Research Article

Using a Pore-Scale Modelling Approach to Study Solute Dilution Process through Cemented Porous Media

Yusong Hou(1), Bill X. Hu(1), Su Liu(1), Hu Xin(1), and Jichun Wu(2)

1School of Water Conservancy and Environment, University of Jinan, Jinan, China
2School of Earth Sciences and Engineering, Nanjing University, Nanjing, China

Correspondence should be addressed to Yusong Hou; houys87@163.com and Jichun Wu; jcwu@nju.edu.cn

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In this study, a pore-scale simulation method is applied to quantitatively study the variation of solute dilution through porous media with different cementation degrees and explore the corresponding mechanisms. The study results indicated that the cementation degrees of the solid grains had a significant effect on the solute dilution process and that the influence was very complicated. The complexity was manifested in that the effect of rising cementation degree on the solute dilution process would be different or even completely opposite in the porous media in which the solid grains cement slightly with that in porous media with a higher cementation degree. For example, for the porous media in which the solid grains were slightly cemented (the percentage of the cemented solid grains $P_c$ is less than 40%), the dilution effects became enhanced with the increase of cementation degree. Then, after $P_c$ increased to about 55%, the dilution effect was obviously weakened, and the solute was in an incomplete dilution state for a long period of time. In addition, this study found that the properties of the flow fields may vary greatly in porous media with different cementation degrees and that those differences in the flow fields resulted in the distinct behavior of the solute dilution. It is interesting to note that a more heterogeneous flow field had not necessarily led to the enhancement of the dilution process.

1. Introduction

Solute dilution in a porous medium has recently received significant attention in many scientific fields and engineering applications. The research on solute dilution would help the studies in many fields, such as the fate and transport of contaminants and groundwater in situ remediation in spatially uncorrelated saturated porous media [1–4]. Dilution is the main mechanism which decreases the concentrations of conservative contaminants [5]. Meanwhile, for reaction solute transport, the dilution process can be regarded as the mixing of the solute with the surrounding substrates or other compounds [6]. It has been found that in many cases, the mixing extent will determine the rate and degree of degradation of a contaminant [5, 7]. Therefore, a detailed understanding of a solute dilution process in a porous medium would improve the solute transport prediction and result in more reliable, efficient, and inexpensive remediation strategies.

There are several challenges to understanding the detailed process for solute dilution in a porous medium. The first one is how to quantitatively achieve a good grasp of the solute dilution process in a porous medium, which would help to explore the mechanism of the dilution and its influencing factors [8]. During the early research investigations, the dilution processes were equated with spreading, and both were quantified by the same term as “dispersion,” characterized by a dispersion coefficient. However, in recent years, many study results have indicated that the dispersion coefficient cannot accurately characterize the dilution process. For example, it was found that the more effective dispersion models tended to overestimate the degree of diluteness in many cases [6, 9]. As the research in this field gained maturity, it became widely understood that dilution was radically different from spreading [10]. It was confirmed that the dispersion and dispersion coefficient used to describe a solute spreading process and its change rate were not equally valid for a dilution process. In fact, spreading
processes are essentially snapshots of the deformations and stretching of the solute plumes caused by the heterogeneity of advective velocity. In contrast, dilution refers to the dispersal of solute mass over a larger volume of solvent or solvent flux, as the result of mass exchanges between different streamlines [11]. Recently, a considerable body of research has been devoted to quantifying the dilution process of solute and distinguishing it from the spreading process. As a result, different metrics, including maximum concentration values, scalar dissipation rates, and the dilution index and its modified version, have been proposed [12–15].

