Geotextiles and Geomembranes 43 (2015) 118–127

Contents lists available at ScienceDirect

Geotextiles and Geomembranes

journal homepage: www.elsevier.com/locate/geotexmem

An analytical solution for contaminant extraction using well injection depth extraction technology

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ARTICLE INFO

Article history:
Received 13 December 2013
Received in revised form
16 December 2014
Accepted 27 December 2014
Available online 15 January 2015

Keywords:
Well injection depth extraction
Remediation
Analytical solution
Boundary condition

ABSTRACT

Well injection depth extraction (WIDE) is used to remediate contaminated fine-grained soil with low hydraulic conductivity. The flow path is short because the prefabricated vertical wells (PVW) are closely installed in the WIDE system. The current analytical solution that considers the infinite extraction boundary is not suitable to describe the close distance between the injection PVWs (IPVW) and the extraction PVWs (EPVW). A Neumann boundary is proposed as an extraction boundary that can reflect the characteristics of the WIDE system. A flux-type boundary is proposed as an injection boundary to meet the requirements for mass conservation. An analytical solution for a simplified planar two-dimensional model of the WIDE system is presented to take into account the proposed extraction and injection boundaries. Moreover, the initial concentration that is exponentially distributed along the depth is taken into account. The results are consistent with those obtained from the finite-difference method and the experimental data. The results indicate that the Neumann boundary is better than the infinite extraction boundary, and the analytical solution with the infinite boundary is a special case of the proposed solution. The proposed analytical solution is relatively simple and can be used for a quick preliminary calculation to evaluate the experimental results and to evaluate more complex numerical methods.

1. Introduction

Remediation of contaminated soils is an important goal of geoenvironmental engineering. There are many remediation approaches such as bioremediation, phytoremediation, electrokinetics, immobilization, and soil flushing (Dermont et al., 2008). The appropriate remediation approach depends on the contaminant and the geologic condition. Soil flushing, which uses the conventional pump-and-treat technology, has been proven to be efficient in extracting contaminants from non-cohesive soils (Bartow and Davenport, 1995; Haley et al., 1991). However, the movement of the flushing solution and the contaminant extraction from the soil make the conventional pump-and-treat remediation technology ineffective in low-permeability soils (Gabr et al., 1996a, 1996b). Additionally, the conventional pump-and-treat technology is expensive because it must be maintained and operated for decades before accurate cleanup time projections can be made (Hoffman, 1993).

Well injection depth extraction (WIDE) is an improved pump-and-treat remediation system using prefabricated vertical wells (PVW), which are installed with relatively close spacing to decrease the flow path and expedite the remediation process. The three-dimensional WIDE system is illustrated in Fig. 1. In this system, the PVW is commonly known as the prefabricated vertical drain (PVD); in particular, an impermeable sleeve is attached to each PVW in uncontaminated areas to compel the flushing water to flow through only the contaminated zones. PVC pipes above the ground are used to connect the injection PVWs (IPVW) and extraction

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Abbreviations: WIDE, Well Injection Depth Extraction; PVW/PVD, Prefabricated Vertical Well/Drain; IPVW/EPVW, Injection/Extraction PVW; IDW/EDW, Injection/Extraction Drain Well; TCE, Trichloroethylene; CRC, Contaminant Recovery Cell; MODFLOW, Modular 3-Dimensional Groundwater Flow Model; MT3D, Modular 3-Dimensional Transport Model.

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http://dx.doi.org/10.1016/j.geotexmem.2014.12.002
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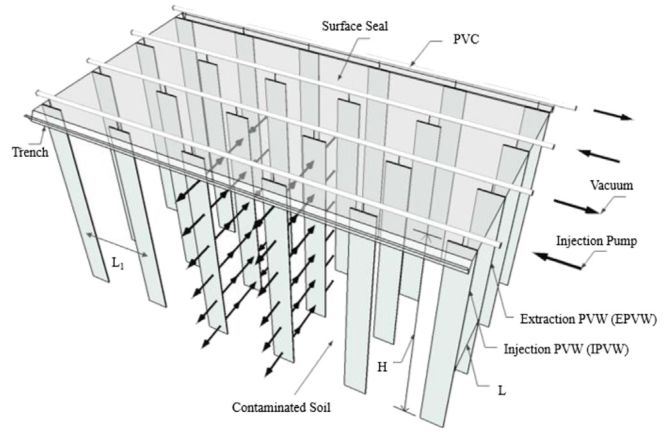

Fig. 1. Well injection depth extraction system.

PVWs (EPVW), by which the vacuum pump and the blower pump are connected to separate extraction and injection rows, respectively.

