Study on horizontal diffusion of agent solutions in underground unsaturated soil: experiments and model simulations

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Abstract

The solute transport or water transport in unsaturated soil plays an important theoretical guiding role in remediation engineering. In order to study the diffusion of agent solutions in practical remediation engineering, the soil column experiments of unsaturated soil were carried out using the self-made laboratory test device. The effects of injection rate and soil pressure (confining pressure) on the solute diffusion in soil were studied. The experimental results show that the injection velocity has a great influence on the solute diffusion in soil, and the change in the diffusion rate is not proportional to the injection velocity. The effect of confining pressure on solute diffusion was first promoted and then suppressed. The fractal Richards equation (FRE) model was used to fit the water content curves. The results show that the FRE model has a fine fitting effect on this series of experiments, proving that it can provide model support for the simulation of solute diffusion in underground unsaturated soil. At the same time, the physical significance reflected by the fitting parameters can be used to analyze the mechanism of the experimental phenomena.

Keywords: Contaminated soil remediation, Fractional Richards’ equation model, Horizontal transport, Laboratory simulation experiment, Underground unsaturated soil

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1. Introduction

In recent years, soil pollution has become increasingly prominent in China [1, 2]. Thus, soil remediation has become urgent. Redox technology, a kind of chemical remediation, is the most common in-situ remediation technology, due to its high efficiency and low cost. Hereinto, the high pressure jet grouting technology [3-5] is an oxidant adding method developed on the basis of the high pressure jet grouting pile. In the implementation of the remediation, the high pressure jet grouting equipment injects agents into deep soil, mixing agents and soil effectively and uniformly, and in order to improve the removal effect of pollutants. Accelerating the diffusion of agent solutions in underground soil is the key point to improve the quality of the high pressure jet grouting technology in practical engineering. During the remediation process, technological parameters (e.g. injection pressure, injection rate and so on [5, 6]) are often determined by empirical values of similar projects, lacking of quantitative experimental or theoretical basis. Therefore, it is of profound significance to explore the law of water transport and solute transport in underground unsaturated soil, to improve the remediation efficiency in actual engineering and to predict the diffusion of pollutants or remediation agents.

The technological parameters of the high pressure jet grouting technology are greatly related to the effective diameter and mixing effect of remediation [7]. In order to accelerate the remediation of contaminated soil, the numerical values of technological parameters are just blindly increased, which results in problems such as agent overflow and insufficient diffusion during the remediation process, leading to limited remediation effect and a mass of waste of agents. During this process of remediation, liquid jet with highly concentrated energy is sprayed continuously through a high flow rate to cut and stir the target soil, and increasing jet flow rate is
a commonly adopted method to accelerate remediation. However, flow rate in soil is not directly proportional to the diffusion velocity, which was put forward by Zhao Wan [5] through field experiments in her research results. Moreover, Nathan W. Haws [8] focused on the effect of fluid velocity on model-estimated rates of radial solute diffusion in a cylindrical macropore column. Jose´ Luis Costa [9] studied the solute transport in fine sandy loam soil under different flow rates, and concluded that dispersion coefficient was different when different water flow rates were applied, at the same location. Other researchers, Yasuda [10] and Bejat [11], have also observed and calculated the similar laws from the agricultural experimental field, which proved that the influence of flow rate on diffusion property cannot be ignored. Therefore, combining with the problems encountered in engineering operations, it is very necessary and urgent to study systematically the influence of flow velocity on diffusion property.

In addition, studies [3, 7] show that the high pressure jet injection technology is applicable primarily to remediate shallow contaminated soil. Even in shallow underground soil, the effect of soil confining pressure cannot be ignored. Lewis [12] found the phenomenon of pollutant accelerated migration by measuring the relevant data of landfill sites that have been put into use. He believed that it is probably the consolidation deformation caused by confining pressure of soil that affected the convection mechanism of solute. In the consolidation process of soil under pressure, various migration coefficients (such as effective diffusion coefficient, pore ratio, etc.) will change in time and space, and the changes of these coefficients and some other factors will have a great impact on solute migration. This has been corroborated by recent research results. Patrick j. Fox [13] and Chuang Yu [14] have both concluded through theoretical and practical studies that the change of diffusion coefficient plays a very important role in
pollutant transport. These studies show that confining pressure is one of the crucial factors affecting the diffusion of pollutants or agent solutions in underground soil. Feng Chu [15] investigated soil-water characteristics of unsaturated undisturbed loess under isotropic compression condition, and influences of net confining pressure on matric suction characteristics of unsaturated undisturbed loess are determined and illustrated. And matric suction on water transport and solute transport in soil is also self-evident [16]. To sum up the previous studies, we can note that the influence of confining pressure on soil consolidation and pore water pressure indirectly affects the diffusion performance of water and solute in soil. Therefore, it is necessary to explore the law of water transport or solute transport in underground soil under different confining pressures, and the confining pressure of soil in laboratory experiments was achieved by applying external forces.