In this study, the dilution index and its modified version are applied to study a solute dilution process in a heterogeneous porous medium. The applied method had been demonstrated as an efficient and reliable one in measuring dilution [8, 16]. The dilution index was first proposed by Kitanidis [3], which was an adaption of the entropy expression. After being improved, the dilution index was able to avoid such a problem as the domain discretization dependence which exists when attempting to use an entropy measurement to describe the solute dilution. The dilution index has been found to be a useful tool to investigate the dilution degree when the solute enters a research region as an individual slug, and the mass flux migrating out of the domain is negligible. However, the dilution index cannot quantify the evolution of the dilution with travel distance in the case that the solute is continuously introduced into a research domain, which is a very common scenario in practice. In order to address the issue, the flux-related dilution index was introduced by Rolle et al. [17], which could be calculated within given cross-sections perpendicular to the main flow direction of fluid. Unlike the original dilution index, the flux-related dilution indexes are measurements of the effective volumetric solvent flux carrying a given mass flux of solute. The flux-related dilution indexes have been adapted in many studies. The types of metrics and their subsequent modified versions have been widely used to determine solute dilution degrees at various scales [16]. Among the modified versions, the transient flux-related dilution index allows for the quantification of the temporal evolution of the solute dilution at different cross-sections by obtaining the dilution breakthrough curves (dBTCs) [18]. The dBTCs are the curves of flux-related dilution indexes over time at a given section. Therefore, dBTCs are the measurements of the evolution with time of the effective volumetric solvent flux carrying a given mass flux of solute, which can provide useful insight into incomplete dilution and interactions between the advective and the diffusion processes.

The investigation of solute dilution at a pore scale would deepen our understanding of solute transport processes, as well as identify and ameliorate the limitations of macroscopic continuum models [19–21]. Solute transport phenomena at the continuum scale can be determined by the solute migration processes occurring in pore spaces. For example, incomplete mixing at smaller scales has been found to generally lead to the reaction extent of the solute being lower than the predictions obtained using Darcy–Scale reactive transport models [6]. In addition, previous studies have revealed that the heterogeneity of a porous medium and the characteristics of pore channels, including the topological features, connectivity, and size distributions of pore spaces, have significant influences on solute dilution processes in a porous medium [22–24]. In particular, the results of previous studies have indicated a strong link between the enhancement of solute dilution and the flow focusing facilitated by the heterogeneous permeability field in a spatially uncorrelated aquifer [25, 26]. The cementation of solid grains is ubiquitous in a natural porous medium and often results in remarkable increases in heterogeneity and flow focusing [27]. However, the data acquired in previous studies regarding solute dilution at the pore scale in porous media with different cementation degrees still have limitations. The main purpose of this study was to investigate at the pore scale the variations of solute dilution in porous media under various cementation degrees of the solid grains and provide further insight into the corresponding inner mechanism.

The remainder of the paper is organized as follows: the methods for generating porous media and the simulation schemes for the flow fields and solute migration were introduced in the second section. In the third section, the distinctions between the solute dilution in porous media with different cementation degrees were analyzed, the inherent mechanism of the varying behaviors of solute dilution was also explored, and results and discussion are provided. The conclusions reached in this study are summarized in Section 4.

2. Methods

It has been observed that in many cases, two-dimensional simulation schemes can grasp the majority of the physical processes of solute transport and reduce the simulation complexity and calculation costs, compared with three-dimensional simulations. In addition, in the previous study, we found that when the cementation degree increases, the velocity probability distribution of fluid in 2D media and 3D media and its change trend are similar [28, 29]. Therefore, this study performed two-dimensional simulations at the pore scale for the purpose of exploring the solute dilution processes in porous media with different cementation degrees.

In the present investigation, porous media with different cementation degrees were constructed using our previous modified version of the procedure presented by Yang et al. [28, 30]. A similar two-dimensional model has been shown to reflect the structural characteristics of real porous media in nature [31–33]. And previous researches have shown that the simulation results in computer generated porous media can reflect the laws of water flow and solute transport in natural aquifer media to a certain extent [34, 35]. The solid grains were represented by circular particles in the two-dimensional model. In order to maintain the completeness and facilitate reading, this study outlined the modified procedure herein using detailed introductions provided in previous related literature [28]. First of all, in this study, the solid grains were continuously generated and randomly arranged in the research domain until the initial porosity had reached the target value. The diameters of the solid
grain were determined using the truncated lognormal distributions, which were consistent with natural soil grains. Then, an algorithm was adopted and executed recurrently in order to search and rearrange overlapping solid grains for the purpose of removing all overlaps between the solid grains. As a result of implementing the aforementioned two steps, a porous medium in which the solid grains were all free from cementation was constructed. Finally, based on the noncemented porous medium, the coordinates of all the circular particles remained constant, and the diameters were increased by the same value until they began to overlap. In other words, the solid grains started to cement. Then, porous media with different cementation degrees were successfully obtained by continuously increasing the sizes of the solid grains in the previously described approach. The porosity values were determined by the cementation degrees, which were quantified by the cementing percentages of the solid grains.