The PVD system and vertical drain were widely used to accelerate the consolidation process of soft ground (Abuel-Naga et al., 2006; Bergado et al., 1993; Rowe and Taechakumthorn, 2008; Shen et al., 2005; Tang et al., 2013). The addition of vacuum pressure accelerates the consolidation rate without increasing the excess pore pressure (Chai et al., 2008, 2010; Indraratna et al., 2012; Saowapakpiboon et al., 2010, 2011). Gabr et al. (1996a, 1996b) presented the potential that introduce PVDs in a scheme for the expedient flushing of contaminated fine-grained soils. The works of Gabr et al. (1996a, 1996b, 1999), Sharmin et al. (2008), Shin and Park (2010), Warren et al. (2006) and Welker and Gilbert (2003) demonstrated that the WIDE system using PVD/PVW is also an effective approach in situ remediation for contaminated groundwater and fine-grained soils with low hydraulic conductivity. Compared with the conventional pump-and-treat technology, the WIDE system can provide steady subsurface control of the hydraulic head and shorten the flow path to expedite the remediation process.

The previous studies for soil flushing that used the WIDE technology were usually completed with bench-scale experiments, pilot-scale field tests and numerical models. For example, Gabr et al. (1996b) performed bench-scale laboratory tests using contaminant recovery cells (CRC) to examine the feasibility of the PVD system for liquid injection-extraction. Welker (1998) performed two bench-scale experiments to study the effectiveness of the PVD remediation system. Warren et al. (2006) conducted a full-scale field study to remove trichloroethylene (TCE) from fine-grained soils using the WIDE technology. Shin and Park (2010) discussed the characteristics and performance of PVDs for contaminant recovery based on a pilot-scale testing. Welker and Gilbert (2003) developed MODFLOW with the MT3D method to numerically model the bench-scale PVD remediation system. Sharmin et al. (2008) analyzed the effect of the extraction process of WIDE technology on the groundwater head distribution and contaminant transportation using the finite element model. These studies analyzed the application of the PVD/PVW remediation technology in low-permeability soils and popularized the PVD/PVW remediation systems. However, simplified analytical methods for the WIDE technology have rarely been reported in the literatures. The analytical methods are necessary because the analytical solutions are usually simple and efficient, and they can also verify the results of complicated numerical methods and evaluate the experimental data.

Gabr et al. (1996a) developed a contaminant transport model, where the PVWs were installed in a circular configuration to simulate the movement of the flushing solution with the solubilized contaminant. In his study, the infinite EPVW boundary condition was adopted so that the contaminant concentration of an infinitely large radial distance was zero, but the infinite EPVW boundary condition is not suitable to describe the short distance between the injection and extraction PVDs. The WIDE system works by shortening the flow path to accelerate the remediation process; however, although the distance between the IPVW and the EPVW is constantly shortened, the analytical solutions with the infinite EPVW boundary will remain constant, which is not consistent with our expectations. Therefore, the model with the infinite EPVW boundary cannot reveal the characteristics of the WIDE system. At the IPVW boundary immediately inside the contaminated soil, the contaminant is moved away by advection and supplemented from the zone with high contaminant concentration by hydrodynamic dispersion. The contaminant concentration gradually decreases to zero at the IPVW boundary. Therefore, the IPVW boundary cannot be assumed to be free of contaminants.

Suitable boundary conditions are critical to predict the movement of the solubilized contaminant in contaminated soil. This paper aims to present a simplified analytical model that can predict contaminant extraction using the WIDE system with more suitable boundary conditions. A finite extraction boundary is proposed: the Neumann boundary, which can reflect the characteristics of the WIDE system that the flow path is shortened. Flux-type boundaries are introduced as the injection boundary and the top surface boundary. Two different bottom boundary conditions, i.e., no mass flux bottom boundary and semi-infinite bottom boundary are considered in this paper. The total injection rate is equal to the retrieval rate to maintain full saturation. The separation of variables is used to derive the analytical solution for the case with the flux-type bottom boundary, whereas the analytical solution that considers the semi-infinite bottom boundary is obtained using Laplace transform. To verify the simplified model, the results obtained from the proposed analytical solution with a planar 2D model are compared with the numerical results obtained using the PVW model. The analytical-model results are compared with the results obtained by the finite-difference method (FDM) and the experimental data, which were presented in Welker and Gilbert (2003). An illustrative example is proposed to compare the analytical solutions with different extraction boundaries, which were proposed in this work and Gabr et al. (1996a).

2. Model and boundary conditions

As shown in Fig. 1, flushing liquids are injected through a row of IPVWs and retrieved through another row of EPVWs, which run parallel to the IPVWs. In the consolidation of soft soils, where large-scale PVDs are also used, the PVDs were converted into an equivalent drain wall, so that the complicated model was transformed into a 2D plane-strain model (Chen and Zhao, 2005; Hird et al., 1995; Indraratna and Redana, 1997). Following this method for consolidation, the PVWs are substituted with equivalent drain walls based on the case that the retrieval rate for both PVWs and equivalent drain walls are made equal. The analytical solutions obtained using the planar 2D model are considered sufficiently consistent with the solutions obtained using the PVW model, and when adjacent IPVWs or EPVWs become closer, the planar 2D model provides more accurate analytical solutions. More details are demonstrated in Section 4.

The governing geometry of the planar 2D model is shown in Fig. 2. The origin of the coordinate system is at the interface between the injection drain wall (IDW) and the contaminated soil and