Considering the complexity of the actual engineering environment and the urgency of solving the problem, a suitable mathematical model plays an important role in exploring water or solute transport in unsaturated soil. Research on migration and transformation of water or solute in underground environment usually adopts the methods of indoor soil column test [17-19], field soil column test and field survey sampling to obtain the measured data [20-23] and analyze the migration and transformation rules of pollutants in soil. On the basis of the above three common methods, the mathematical model is used for numerical simulation, which can predict the solute transport of pollutants and evaluate potential problems in the underground environment. For the study of one-dimensional water transport in unsaturated soil, researchers have formed a research system combining mathematical model simulation and experimental verification. Wang quanjial [24] developed a simple method, a horizontal one-dimensional infiltration test, to estimate water
diffusivity of unsaturated soil. Moreover, several models have been proposed for the study of water transport [25, 26]. The classical Richards model [27], proposed by Richards in 1937, is a widely recognized mathematical model of water transport in unsaturated soil. Many researchers have modified and simplified the Richards model, and various mathematical models have been proposed [28, 29] based on the experimental results. The water or solute transport in unsaturated soil is often influenced by the complex pore structure of soil and the external conditions. Previous studies have shown that particle distribution, pore structure and pore connectivity in soil all present fractal characteristics [30-32]. More and more researchers [33-35] begin to use fractal tools to describe the complex soil pore structure, and then use fractal tools to study the anomalous transport of water in unsaturated soil. On this basis, Sun et al. [36] proposed a fractal Richards equation model (FRE), and verified that the FRE model has a good simulation effect on water transport in unsaturated soil, which exhibit anomalous non-Boltzmann scaling. In addition, Fan et al. [37] also verified through experiments that the simulation effect of the FRE model would not be weakened by the accumulation of time or space distance, and the water or solute transport could be predicted accurately. Therefore, it is necessary to explore whether the FRE model can be used to characterize the diffusion law of water or solute in unsaturated soil under complex conditions, and whether its parameters can reflect physical properties. It is very important to solve the problem of insufficient diffusion and to predict the transport of agents in soil.

In summary, the study on the water transport or solute transport in unsaturated soil is to explore the diffusion law of agents in underground soil in actual remediation engineering. Transport of water or solute in unsaturated soil plays an important theoretical guiding role in
remediation engineering. Therefore, it is extremely important to carry out quantitative laboratory simulation experiments and to find a suitable and effective mathematical model. In this paper, a technical parameter (injection rate) and one physical property (confining pressure) of contaminated soil are taken as research objects, and a series of experiments considering two influencing factors are carried out. On this basis, the FRE model was used to characterize the water retention curves, by fitting the experimental data. The rest of this work is organized as follows. The experimental apparatus, experimental process and the FRE model are presented in section 2. The results obtained from experiments and fitting curves are shown in section 3. At the same time, the physical significance reflected by the fitting parameters is used to analyze the mechanism of the experimental phenomena. Then the conclusions are drawn in section 4.

2. Test and Methods

Considering that the diffusion of agents in soil is symmetrical in all horizontal directions, this paper chooses one-dimensional horizontal diffusion as the research object. A solution of sodium phosphate (Na₃PO₄) was injected, as the remediation agent. The soil water content was measured in real time by using the soil water content detector in each test hole of equal distance. Data was collected and recorded in the process of experiments.

2.1. Test Principle

The principle of high pressure jet grouting technology is to inject chemical agents into underground soil by air flow and liquid flow with high pressure. And then pollutants are oxidized by the chemical oxidant (the remediation agent), degraded or transformed to low toxic products.
The effective action range of high-pressure jet grouting technology includes core cutting part, diffusion part or extrusion part. As shown in Fig. 1, the effective range is a cylindrical consolidation body composed of the agent and soil mixing slurry body, the stirring mixing part and the diffusion part. However, it is understood that core cutting part will mainly depend on the cutting action of the jet and on the soil resistance to disaggregation. This is mainly a physical effect on soil, extremely complex to be quantified. In practical projects, the radius of effective range in the horizontal direction is often to measure the remediation effect and efficiency. Therefore, the study on the water or solute transport in underground soil mainly focuses on the diffusion part in the horizontal direction, and the diffusion in the vertical direction is not considered in this paper. The diffusion conditions were simulated by laboratory experiments, and influences (injection rate and confining pressure) were discussed.