In this study, a noncemented porous medium was constructed within a domain measuring 80 mm by 60 mm (x by y). The mean value and standard variance of the truncated lognormal distribution controlling the radii of the solid grains were 1.07 mm and 0.25 mm, respectively. In addition, the maximum and minimum of the solid grain diameters were set as 0.55 and 1.80 mm, respectively. The initial porosity of the porous medium was 0.40. The constructed noncememted porous medium was denoted as PM39, representing porous medium with a porosity of 0.39. Then, three other porous media with different cementation degrees were built and denoted as PM35, PM30, and PM25, which indicated porous media with porosities of 0.35, 0.30, and 0.25, respectively. For each given degree of cementation, three porous media were generated, and the simulations were performed in all porous media. The constructed porous media properties are shown in Table 1, and Group 1 porous media are shown in Figure 1. The properties included the average radii of the solid grains ($r_{ave}$), along with the percentage $P_c$ of the cemented solid grains. As detailed in Table 1, it can be seen that the cementation degrees became larger with the decreases in porosity. For example, for three groups of media, from PM39 to PM25, the cementing percentages of the solid grains increased from 0.00% to 55.89%, 55.16%, and 55.77%, respectively.

In the present study, a COMSOL Multiphysics 5.1 finite element software package was adopted to simulate the flow fields and solute migration [36]. Then, the volume conservation Equation (1) and Navier-Stokes Equation (2) were solved in order to simulate the flow fields as follows:

$$\nabla \cdot \mathbf{u} = 0, \quad (1)$$

$$\rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \mu \nabla^2 \mathbf{u}, \quad (2)$$

where $\mathbf{u}$ represents the velocity vector; $\mu$ and $\rho$ are the viscosity and density of the water, respectively; and $p$ indicates the pressure. The steady study was used to simulate the flow field to ensure the flow field reaches the steady state, and the fully coupled solver was used to solve the above equations. In this study’s model, the upper and lower boundaries and the fluid-solid boundary were set to no-flow conditions. First-type boundaries were applied to the left and right boundaries, and the water flowed from left to right under different pressure levels, as shown in Figure 1. Pressure differences were then adjusted so that the average velocities of fluid inside the pores in all of the porous media were 10.0 m/d, which was considered to be the typical velocity of groundwater in a spatially uncorrelated aquifer system under a natural hydraulic gradient. The pressure difference $\Delta P$, permeability coefficient $K$, and Reynolds numbers Re for each porous media are calculated and shown in Table 1 [37]. It can be seen from the table that the medium permeability decreases sharply with a rising cementation degree. In addition, the Reynolds numbers Re are all less than 1, which are in the scope of application of the Navier-Stokes equation.

The solute transport was described by the following advection diffusion equation:

$$\frac{\partial C}{\partial t} + \mathbf{u} \cdot \nabla (\mathbf{u} C) - \nabla \cdot (D_{aq} \nabla C) = 0, \quad (3)$$

where $u$ is the 2D velocity vector obtained from the simulation of flow field, $C$ indicates the tracer concentration, and $D_{aq}$ represents the aqueous diffusion coefficient. The advection diffusion equation was also solved by the fully coupled solver. In the model, the solute was continuously injected from the middle of the left boundary to reduce the effect of side boundaries on solute dilution ($x = -2, 25 \leq y \leq 35$), and the width of injection area was set as 10 mm, as shown in Figure 2. The injected solute concentration was 5.0 mol/m$^3$. Then, no-flux boundaries were applied to the remainder of the left boundary, as well as the upper, lower, and fluid solid boundaries. The right boundary was the outflow boundary. The diffusion coefficient of the solute $D_{aq}$ was $1 \times 10^{-2}$ m$^2$/s

