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Development of an artificial neural network model for determination of longitudinal and transverse dispersivities in a convergent flow tracer test

Hung-Yu Shieh [a], Jui-Sheng Chen [b], Chun-Nan Lin [a], Wei-Kuang Wang [a], Chen-Wuing Liu [a,*]

[a] Department of Bioenvironmental Systems Engineering, National Taiwan University, Taipei 106, Taiwan, ROC
[b] Graduate Institute of Applied Geology, National Central University, Taoyuan 320, Taiwan, ROC

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SUMMARY

The convergent flow tracer test is an efficient method for determining dispersivity in field, but the traditional curve-fitting method for the estimation of dispersivity from a convergent flow tracer test is quite time-consuming. In this study, we present a model to improve the evaluation of longitudinal and transverse dispersivities from a convergent flow tracer test which couples a back-propagation neural network (BPN) model with a two-dimensional convergent flow tracer transport model. The prediction errors for the training and validation data show that with the effective porosity fitting model, the scale-dependent longitudinal dispersivity fitting model, and the scale-dependent transverse dispersivity fitting model, we can obtain satisfactory prediction accuracy with much less computational time. The applicable ranges of parameters are: The Peclet number is between 0.5 and 100, the effective porosity is between 0.05 and 0.5 and the scale-dependent transverse dispersivity is between 0.01 and 10 m. One set of hypothetical data and one set of field data are used to demonstrate the robustness and accuracy of the back-propagation neural network fitting model (BPNFM). The results demonstrate that BPNFM has the advantage of significantly saving the computational time and giving more accurate transport parameter values. The developed BPNFM is an effective tool for fast and accurate evaluation of the longitudinal and transverse dispersivities for a field convergent flow tracer test.

1. Introduction

The advection–dispersion equation (ADE) is widely used to describe and predict the chemical transport in the environment. In the subsurface solute transport, the advection process in the ADE depicts solute movement with the average groundwater flow, whereas the dispersion process accounts for solute spreading caused by the combined effects of diffusion (following the Fick law) and mechanical dispersion (variations in pore-water velocity). Such velocity variations reflect the complex nature of medium heterogeneity on different scales and are difficult to resolve solely by looking at the macroscopic advective flow (Gelhar, 1992). Dispersivities are the key parameters for ADE and can be determined in field using tracer tests. The analysis of a tracer test generally consists of two steps. The first step is to choose or develop an appropriate mathematical model to represent the flow field and solute transport processes during the tracer test. After the mathematical model has been established, the second step is to determine the values of the transport parameters so that the computed results agree well with the field response. The type curve matching method is traditionally used in this parameter estimation processes. Of the various types of tracer tests, the convergent flow tracer test is preferred over others, because it facilitates the recovery of injected mass, reduces the effect of apparent dispersion due to the flow field, and minimizes the test duration.

Sauty (1980) proposed a type curve-fitting method to yield the longitudinal dispersivity for a convergent flow tracer test. Subsequently, Carrera and Walters (1985), Guvanasen and Guvanasen (1987), Moench (1989), Wang and Crampon (1995) and Chen et al. (1996) presented the one-dimensional analytical or numerical solutions for estimating the longitudinal dispersivity in a convergent flow tracer test. In addition to longitudinal dispersivity, transverse dispersivity is also an important control factor affecting the shape of contaminant plume in two-dimensional mass transport in an aquifer. When predicting the fate and behavior of contaminants, it is important to have some knowledge of the transverse dispersivity in addition to the longitudinal dispersivity. Accordingly, Chen et al. (1999) presented a two-dimensional mathematical model describing solute transport during a convergent flow tracer test. Chen et al. (1999) also proposed an analytical procedure for simultaneously determining the longitudinal and transverse dispersivities from a convergent flow tracer test based on

* Corresponding author. Tel.: +886 2 2362 6480; fax: +886 2 2363 9557.
E-mail address: lcw@gwater.agec.ntu.edu.tw (C.-W. Liu).

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analysis of the transient concentration breakthrough curves at the extraction well and one observation well.

The aforementioned models for convergent flow tracer tests are mostly based on the assumption that dispersivity is constant. Over the past three decades, many investigators have demonstrated that dispersivity increases with chemical transport distance in the environment. This phenomenon has been identified as the scale effect of dispersion (Anderson, 1979; Pickens and Grisak, 1981a; Gelhar et al., 1992). To accurately predict the scale-dependent solute transport in heterogeneous media, many investigators have treated the values of dispersivity as functions of the spaces when incorporating the scale-dependent dispersivity functions into the ADE. Pickens and Grisak (1981b) reorganized the results of several field and laboratory tracer tests. They proposed characterizing the scale effect of dispersion with four types of function (linear, parabolic, asymptotic and exponential) which can be determined from the observed relationship between variance and mean travel distance obtained from a field tracer test. Chen et al. (2003, 2006) depicted the tracer transport in a radially convergent or divergent flow tracer test by utilizing one-dimensional analytical solutions to ADE in cylindrical coordinates with linear distance-dependent dispersivity. Moreover, Chen et al. (2006) developed a two-dimensional mathematical model for a radially convergent flow tracer test with linearly distance-dependent, longitudinal and transverse dispersivities. They proposed the analysis procedures for determination of the longitudinal and transverse scale-dependent dispersion parameters.

