative, and $\psi_{ae}$ is the air-entry value.

With these two exponential functions, Eq. (1) can be transformed to the following linear equations:

$$\frac{\partial^2 k}{\partial z_*^2}+\alpha\cos\gamma\frac{\partial k}{\partial z_*}=\frac{\alpha(\theta_s-\theta_r)}{k_s}\frac{\partial k}{\partial t} \tag{4}$$

The rainfall intensity is measured vertically and must be converted to a component perpendicular to the ground surface (i.e., decreased by the cosine of the slope angle) [18]. Therefore, the upper boundary condition of the monolithic cover can be written as

$$\left(k\cos\gamma+k\frac{\partial\psi}{\partial z_*}\right)\Bigg|_{z_*=H_*}=q\cos\gamma \qquad t>0 \tag{5}$$

where $H_*$ is the thickness of the monolithic cover, as shown in Fig. 1 and $q$ is the rainfall intensity that can completely infiltrate into the

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