| Porous media | Porosity | $r_{ave}$ (mm) | $P_c$ (%) | $\Delta P$ (Pa) | $K$ (m/d) | Re |
|--------------|----------|----------------|-----------|----------------|-----------|----|
| PM39         | 0.39     | 1.050          | 0.00      | 1.40           | 2819.10   | 0.242 |
| PM35         | 0.35     | 1.089          | 1.32      | 2.32           | 1394.33   | 0.251 |
| PM30         | 0.30     | 1.134          | 30.29     | 10.80          | 302.80    | 0.261 |
| PM25         | 0.25     | 1.179          | 55.89     | 241.81         | 6.9      | 0.271 |
| PM39         | 0.39     | 1.054          | 0.00      | 1.57           | 2535.25   | 0.243 |
| PM35         | 0.35     | 1.091          | 0.48      | 3.40           | 1089.86   | 0.251 |
| PM30         | 0.30     | 1.134          | 26.44     | 15.21          | 220.59    | 0.261 |
| PM25         | 0.25     | 1.183          | 55.16     | 510.69         | 5.77      | 0.272 |
| PM39         | 0.39     | 1.057          | 0.00      | 1.82           | 2166.08   | 0.243 |
| PM35         | 0.35     | 1.095          | 4.93      | 4.40           | 835.58    | 0.252 |
| PM30         | 0.30     | 1.139          | 37.14     | 29.58          | 114.15    | 0.262 |
| PM25         | 0.25     | 1.177          | 55.77     | 7653.86        | 0.40      | 0.271 |
Figure 1: Details the porous media (Group 1) with different cementation degrees and the flow fields in the pore spaces. In the figure, the solid grains are represented by white circular shapes. The boundary conditions of the flow problems indicated in PM39 were also applied to the other media. The color coding indicates the fluid flow velocities, with an average velocity of 10 m/d in all of the porous media.

Figure 2: Migration patterns of the solute plumes in Group 1 porous media: PM39 (a, b); PM35 (c, d); PM30 (e, f); PM25 (g, h) at 500 and 6000 s. Note: in the figure, PM39, PM35, PM30, and PM25 represent media with porosities of 0.39, 0.35, 0.30, and 0.25, respectively. The boundary conditions of the solute transport model indicated for PM39 were also applied to the other media.
in all of this study’s simulations, which was a standard value for free molecular diffusion in liquid.

The solute dilution was quantified using the dilution breakthrough curves (dBTCs), which were obtained by calculating the transient flux-related dilution index as follows and represented the evolution of the effective volumetric solvent flux carrying a given mass flux of solute with time:

\[
E_Q(x, t) = \exp \left( -\int_{\Omega} p_Q(x, t) \ln (p_Q(x, t)) q_x d\Omega \right),
\]

\[
p_Q(x) = \frac{C(x)}{\int_{\Omega} C(x) u_x(x) d\Omega}, \tag{4}
\]

where \(u_x\) indicates the longitudinal component of the flow velocity normal to the cross-section, \(C(x)\) represents the concentration at any point on the cross-section at distance \(x\), and \(p_Q\) represents the flux-related probability density function.

3. Results and Discussion

3.1. Changes in the Solute Dilution. As stated in the introduction section, the dBTCs can be utilized to describe the temporal evolution of the solute dilution at any given cross-section, and the true solute dilution can be accurately interpreted. In this study, the dBTCs were calculated at four cross-sections, which were located at 23, 43, 63, and 84 mm away from the tracer source in all of the porous media. The results are shown in Figure 3.

