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Transient design of landfill liquid addition systems

Pradeep Jain [a,*], Timothy G. Townsend [b,1], Thabet M. Tolaymat [c,2]

[a] Innovative Waste Consulting Services, LLC, 6628 NW 9th Blvd. Suite 3, Gainesville, FL 32605, USA
[b] Department of Environmental Engineering Sciences, University of Florida, P.O. Box 116450, Gainesville, FL 32611-6450, USA
[c] United States Department of Environmental Protection, National Risk Management Research Laboratory, 26 W. Martin Luther King St., Cincinnati, OH 45268, USA

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ABSTRACT

This study presents the development of design charts that can be used to estimate lateral and vertical spacing of liquids addition devices (e.g., vertical well, horizontal trenches) and the operating duration needed for transient operating conditions (conditions until steady-state operating conditions are achieved). These design charts should be used in conjunction with steady-state design charts published earlier by Jain et al. (2010a, 2010b). The data suggest that the liquids addition system operating time can be significantly reduced by utilizing moderately closer spacing between liquids addition devices than the spacing needed for steady-state conditions. These design charts can be used by designers to readily estimate achievable flow rate and lateral and vertical extents of the zone of impact from liquid addition devices, and analyze the sensitivity of various input variables (e.g., hydraulic conductivity, anisotropy, well radius, screen length) to the design. The applicability of the design charts, which are developed based on simulations of a continuously operated system, was also evaluated for the design of a system that would be operated intermittently (e.g., systems only operated during facility operating hours). The design charts somewhat underestimates the flow rate achieved and overestimates the lateral extent of the zone of impact over an operating duration for an intermittently operated system. The associated estimation errors would be smaller than the margin of errors associated with measurement of other key design inputs such as waste properties (e.g., hydraulic conductivity) and wider variation of these properties at a given site due to heterogeneous nature of waste.

1. Introduction

Liquids (leachate, groundwater, other liquids source such as industrial liquids and biosolids) addition to the conventional municipal solid waste (MSW) landfill (also commonly referred as a dry tomb landfill) is the most common approach to bioreactor operation. Vertical wells and horizontal sources (trenches, infiltration galleries) are frequently used to add liquids to landfilled waste. Like any other landfill components, (e.g., leachate collection system, gas collection system) the liquids addition system (also commonly referred as leachate recirculation system or liquids introduction system) needs to be designed for permitting, construction, and operation of bioreactor landfills. Based on the authors' design and review experience, a common approach for design of a liquids addition system is design for steady state conditions.

Jain et al. (2010a, 2010b) presented charts a designer can use for steady-state design of a vertical well and horizontal source system for liquids introduction. These charts can be used to estimate the achievable flow rate, lateral and vertical extents of the zone of impact, and the associated total liquids volume and operating time based on device dimensions and waste properties (hydraulic conductivity, anisotropy, porosity) at steady state conditions. For a design based on steady-state conditions, liquids addition devices are spaced based on the maximum possible lateral extent of the zone of impact of a device, which requires the addition of the liquid volume needed to reach the steady state, which in turn dictates the operating duration to achieve the steady state. Conditions however, may exist such that the timeframe over which liquids can be added is shorter than necessary to reach steady state; the timeframes needed to reach steady state were almost 19 years for the design chart application examples presented in Jain et al. (2010a) for vertical well systems, which is significantly greater than the typical life of a cell at MSW landfills in the US. Therefore, there is a need for tools to design liquids addition systems for conditions

* Corresponding author. Tel.: +1 352 2834742, +1 352 3314828; fax: +1 352 3314842.
E-mail addresses: pjain@iwcs.biz (P. Jain), ttown@ufl.edu (T.G. Townsend), tolaymat.thabet@epa.gov (T.M. Tolaymat).
[1] Tel.: +1 352 3920846; fax: +1 352 3923076.
[2] Tel.: +1 513 4872860; fax: +1 513 5697879.

