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Technical Note

Investigation of flow and solute transport at the field scale through heterogeneous deformable porous media

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SUMMARY

This work describes an investigation of the spatial statistical structure of specific discharge field and solute transport process of a nonreactive solute at the field scale through a heterogeneous deformable porous medium. The flow field is driven by a vertical gradient in the excess pore water pressure induced by a step increase in load applied on the upper part of a finite-thickness aquifer. The non-stationary spectral representation is adopted to characterize the spatial covariance of the specific discharge field necessary for the development of the solute particle trajectory statistics using the Lagrangian formalism. We show that the statistics of the specific discharge and particle trajectory derived herein are non-stationary and functions of the coefficient of soil compressibility, μ. The effect of μ on the relative variation of specific discharge and the solute particle trajectory statistics are analyzed upon evaluating our expressions.

1. Introduction

A non-Fickian behavior associated with nonlinear dependence of the second moment of the solute plume on time persisting over travel distances is frequently observed in field-scale transport processes through heterogeneous media in non-stationary flow fields (e.g., Rubin, 2003). Great underestimation is therefore anticipated in the prediction of solute concentration over a relatively large scale by applying the convection–dispersion equation with an effective macrodispersivity (e.g., Rubin and Bellin, 1994; Rubin and Seong, 1994; Indelman and Rubin, 1996; Li and Graham, 1999). For regulatory purposes and/or designing remediation measures, quantifying this non-Fickian behavior of field-scale solute transport in non-stationary fields is critical and desires further study, which is the motivation of the study.

Natural hydraulic property of aquifer formations such as hydraulic conductivity is spatially heterogeneous. The heterogeneity of this property has a strong effect on the groundwater flow and contaminant transport in aquifers in an erratic way. A large degree of uncertainty in the groundwater flow system is therefore anticipated when applying the classical deterministic equation to model field groundwater flow. Many practical problems of subsurface flow or solute transport require predictions over large scales where direct measurements are generally very difficult or impossible to achieve. Treating the natural heterogeneity that influences groundwater flow as a random field, the stochastic approach provides a clear understanding of larger-scale controlling processes under the field conditions. The stochastic methodology is therefore adopted to perform the analysis of transport process in nonstationary flow fields.

In general, the non-stationarity in the statistics of flow fields stems from nonuniformity in the mean flow by various sources, such as the effects of groundwater recharge, radial flow, or a linear trend in the hydraulic conductivity field. Several studies have devoted to analyze the transport of inert solutes at the field scale in non-stationary groundwater flow fields through heterogeneous media, for example, nonuniformity in the mean flow due to the presence of groundwater recharge (Rubin and Bellin, 1994; Destouni and Graham, 1995; Li and Graham, 1998; Butera and Tanda, 1999; Destouni et al., 2001;Ye et al., 2004; Chang and Yeh, 2008; Yin et al., 2015), the impact of radial flow (Indelman and Dagan, 1999; Chao et al., 2000; Severino et al., 2011; Dentz et al., 2015), and the presence of a linear trend in conductivity (Rubin and Seong, 1994; Indelman and Rubin, 1996; Cirpka and Nowak, 2004).

Changes in applied stress in fluid-saturated porous materials typically produce changes in pore pressure. When the rate of change of stress is large relative to the rate at which pressure

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perturbations are dissipated by flow, the changes in fluid pressure can be significant (e.g., van Der Kamp and Gale, 1983; Wang, 2000; Neuzil, 2003). A gradient in excess pressure is therefore created and the flow occurs in response to that. If there is a nearby contaminant source, this induced flow may cause the migration of contaminants into groundwater.

To the best of our knowledge, quantification of the field-scale solute transport process of a nonreactive solute through a heterogeneous deformable porous medium in non-stationary flow field induced by a step increase in load applied on the upper part of a finite-thickness aquifer has so far not been presented within the stochastic framework and this is the task undertaken here. Toward this goal, the nonstationary spectral representation (Priestley, 1965, 1981) is adopted to characterize the spatial covariance of the specific discharge field, and the Lagrangian formalism (Dagan, 1989; Butera and Tanda, 1999) to characterize the statistics of displacement of a nonreactive solute. It is hoped that the findings will be useful for predicting the field-scale solute transport behavior in heterogeneous deformable aquifers and interpreting the field data.

2. Statement of the problem

This work deals with the problem involving fluid-filled saturated granular media which deform in response to changes in total stress. Initially, the flow in the porous media is under the hydrostatic condition. The media are then subject to step changes in applied stress instantly and tend to deform in response to these changes. This can result in changes in pore-water pressure, deviating significantly from the hydrostatic conditions. The groundwater flow therefore occurs in response to the gradient in excess pressure head. The total stress change in this study is referred to the change in mechanical load on the aquifer induced by, for example, water-level fluctuations due to earth tides (e.g., Van Der Kamp and Gale, 1983; Hsieh et al., 1987) or changes in barometric pressure (e.g., Rojstaczer, 1988; Butler et al., 2011), stream stage fluctuations (Francisco et al., 2010; Boutt, 2010), seasonal changes of soil moisture storage (e.g., van der Kamp and Maathuis, 1991; Sophocleous et al., 2006), erosion (e.g., Neuzil and Pollock, 1983) and sediment loading (e.g., Gibson, 1958; Wang, 2000).