The obtained experimental results of three groups of porous media indicated that the cementation degree of the solid grains had significant influencing effects on the temporal evolution of the dilution breakthrough curves. As shown in Figure 3, for the porous media in which the solid grains were slightly cemented (PM35, PM30), the values of the
transient flux relation at different cross-sections located at different distances from the solute source (23, 43, 63, and 84 mm) increased rapidly to levels higher than the asymptotic values of the transient flux-related dilution index in the noncemented porous medium (PM39). In addition, it was found that the higher the cementation degree, the greater the asymptotic value of the flux-related dilution index. These results indicated that the solute dilution effects were significantly enhanced when the cementation degree increased within a certain range.

In this study, in order to quantitatively examine the aforementioned enhancement effects of the solute dilution, the asymptotic values of the transient flux-related dilution indexes of PM35 and PM30 were calculated at the cross-sections located 43, 63, and 84 mm from the tracer source, and the required times to reach them were determined. The results are shown in Figure 4 and Table 2. The results indicated that for PM35 and PM30, the asymptotic values of the flux-related dilution indexes were significantly greater than those from the noncemented porous medium. For example, for the Group 1 porous media, at the cross-section located 63 mm away from the tracer source, the values of dBTC_{asym} were $1.79 \times 10^{-6}$ and $2.45 \times 10^{-6}$ m$^3$/s in the PM35 and PM30, respectively, which were significantly greater than the value of dBTC_{asym} ($1.69 \times 10^{-6}$ m$^3$/s) in PM39. In addition, we found that, when the cementation degree was relatively small, the time required for dBTC to reach the asymptotic value $t_{asym}$ increases to a certain extent with the cementation degree (although $t_{asym}$ in PM35 of Group 1 was reduced compared with that in PM39, the reduction was small and negligible). For instance, for PM30 (Group 1), the values of $t_{asym}$ at the cross-sections located 23, 43, 63, and 84 mm from the tracer source were 2760,
cross-sections located 23, 43, 63, and 84 mm away from the tracer source in all the porous media. The value of the flux-related dilution index at the end of the simulation. The changes in the asymptotic values of the dilution index had not reached the asymptotic value at the end of the simulation. The simulation results of the other two groups of media are consistent with this. At most sections, the transient flux-related dilution index had not reached the asymptotic value at the end of the simulation. In addition, it can be seen from Figure 3 that, at the cross-section closest to the solute source (23 mm), the strength of the solute dilution effect in the porous media with the largest cementation degree (PM25) is lower than that in the completely noncemented porous medium (PM39) for a long period of time. This was the same as the simulation results of the cross-sections located farther away from the solute source. The difference from the cross-sections located farther away from the solute source was that at the section located closest to the solute source (23 mm), the asymptotic values of the transient flux-related dilution index in PM25 did not drop significantly compared with that in PM30. The weakening of dilution is mainly caused by the increase in the time that the solute is in an incomplete dilution state. The aforementioned analysis results clearly revealed that the cementation degree of the solid grains had a significant effect on solute dilution. For example, when the cementation degree was within a certain range (PM35, PM39), the dilution effects became enhanced with the increase of the cementation degree. In addition, as the cementation degree grew, the time of solute in the incomplete dilution state increased. However, the increase in the duration of incomplete dilution with a cementation degree was relatively small, which had little impact on the dilution intensity. Then, after

Table 2: Asymptotic values of the dilution breakthrough curve (dBTC\text{asym}) and the time required to reach the asymptotic value \(t_{\text{asym}}\) at cross-sections located 23, 43, 63, and 84 mm away from the tracer source in all the porous media.