2.2. Test Apparatus

The laboratory scale experiment of water transport in horizontal unsaturated soil column, the most widely used in experimental research, can eliminate the influence of gravity on water transport in unsaturated soil, which can make the influencing factors of water transport single and parameters more accurate. Horizontal soil column method is a laboratory method for the determination of unsteady flow in soil hydraulic diffusion, which was first proposed by Bruse and Klute (1956). This method is calculated based on the horizontal transport of water in a long (horizontal semi-infinite boundary) homogeneous soil column. The experimental instrument in this paper is an improved laboratory test device, based on the commonly used horizontal
unsaturated soil column, in order to simulate the injection rate and confining pressure of agent solutions.

The diffusion experimental system used in this paper consists of four parts: a diffusion experiment pipe, injection device, pressure device and detection device. The assembly and dimensions of the experimental apparatus are shown in Fig. 2. The inside diameter of the diffusion experiment pipe is 90 mm, and the total length is 1,200 mm. The length of the soil column is much longer than its diameter, forming a horizontal semi-infinite boundary constraint. The experimental pipe is equipped with 10 holes spaced 100 mm apart for injecting simulated agents and measuring water contents and pH values of soil. The front end of the soil column is the injection end, and vent holes are left at the end, to ensure that the air in the pores of the soil column is always connected with atmospheric pressure during the experiment. The simulated agent is injected quantitatively and at a constant rate through KCS PRO peristaltic pump. The pressure device is composed of air compression pump, air bag, earth pressure sensor and static strain gauge. A bottom plate with a diameter of 89 mm and a thickness of 50 mm is used to isolate the air bag and the experimental soil column. The plate can sustain a certain pressure and make soil samples under uniform pressure, while ensuring the sealing, and ensure that the soil column formed normal consolidation under pressure.

2.3. Sample Preparations and Test Procedures

In order to minimize the error between laboratory experiments and actual situations, the experimental soil used in this paper was undisturbed. Soil samples were shallow soil, taken from the middle area of Jiangsu province. After removing impurities and drying, soil samples were
reconfigured to meet the required water contents. The initial water content of undisturbed soil was 17.58%. When the in-situ remediation is carried out by high-pressure jet grouting technology, the agent is required to be water-soluble, relatively stable under high-pressure conditions, and has little side effect on the environment [5]. Sodium phosphate (Na₃PO₄) selected in this paper is a kind of inorganic compound, and it is easily soluble in water (its solubility is 28.3 g/100 mL).

In view of problems in practical engineering application of high-pressure jet grouting technology, such as agent overflow and insufficient diffusion, which are mainly affected by injection rate and confining pressure. Therefore, two factors are selected to study the influence on the diffusion rate of agents in soil, namely, injection rate (60 ml/min, 40 ml/min, 20 ml/min), and confining pressure (5 kPa, 10 kPa, 15 kPa, 20 kPa, 30 kPa, 40 kPa, 50 kPa).

The experimental pipe was placed vertically to fill with the prepared soil samples and form an experimental soil column, and then laid horizontally for subsequently diffusion experiments. The liquid feeding hole at the front of the pipe was the injection hole for simulating the agent. The prepared agent solution was injected into the experimental soil column by KCS PRO peristaltic pump at a fixed time and a constant speed. Soil detectors inserted into holes 1-9 were used to record the time data, and water contents and pH of soil samples in the diffusion process were measured in real time. An air bag can be placed at the end of pile and near the injection hole, and it inflated to a certain pressure by an air compression pump to simulate the confining pressure. After the diffusion completed, soil samples were taken through holes 1-9 for further determination. To improve the accuracy of experiments and ensure the repeatability, two or three effective repetitions were carried out by the same group of experiments in this paper.
3. Mathematical Model and Method

Scholars have done a lot of research on the water and solute transport in unsaturated soil, and gradually developed from simple experimental research to the prediction of the transport process of water and solute in unsaturated soil by mathematical models. In terms of mathematical models, Richards’ equation is commonly used to describe characteristics of transport of water in soil, and the convection diffusion theory is used to describe the solute transport process.