According to Van Der Kamp and Gale (1983) and Wang (2000), if an aquifer of infinite lateral extent is loaded above by a vertical stress applied over a large area, the horizontal deformation in the system will tend to be much smaller compared to vertical one. As such, the resulting deformations (displacements) of the porous matrix can be considered as purely vertical, i.e., the lateral gradient in excess pressure generated by the lateral deformation of the media is negligible. This leads the problem of fluid diffusion to be one dimensional (no horizontal flow).

In this work, we are interested primarily in heterogeneous unconfined aquifers with infinite lateral extent and finite-thickness. Only groundwater water occupies the entire void space of a porous medium domain. A load is applied instantaneously and vertically (in the Z-direction) on the upper part of the unconfined aquifer over a large area denoted as

$$\sigma_t = \Gamma H(t) \tag{1}$$

where σ_t is the octahedral normal stress, $H(t)$ is the step function and Γ denotes the magnitude of the vertical stress increase. A transient vertical fluid flow in response to deformation of the porous matrix is then derived by the gradient of excess pressure head during loading. This groundwater flow problem is described in detail by Chang and Yeh (2015). As we shall show, this study focuses on characterizing the variability of the induced non-stationary flow field and its associated field-scale solute transport process of inert dissolved solutes and carried by the groundwater water through the finite flow domain.

Our analysis herein is based on the following assumptions inherent in theory of linear poroelasticity (e.g., de Marsily, 1986; Domenico and Schwartz, 1998; Wang, 2000):

1. The hydraulic conductivity of the soil does not vary during the loading process.
2. The water and the solid grains in the soil are incompressible so that compression simply means the decrease in pore volume.
3. There is a linear relation between the effective compression stress and the decrease in soil volume.
4. The outflow of the interstitial water obeys Darcy's law.

Through Darcy's law, the fluctuations in this induced specific discharge q' can be related to those in log-hydraulic conductivity by (e.g., Gelhar and Axness, 1983)

$$q' = -K_G\left[\frac{\partial \phi}{\partial Z} + f\frac{\partial \Phi}{\partial Z}\right] \tag{2}$$

where $K_G = \exp[F]$, F is the mean of $\ln K$, K is the hydraulic conductivity, f represents the deviation of $\ln K$ from the mean, Φ represents the mean of excess pressure head, and ϕ represents small pressure head fluctuations about the mean. Eq. (2) is obtained from small-perturbation expansion of Darcy's law by retaining only first-order term in the perturbations. Note that this linearized expression (first-order approximation) is expected to be valid only for mildly heterogeneous media (variance of $\ln K$, σ_f^2, $\ll 1$).

It is well recognized in the hydrogeology literature that the flow properties of natural geological formations are observed to be highly variable. The vertical log hydraulic conductivity field ($\ln K$) is therefore regarded as a spatially random process (a stochastic process). It is typically represented by the sum of a mean and a zero-mean perturbation, namely, a spatially correlated and statistically stationary random field. The spatially random heterogeneity in $\ln K$ results in spatially random perturbations in excess pressure head (Chang and Yeh, 2015). As such, Eq. (2) is viewed as a stochastic equation with a stochastic parameter f and a stochastic input ϕ and therefore a stochastic output q'.

Chang and Yeh (2015) present a stochastic analysis of the field-scale poroelastic response of the heterogeneous medium to step increase in the aquifer's total stress. In their work, it has been shown that the mean and fluctuations of excess pressure head field are governed by the diffusion-type equations which admit the closed-form solutions given by Chang and Yeh (2015, Eqs. (13) and (22))

$$\Phi(Z,t) = \frac{2}{\pi}\frac{\mu\Gamma}{S}e^{-\tau}\sin(\pi\xi) \tag{3}$$

$$\phi(Z,t) = \int_{-\infty}^{\infty} A_\phi(Z,t;R)e^{iRZ}dZ_f(R) \tag{4}$$

where $\tau = \pi^2K_Gt/(SL^2)$, S is the storage coefficient, defined as $S = \rho_f g(\mu + n\beta)$, ρ_f is the density of fluid, μ and β are the coefficients of soil compressibility and fluid compressibility, respectively, n is the porosity, L is the vertical length of the flow domain, $\xi = Z/L$, $dZ_f(R)$ is the random complex spectral amplitude of the $\ln K$ perturbations, R denotes the wave number,

$$A_\phi(Z,t;R) = \pi\frac{\mu\Gamma}{SL^2}\left\{i\frac{4}{\pi^2}\frac{L}{R}\frac{2\eta^2 - R^2}{R^2 - 4\eta^2}[1 - e^{iRL}]\tau + \frac{1 + e^{iRL}}{R^2 - \eta^2}\right\}e^{-iRZ}e^{-\tau}\sin(\pi\xi) \tag{5}$$

and $\eta = \pi/L$. Note that Eqs. (3) and (4) are valid under the condition of $\tau \gg 1$.

Eq. (2) along with Eqs. (3) and (4) serves as our starting point for quantifying the variability in specific discharge. In what follows, we