Like hydrological parameters estimation, it is also time-consuming to use type curve-fitting method for estimation of the dispersivity. Recently, some researchers have applied artificial neural networks (ANN) to the estimation of groundwater and hydrogeological parameters. Daliakopoulos et al. (2005) used a back-propagation neural network (BPN), radial basis function network (RBF) and recurrent neural network (RNN) with three error algorithms to predict changes in groundwater level. Coppola et al. (2005) developed a BPN model to forecast variations in groundwater levels at two monitoring wells. Lin and Chen (2006) developed an ANN model for hydrogeological parameters estimation, which combines a BPN and the Theis solution to determine the transmissivity and storage coefficient. Samani et al. (2007) utilized the principal component analysis (PCA) technique and the Levenberg–Marquardt training algorithm to enhance the efficiency of the ANN approach proposed by Lin and Chen (2006). Their model has the advantages of reduced training time and the number of required input variables, and also improves the network performance compared to Lin–Chen networks.

ANN has also been used to predict solute breakthrough curves (Akin, 2005; Yoon et al., 2007) for solute transport problem. Akin (2005) used synthetic tracer test data generated by analytical one-dimensional homogeneous, double-porosity pseudo-steady state, multi-fracture, and fracture matrix models to train the ANN. The input variables contained 29 concentrations from 29 time stages for each breakthrough curve data set generated by four mathematical models. The proposed model successfully identified a wide variety of reservoir models in most cases. Yoon et al. (2007) used two ANN models to predict solute breakthrough curves through the unsaturated zone, one for solute arrival times and the other for solute mass breakthrough curves. The ANN model yielded a value of correlation coefficient between target and output solute mass of 0.983. However, the ANNs proposed by Akin (2005) and Yoon et al. (2007) are site-specific. It is necessary with both models to re-train the ANN to comply with different experimental site conditions. Additionally, the ANN proposed by Akin (2005) is time-consuming in the training stage due to the use of 29 input variables.

In this study we develop an ANN model to evaluate the longitudinal and transverse dispersivities for a two-dimensional convergent flow tracer test.

2. Scale-dependent dispersivity model (SDM)

The mathematical model presented by Chen et al. (2006) for describing scale-dependent dispersive solute transport in a radially convergent flow tracer test is chosen for determining transport

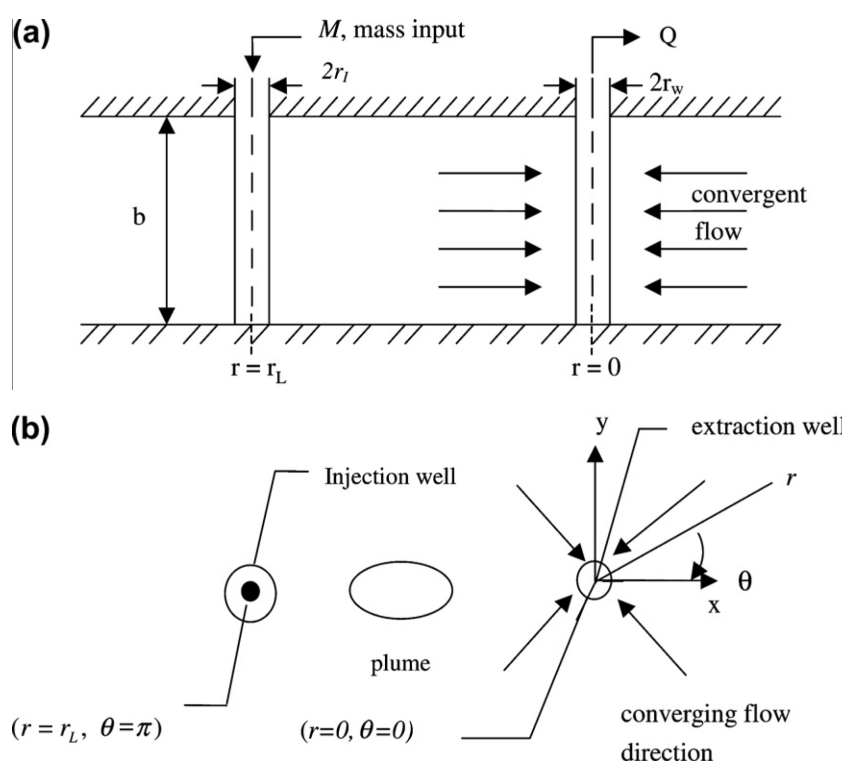

Fig. 1. Schematic diagram of radically convergent tracer test: (a) side view and (b) plane view (Chen et al., 2006).