| Porous media | Group 1 | | | Group 2 | | | Group 3 | | |
|--------------|---------|---------|---------|---------|---------|---------|---------|---------|
|              | 23 mm   | dBTC\text{asym} (10^{-6} m^3/s) | 23 mm | dBTC\text{asym} (10^{-6} m^3/s) | 23 mm | dBTC\text{asym} (10^{-6} m^3/s) | 23 mm | dBTC\text{asym} (10^{-6} m^3/s) |
| PM39         | 1.17    | 1.30    | 1.69    | 1.98    | 1.80*   | 1.76*   | 2.11*   | 2.29*   |
| PM35         | 1.32    | 1.57    | 1.79    | 2.22    | 1.46    | 1.85    | 1.89    | 2.59    |
| PM30         | 1.72    | 2.22    | 2.45    | 2.60    | 1.61    | 1.95    | 2.34    | 1.59    |
| PM25         | 1.80*   | 1.76*   | 2.11*   | 2.29*   | 1.63*   | 1.47    | 1.84    | 1.59*   |
| PM39         | 1.27    | 1.47    | 1.69    | 1.98    | 1.92    | 1.76    | 2.34    | 2.59    |
| PM35         | 1.46    | 1.85    | 1.89    | 2.22    | 2.22    | 2.19    | 2.60    | 2.54    |
| PM30         | 1.61    | 1.95    | 2.34    | 2.60    | 1.62    | 2.00    | 3.00    | 3.54    |
| PM25         | 1.63*   | 1.47    | 1.84    | 1.59*   | 1.9860  | 1.9740  | 1.9860  | 1.9740  |

Note: the superscript "*" indicates that the asymptotic value of flux-related dilution index has not been reached by the end of simulation and is represented by the value of the flux-related dilution index at the end of the simulation.
the cementation degree increased to a certain degree (PM25), the dilution effects were not enhanced but weakened with the increase of the cementation degree. And the growth of time of solute in the incomplete dilution state was pretty significant, which had a great impact on the dilution intensity and was an important factor for its weakening.

3.2. Mechanism. In this section, the mechanism for the solute dilution variation under the different cementation degrees was explored. The characteristics of the flow fields suggest that they are the bridges connecting the medium properties and the solute transport characteristics. It has been found that the mechanisms of many solute transport phenomena can be explained by analyzing the characteristics of the flow fields [38, 39]. For example, previous studies have shown that the heterogeneity of a flow field has significant impacts on solute dilution. Therefore, this study analyzed the characteristics of the flow fields in order to reveal the internal mechanism of the varying behaviors of the solute dilution processes when the cementation degrees change.

The simulation results of the examined flow fields in Group 1 porous media are shown in Figure 1. It is shown in the figure that the characteristics of the flow fields may differ greatly among the porous media with different degrees of cementation. It was found that for the noncemented porous medium (PM39), the flow field was relatively uniform, and there was no obvious flow focusing observed. However, with the increases in cementation degree, flow focusing became increasingly pronounced. In the porous medium with the highest cementation degree (PM25), the slow flow focusing areas were the areas where the local fluid flow velocity was 5-fold greater than the average velocity, and the slow flow regions were the areas in which the local fluid flow velocity was 100-fold lower than the average velocity. Meanwhile, a coefficient of variation $CV_u$ was adopted as the metric of the heterogeneity of the flow field as follows:

$$CV_u = \frac{\sigma_u}{u_{av}} = \sqrt{\frac{\int_{V_p} [u_x(x) - u_{xav}]^2 dV_p}{\int_{V_p} u_x(x) dV_p}} \frac{V_p}{V_p},$$

where $u_x, u_{xav}$, and $\sigma_u$ represent the velocity in the direction of water flow, corresponding average value, and standard variance, respectively, and $V_p$ indicates the pore spaces occupied by the fluid.

![Figure 5: The slow flow regions (the blue areas in a, c, e, g) and flow focusing regions (the colored areas in b, d, f, h) in Group 1 porous media: PM39 (a, b); PM35 (c, d); PM30 (e, f); PM25 (g, h).]
The internal mechanism of the different temporal evolution of the solute dilution was considered to most likely be related to the abovementioned changes in the flow field properties. It was found that with the increases in the cementation degrees, the flow fields became more heterogeneous, and the flow focusing and slow flow areas had obviously increased. This had led to more solute migration through the flow focusing channels. The increases in the flow focusing area and flow slow area were the two main influencing effects on the solute dilution. First of all, more solute was able to migrate through the flow focusing channels, and the solute entering the surrounding slow flow regions decreased accordingly. This resulted in an increased solute concentration gradient between the flow focusing channels and the surrounding slow flow regions. In addition, when the cementation degrees became larger, it was found that the shapes of the solute plumes became increasingly irregular. Consequently, the solute plume areas increased. Then, the larger concentration gradients and the solute plume areas resulted in more solute diffusing into the adjacent streamline, which was the only real dilution effect. Therefore, under the abovementioned influences, the solute dilution tended to become enhanced in the porous media with higher degrees of cementation. However, the hydraulic connections between the flow focusing channels and the surrounding slow flow regions were observed to gradually weaken when the cementation degrees became higher. This had led to gradual increases in the resistance of the diffusion of the solute to the adjacent streamlines. The abovementioned changes caused the solute dilution to become weakened with the increase in cementation degree.