The numerical solution of Richards’ equation has always been a hot topic and remains a challenge. Farthing and Ogden [40] indicated that analytical solutions of Richards’ equation exist only for simplified cases, so most practical situations require a numerical solution in one- two- or three dimensions, depending on the problem and complexity of the flow situation. For instance, Marco Berardi et al. [41] discussed a transversal method of lines for solving Richards’ equation, whose application is closely related to the choice of boundary conditions. For water transport through one dimensional horizontal soil columns, Richards’ equation takes the form

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[D(\theta) \frac{\partial \theta}{\partial x}\right]$$

(1)

where, $\theta$ is the water content, $D(\theta)$ is the water diffusivity, which is assumed to only related to water content, $x$ is the transport distance of water in soil, and $t$ is the ordinary time. The Boltzmann scaling $x \sim t^{1/2}$ makes transport distance grow as the square root of time.

Classical Richards’ model has a good simulation effect on the flow through unsaturated media in accordance with the Boltzmann scaling, but has great limitations on exhibiting the
anomalous non-Boltzmann scaling. In many laboratory experiments and field observation \cite{29, 42}, the relationship between distance of the wetting front transport reflects anomalous non-Boltzmann scaling

\[ x = \lambda (\theta) \cdot t^\alpha \]  

(2)

Where the dimensionless exponent $\alpha \in (0, 2),$ $\alpha \neq 1.$

The transport of water in unsaturated soil is often affected by the complex pore structure and boundary conditions inside the soil, and the pore structure is not fixed during the transport process of water. So, it is difficult to describe the transport law of water in unsaturated soil accurately. Up to now, fractional derivative and fractal derivative are the mathematical methods widely used to describe anomalous diffusion. Pachepsky et al. \cite{29} come up with a generalized Richards' equation includes a fractional derivative on time, however, the equation is inconvenient for the practical computation because of the complications with fractional product rule. Previous studies have demonstrated that particle distribution, pore structure and pore connectivity in soil all present fractal characteristics \cite{30, 32, 43}. Chen et al. \cite{44} proposed the concept of fractal derivative, providing a method for the study of water transport in unsaturated soil with fractal tools. On this basis, Sun et al. \cite{36} proposed the fractal Richards’ model to explain and characterize the non-Boltzmann scaling, which equation is expressed as

\[ \frac{\partial \theta}{\partial t''} = \frac{\partial}{\partial x} \left[ D_x (\theta) \frac{\partial \theta}{\partial x} \right] \]  

(3)
where $D_{\alpha}(\theta)$ denotes a fractal water diffusivity. The fractal Richards’ model can be transformed into ordinary differential equation. Two basic forms of diffusivity $D_{\alpha}(\theta)$ were proposed: power-law and exponential [45, 46]. The power-law form assumes $D_{\alpha}(\theta) = D_0 \theta^n (n>0)$ in a semi-infinite domain. Sun et al. [36] have provided an approximate solution of Richards’ equation with a power-law diffusivity $D_{\alpha}(\theta) = D_0 \theta^n$, which is given by

$$\theta^n = 1 - \frac{n}{2C_0} \left[ \frac{2C_0(1-g/2)}{n+1} xt^{-\frac{a}{2}} + g \left(\frac{xt^{-\frac{a}{2}}}{2}\right)^2 \right]$$

(4)

$$g = 1 - \left(2\sqrt{(n+1)/n-1}\right)^{-1}$$

(5)

where the initial condition is

$$\theta(t = 0, x) = 0$$

(6)

the boundary condition is

$$\theta(t, x = 0) = 1.0$$

(7)

Three parameters need to be determined in Eq. (4) and (5): $C_0$, $\alpha$ and $n$. Moreover applications presented by Sun [36] and Fan [37], showed that the fractal Richards’ equation can predict wetting front dynamics for soil examples in a laboratory setting.

In this paper, the water content curve is obtained by observing the wetting front transport in the indoor soil column experiments, to further explore the water transport in unsaturated soil under different conditions. The researches mentioned above indicate that the FRE model may be used as a mathematical model to characterize laws of the water transport in the laboratory experiments in this paper. Therefore, water content curves were presented, fitting the
approximate solution Eq. (4) of the FRE model from the experimental data, and the mechanism of experiments was explored through analyzing three parameters ($C_0$, $\alpha$ and $n$) of the FRE model. The parameter $n$ of the FRE is positively correlated with the change rate of water content in soil [37], and the fractal order $\alpha$ of the FRE can characterize the underlying water transport environment property in heterogeneous soil [47].