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Nomenclature

α	Van Genuchten parameter related to air entry pressure
α_L	fluid compressibility ($M^{-1} L T^2$)
η	dimensionless variable
ρ	density of fluid ($M L^{-3}$)
θ	moisture content (dimensionless)
θ_r	residual moisture content (dimensionless)
θ_s	porosity of the media (dimensionless)
β'	constant equals to 1 when $p \geqslant 0$ and 0 when $p < 0$
a	anisotropy ratio (ratio of hydraulic conductivity in horizontal direction to that in the vertical direction) (dimensionless)
C	specific moisture capacity (L^{-1})
d	depth of the top of the well screen or horizontal source below the landfill surface (L)
k	relative permeability (dimensionless)
K	hydraulic conductivity ($L T^{-1}$) tensor
K_r	saturated hydraulic conductivity in radial direction ($L T^{-1}$)
K_z	saturated hydraulic conductivity in vertical direction ($L T^{-1}$)
l	horizontal source width (L)
m, n	Van Genuchten parameters related to pore size distribution
m_v	media compressibility ($M^{-1} L T^2$)
p	fluid pressure head (L)
p_I	injection pressure measured at the bottom of a introduction device
Q_v	flow rate added to a vertical well ($L^3 T^{-1}$)
Q_{vs}	flow rate added to a vertical well at steady state ($L^3 T^{-1}$)
q	dimensionless flow rate added to a introduction device
q_s	dimensionless steady-state flow rate added to an introduction device
r, z	cylindrical coordinates (L)
r_I	lateral extent of zone of impact of a vertical source (L)
r_{Is}	lateral extent of zone of impact of a vertical source at steady state
r_w	well radius (L)
S_s	specific storage (L^{-1})
t	time (T)
t_s	time to achieve steady state (T)
V_t	cumulative volume of liquids added to an introduction device in time t (L^3)
V_{ts}, $V_{t,critical}$	cumulative volume of liquids added to reach steady state (L^3)
w	vertical well screen length (L) or horizontal source depth (L)
x_I	lateral extent of zone of impact of a horizontal source (L)
x_{Is}	lateral extent of zone of impact of a horizontal source at steady state (L)
z	vertical coordinate (L)
z_I	vertical extent of zone of impact from the bottom of the source (L)
z_{Is}	vertical extent of zone of impact from the bottom of the source at steady state (L)

where the liquids volume added would be a fraction of that needed to achieve the state-state conditions.

All of the design charts presented in this paper and those presented by Jain et al. (2010a, 2010b) were developed based on assumption that the liquids are continuously (24 h a day, 365 days a year) added to a landfill. However, liquids introduction systems at bioreactor landfills are, usually, operated intermittently (typically during working days and hours of the landfill). In addition, liquids addition in a source (or a cluster of sources) is conducted on a rotational basis due to limitations on the available liquids, or allowable volume (per permit conditions) over a given duration, most likely, is smaller than the cumulative intake capacity of all sources installed at the site. The primary objective of this paper is to present additional design charts for system operation under transient operating conditions, and evaluate the applicability of the design charts for intermittent operating conditions.

2. Numerical modeling

The results of the simulations conducted by Jain et al. (2010a, 2010b) were analyzed to develop design charts for transient conditions. A brief description of the modeling effort is presented here. More details are presented elsewhere (Jain et al. (2010a, 2010b)). A modified version of Richard's equation (Eq. (1)) was used to model fluid flow through a liquids addition device (partially screened vertical well, area source, horizontal trench) in a homogenous and anisotropic porous medium under transient conditions (Stephens, 1995).

$$\nabla \cdot (k_r K \nabla (p + z)) = (C + \beta' S_s) \frac{\partial p}{\partial t} \tag{1}$$

where p is the pressure head (L), k_r is the relative hydraulic conductivity (dimensionless), K is the hydraulic conductivity (LT^{-1}) tensor, C is the specific moisture capacity (L^{-1}), S_s is the specific storage (L^{-1}), t is time, z is the vertical coordinate (elevation) (L), and β' is a constant equal to 1 when $p \geqslant 0$ and 0 when $p < 0$. Van Genuchten's equation was used to estimate C and k as a function of p, porosity (θ_s), residual moisture content (θ_r), and Van Genuchten parameters (α and n) (Van Genuchten, 1980). Specific storage, S_s, is a function of the media porosity (θ_s), media compressibility (m_v), and fluid compressibility (α_L). SEEP/W was used to numerically solve Eq. (1) (Krahn, 2004). SEEP/W uses a combination of finite element and finite difference methods to approximate eqns governing liquid flow in saturated and unsaturated porous media. More details on SEEP/W can be found elsewhere (Krahn, 2004).

Table 1 presents the waste and fluid properties and vertical well dimensions along with the injection pressure used for simulations conducted in this study. An initial waste moisture content (θ) of 15% (v/v) was specified by prescribing a pressure of −0.141 m (pressure and moisture content are related for unsaturated porous media); a moisture content of 15% (v/v) is equal to a moisture content of approximately 21.4% on a wet weight basis (assuming a bulk waste density of 700 kg m^{-3}), typical of MSW (Tchobanoglous et al., 1993).

Fig. 1(a) and (b) (reproduced from Jain et al. (2010a, 2010b), respectively) schematically present the system modeled and associated boundary conditions. A conceptual zone of waste around the liquid addition device impacted by liquids addition at a given time is included for definition purposes in Fig. 1(a) and (b). The lateral extent of liquids movement (x_I, r_I) at any point of time was measured from the bottom of the device to a laterally outward point where the waste moisture content is greater than its initial value