The influencing effects of the above two aspects may lead to the complex temporal evolution of the solute dilution in the examined porous media with different degrees of cementation.
cementation. When the cementation degree increases within a certain range, the resulting increases in the solute diffusion resistance had weak effects on the dilution process. The influencing effects on the solute dilution are mainly due to the increases in the solute concentration gradient and the solute plume area. Therefore, for PM35 and PM30, the solute dilution was observed to be significantly enhanced at all cross-sections. However, when the cementation degree increased to a certain degree, the influences of the increases in the resistance of the diffusion on the dilution process became the main effects. Therefore, the asymptotic values of the dilution coefficients in PM25 were found to decrease dramatically when compared with PM30. Moreover, the time of solute in the incomplete dilution state had increased.

To verify the analysis, the transport patterns of the solute plumes in the different types of media were analyzed in detail. The results of the solute transport simulations at 500 and 6000 s in the porous media (Group 1) with different degrees of cementation are presented in Figure 2. As can be clearly seen in the figure, the shapes of the solute plumes clearly became increasingly irregular with the increases in the degree of cementation.

It was determined in this study that for the noncemented porous medium (PM39), the solute mainly moved forward along the central area corresponding to the entrance, and there were no obvious channels to move to the surrounding areas on both sides. The solute migration in the lateral direction was mainly through diffusion and was observed to be relatively uniform and slow. As detailed in Figure 2(b), even long after solute plumes had reached the outflow boundary, the solute plumes were still mainly distributed in the central area. However, due to the enhancement of the flow focusing process, significant lateral solute transport channels had appeared along the flow focusing channels when the cementation degree became larger. Then, after the solute had migrated laterally along those flow focusing channels, it had quickly diffused into the surrounding slow flow areas. This had eventually led to the lateral expansion of the solute plumes and the enhancement of the solute dilution process, as shown in Figure 2(f). It was also noted that when the cementation degree increased to a certain extent (PM25), due to the deterioration of the hydraulic connectivity, the solute which had moved laterally along the flow focusing channels to both sides had difficulty migrating into the surrounding slow flow areas. There were observed to be many “invalid” slow flow areas where the solute could not easily enter for a long period of time. As stated in Introduction, solute dilution is the result of the mass exchanges between different streamlines, and the deformations and stretching of the solute plumes caused by the heterogeneity of the advective velocity do not contribute to the dilution process. This was the mechanism by which the solute dilution decreased in the porous medium with the highest degree of cementation (PM25). The migration morphology of the solute plumes confirmed the abovementioned analyses regarding the mechanism of varying solute dilution with growing cementation degrees.

4. Summary and Conclusions
This study explored the changes in solute dilution in porous media and the corresponding inner mechanism when the cementation degrees of solid grains varied. In the study, three groups of porous media were constructed (Group 1, Group 2, and Group 3), and each group of media included four types of porous media with different degrees of cementation. These were denoted as PM39, PM35, PM30, and PM25, which represented porous media with porosities of 0.39, 0.35, 0.30, and 0.25, respectively. The percentages of the solid grain cementation with other \( P_c \) were adopted as the indexes for measuring the cementation degree. For instance, for the PM39, PM35, PM30, and PM25 of Group 1 porous media, the \( P_c \) values were 0.00, 1.32, 30.29, and 55.89%, respectively. The results indicated that the degrees of cementation had become increasingly higher as the porosity levels decreased.

