Seeing Macro-dispersivity from Hydraulic Conductivity Field with Convolutional Neural Network

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Motivation

For applying the advection-dispersion models under field conditions, hydro-geologists have proven that the magnitude of field-scale dispersivity (macro-dispersivity) can be several orders of magnitude higher than lab-scale values for the same material (Finn et al., 2017). This increase mainly attributes to the spatial variability of aquifer structure which can be generally described by the spatial distribution of the hydraulic conductivity. Considering the heterogeneous distribution of hydraulic conductivity as a random field and relating flow and transport to its statistical moments has been one of the primary goals of the field of stochastic modelling (e.g. Dagan, 1989; Gelhar, 1993). A fundamental issue addressed by these works is how macro-dispersivity can be related to the statistical properties of the hydraulic conductivity field. However, the general applicability of the stochastic approach is sometimes questionable due to several foundational assumptions. And the first and second–order spatial statistics cannot hold sufficient information to estimate macro-dispersivity. The conductivity fields with the same first two moments may produce very different solute spreading because of the spatial patterns that are not characterized by these statistics (e.g. Zinn and Harvey, 2002; Bianchi and Pedretti, 2018). The concepts of connectivity and geological entropy then emerge as other attempts to characterize the transport behavior from the heterogeneous conductivity fields (e.g. Rizzo and Axness, 2007; Bianchi and Pedretti, 2017, 2018). In short, researchers have made great efforts to predict solute transport behavior only from a characteristic description of the conductivity field. Despite the helpfulness of these works in understanding the correlation between the heterogeneity of conductivity field and the transport behavior, a direct and efficient functional mapping between the conductivity field and the transport behavior for predictive purposes remains to be solved.

Methodology

a) Generating training datasets. Two-dimensional random fields of the hydraulic conductivity are generated. Direct simulations with the random walk particle tracking method (Salamon et al., 2008) are then used to compute the macro-dispersivities of the generated conductivity fields. The field dispersivity pairs consist of the training datasets for the neural network model.

b) Training the CNN. The training datasets from the previous step are then used to train our CNN that takes a heterogeneous conductivity field as input and gives macro-dispersivity as output.

c) Estimating macro-dispersivities. The trained CNN is then used to estimate macro-dispersivities of new conductivity fields that are not in the training datasets.

Synthetic Experiments Setting

Synthetic experiments are conducted to demonstrate the capability of the neural network to estimate the macro-dispersivity by considering different variances of conductivity fields.

Results and Discussion

Fig. 6 displays the comparison of R² from the above three experiments. Generally, the CNN trained by conductivity fields with relatively large variances can achieve better performance on estimations of macro-dispersivities for conductivity fields with relatively small variances. The neural network trained by heterogeneous conductivity fields seems to have a high ability to extract features of heterogeneity. In Fig. 6(a), the neural network trained by Var0.5 has much better performance than the neural network trained by Var1.0, although the neural network trained by Var0.5 has worse performance in its own test set.

Conclusions

The following conclusions can be drawn from these experiments:

1. The estimating performance of CNN generally drops with increasing variances of conductivity fields (increasing heterogeneity) for the given size of training datasets (4000 fields) and data points (140×140).

2. The CNN trained by conductivity fields with a specific variance has universality in estimating macro-dispersivity to a certain extent because a well-trained CNN will have the capability to achieve different variances of heterogeneity. Consequently, the trained CNN can extract some standard heterogeneous features of conductivity fields for estimating macro-dispersivities.

3. Furthermore, the utility of the trained CNN decreases with the increasing disparity between variances of conductivity fields in the set and test set. And the CNN trained by conductivity fields with relatively large variances can have stronger universality of estimating.

4. In general, the deep neural network is a very promising approach in building direct mapping between complicated subsurface structure and solute transport behavior.