4. Conclusions

4.1. Influence of The Injection Rate on The Speed of Diffusion

4.1.1. Experimental results

In the remediation construction process of high-pressure jet grouting, different injection rates are often selected according to different construction conditions. The purpose of this section is to obtain the effect of injection rate on the diffusion rate of agents. Three injection rates are selected: 20 ml/min, 40 ml/min and 60 ml/min, and then the influence laws are analyzed according to experimental results.

In this group of experiments, the agent with a concentration of 10 g/L was diffused freely in the soil column with an initial water content of 15%. Fig. 3(a)-(b) show time curves when the water content of soil samples reaches 20% and 30% after diffusion at different injection rates. It can be clearly seen from the figure that the faster the injection rate is, the shorter the diffusion time is, i.e. the faster the diffusion rate is. However, the increase of diffusion velocity is not proportional to the increase in injection rate. Considering that the total time of remediation agents of the same volume at different injection rates is different, the concept of relative time is introduced.
\begin{equation}
T_1 = \frac{T_2}{T_3} \times T_4 \tag{8}
\end{equation}

$T_1$: the relative time, $T_2$: the actual time when soil samples at a certain location reaches a certain water content, $T_3$: the total time spent on this full experiment, and $T_4$: the total diffusion time of the slowest rate group.

Fig. 3(c)-(d) show the relative time curves when the water contents of soil samples at different positions increase to 20% and 30%, under different injection rates. In the case of the same relative time, the effect of different injection rates on diffusion efficiency can be directly reflected from figures above. It can be seen from the observation that the increase of injection rates does not significantly improve the diffusion efficiency per unit time, on the contrary, the diffusion effect with low injection rate is fine.

4.1.2. The FRE model fitting results

Fig. 4 illustrates the results of fitting the FRE to water content data measured above under three groups of injection rates (20 ml/min, 40 ml/min and 60 ml/min). The solid lines show the FRE fitting solutions, and the dots are eight groups of water content. The corresponding positions for eight groups of data are $X = 100$ mm, 200 mm, 300 mm, 400 mm, 500 mm, 600 mm and 700 mm, respectively. There are a number of ways to deal with model fitting results. For example, Marco Berardi et al. [48] presented a new data assimilation technique and applied it to Richards’ equation. In this paper, correlation coefficient and root mean square error are used to reflect the fitting degree of the FRE model to experimental data. Best-fit parameters ($C_0$, $n$, $\alpha$) for the FRE, correlation coefficient (R-square) and root mean square error (RMSE) of fitting curve are shown
in Table S1. Fig. 4 indicates that FRE can describe the trend of water transport in soil column experiments under three different injection rates, and they fit well at all positions. The R-square and RMSE in Table S1 were computed by pooling data from all curves shown.

The parameter $n$ of the FRE is positively correlated with the change rate of water content in soil [37]. And, the parameter $n$ in the three groups of experiments is drawn as the change curves in Fig. 5. Fig. 5 shows that the lower injection rate is, the faster the water content of soil changes, that is, the faster the diffusion rate of the simulated agent in the soil column increases, which is consistent with the law reflected in Fig. 4. In addition, the R-square and RMSE in Table S1, reflecting a fitting effect, show that the FRE fits the water transport under a low injection rate more closely than the high group. Especially, in the experimental group (c) with higher injection speed, it can be found that the fitting effect of the forward position ($X = 200\ \text{mm}$, $400\ \text{mm}$...) is significantly decreased.

The diffusion of solute or transport of water in soil mainly flows through pore channels formed by the liquid phase of soil and self-infiltration [49]. With the increase in injection rates, more and more pore channels will participate in the diffusion. When the injection rate is too high, pore channels are not enough to pass through a large amount of liquid, so the growth rate of diffusion will gradually slow down. Moreover, due to the injection of a large amount of liquid in a short period of time, the liquid that has no time to diffuse and gradually accumulates, which will cause a certain degree of damage to the originally stable structure of the soil, and the pore channels used for liquid diffusion and transfer will also be damaged to a certain extent. When the injection rate is relatively low, the agent has enough time to permeate and diffuse, and it provides a stable environment for the agent filled in pores of the soil to react with pollutants. Therefore,
with the decrease of injection rates, the remediation is improved and the utilization rate of agents will be higher.

In actual construction processes, on the one hand, sampling should be carried out in advance to determine the optimal injection rate. On the other hand, if the remediation agent is expensive, the injection speed should be appropriately reduced on the premise of the remediation effect. Balancing the time cost and economic cost is to achieve the maximum benefit.