The simulation results of the transient flux-related dilution index showed that the influencing effects of the cementation degrees on the solute dilution were very significant and complicated. First of all, the complexity of the effects of the increases in the degree of cementation on the solute dilution process was manifested in the fact that the effects had differed or even become the complete opposite when the degree of cementation changed within different ranges. It was determined that the solute dilution became significantly enhanced with the rising cementation degrees when the cementation degree was relatively small. For example, the values of flux-related dilution indexes in the porous media in which the solid grains were slightly cemented (PM35, PM30) were soon greater than those in the completely noncemented medium (PM39). However, this enhancement of the solute dilution caused by the rising cementation degrees could not be sustained. It was found that when the degree of cementation increased to a certain extent, the solute dilution changed to become gradually weaker with the increases in cementation. For instance, the values of the flux-related dilution index in the porous medium with the largest cementation degree (PM25) had displayed a major degree of decline when compared with that in PM30 and was even smaller than that in the noncemented porous medium (PM39) for a long period of time. In addition, we found that the growth of time of solute in the incomplete dilution state was pretty significant in the porous media with the largest cementation degree, which was an important factor causing the weakening of the dilution effect.

The inner mechanism of the influencing effects of the cementation degrees on the solute dilution process was explored by analyzing the varying characteristics of the flow fields. The results revealed that when the cementation degrees became larger, the flow focusing phenomena became increasingly obvious. As a result, the percentages of flow focusing regions and slow flow regions also obviously increased, and the heterogeneity of the flow fields was gradually enhanced. For example, for the Group 1 porous media, as the \( P_c \) rose from 0.00 to 55.89%, it was found that the percentage of the flow focusing areas \( P_{focus} \) had grown from 1.05 to 6.07%, and the percentage of the slow flow regions \( P_{slow} \) increased from 3.57 to 48.74%. The analysis results of the migration morphology of the solute plumes confirmed that the abovementioned changes in the flow fields resulted in
more solute migrating through the flow focusing channels. This had two main effects on the solute dilution process. First of all, more solute migrated laterally through the flow focusing channels and then quickly diffused into the surrounding slow flow areas. Those influences caused the solute dilution to tend to become enhanced in the porous media with higher cementation degrees. Secondly, the hydraulic connections between the flow focusing channels and the surrounding slow flow areas were gradually reduced when the cementation degrees became higher, which led to the resistance of the solute entering the flow focusing channels to diffuse into the surrounding slow flow regions becoming greater. This mechanism caused the solute dilution to weaken with the increases in cementation. Therefore, it was the joint influences of the abovementioned two aspects which had given rise to the complex temporal evolution of the solute dilution in porous media with different degrees of cementation.

The results obtained in this study provide new insight into the inner mechanism of the different temporal evolutions of solute dilution, as well as a theoretical basis for the accurate description of solute dilution in porous media. In addition, it was found to be interesting to note that the more heterogeneous flow fields had not necessarily led to the enhancement of solute dilution. This was contrary to the traditional understanding. Therefore, going forward, caution should be taken when judging solute dilution degrees based on the heterogeneity of the flow fields. Besides, what must be noted is that fully understanding and capturing the solute dilution process in porous media with different cementation degrees may still be a long way off, although previous works have shown that the computer generated porous media constructed using the method in this paper can reflect some structure characteristics of actual aquifer media to a certain extent. However, the pore-scale structure of actual aquifer media is much more complex than that of computer generated media. Consequently, much more in situ experiments in the actual aquifer media are needed in the future to further check and fully capture the influence of the complex pore-scale structure of the porous media with different cementation degrees on the solute dilution. Moreover, the model in this paper does not consider the spatial correlation of porous medium properties. However, there are some differences between the characteristics of the groundwater flow field and solute transport in spatially correlated groundwater systems and those in spatially uncorrelated systems [40–42]. Therefore, these conclusions are specific to spatially uncorrelated groundwater systems. Further research is needed to determine whether these conclusions hold for spatially correlated groundwater aquifers.

**Data Availability**

The data used to support the findings of this study are included within the article.

**Conflicts of Interest**

On behalf of all authors, the corresponding authors state that there is no conflict of interest.

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