4.2. Influence of The Confining Pressure of Soil on The Speed of Diffusion

4.2.1. Experimental results

In engineering application, the high-pressure jet grouting technology is mostly used in the polluted soil with a depth of 0 ~ 4 m (the corresponding confining pressure of soil is 0 ~ 40 kPa). Confining pressure is an important factor affecting the diffusion of agents in underground soil. Therefore, the influence of a certain confining pressure (no higher than 50 kPa) on solute transport in subsurface soil will be considered in this paper.

In this group of experiments, the agent solutions with the concentration of 15 g/L was injected at the rate of 10 ml/min, and the pressure diffusion was carried out in the soil sample with the initial water content of 15%. Fig. 6 shows the time for the water content of soil samples to reach 20% after agents diffusion, under various confining pressures. It can be seen from Fig. 6 that the time for the diffusion of agents decreases first and then increases with the increase of confining pressure of soil, that is, the diffusion velocity of agents increases first and then decreases with the increase of confining pressure. In addition, there is an obvious optimal confining pressure value (15 kPa) in this group of experiments. By decomposing Fig. 6 into Fig.
6(a) and Fig. 6(b), it can be clearly seen that when the confining pressure of soil is 15 kPa, the diffusion time of remediation agent is the shortest. In the process of diffusion, the appropriate increase of confining pressure can promote the diffusion of agents in underground soil. And when the confining pressure increases gradually, the effect of promoting diffusion decreases gradually, and it presents a restraining trend when the confining pressure is larger.

4.2.2. The FRE model fitting results

Fig. 7 illustrates the results of fitting the FRE to water content data measured above under seven groups of confining pressures (5 kPa, 10 kPa, 15 kPa, 20 kPa, 30 kPa, 40 kPa and 50 kPa). The water content curve in each figure is composed of four to five groups of water content points at different positions and their corresponding FRE fitting curves. Fig. 7 indicates that FRE can describe the trend of water transport in soil column experiments under seven groups of confining pressures, and they fit well at all positions. Best-fit parameters ($C_0$, $n$, $\alpha$), R-square and RMSE of fitting curve are shown in Table S2.

The fractal order $\alpha$ of the FRE can characterize the underlying water transport environment property in heterogeneous soil, and CHEN Wen [47] pointed out that the smaller the value of $\alpha$, the more complex the water transport environment would be. Fig. 8 shows curves of parameter $\alpha$, fitted by FRE in each group, and according to the experimental law shown in Fig. 6, they are also divided into two groups: (a) and (b). Fig. 8 indicates that with the increase of the confining pressure, values of $\alpha$ first decreases (Fig. 7(a)) and then increases (Fig. 7(b)), which is consistent with Fig. 6. This represents that the rate of water transport is related to the complexity
of soil environment caused by the confining pressure, which can also be seen from the change of parameter $C_0$ in Table S2.

After the agent solution is injected into the soil column, it diffuses from the injection point to all directions. For the reason of the horizontal loading pressure in this experiment, proximal soil samples will be compressed first and pores will be reduced. Since liquid diffusion is mainly formed by filling soil pores to form water channels, so compact pores of soil particles shrinking make diffusion easier, and the diffusion speed tends to increase with the increase of confining pressure. When the confining pressure reaches a certain value, the pores in all directions are squeezed to a certain extent, and the compactness of soil reaches a certain degree. The shrinkage of pores in the soil will lead to the obstruction of flow paths for the liquid, and the diffusion of agents becomes very difficult. At this time, with the increase of the confining pressure, the diffusion rate of agents will gradually slow down.

Due to different confining pressures on contaminated soil at different depths in engineering projects, the diffusion in the remediation process is also different, leading to different remediation effects. For the shallow underground soil, some confining pressure can promote its diffusion. Owing to the deep underground soil under the higher confining pressure, the diffusion velocity will be restrained to some extent. Therefore, through changing other external conditions, the diffusion can be accelerated to achieve an optimal remediation effect.

5. Conclusions

Based on the problems of agent overflow and insufficient diffusion existed in the actual high-pressure jet grouting remediation project, the indoor simulation experiments were carried out.
Through the experimental study of different injection rates of agents and confining pressures of soil, influence rules of the two factors on diffusion are obtained. With the increase of the injection rate, the diffusion speed of agents gradually increases, but the rate of growth has slowed significantly. With the increase of the confining pressure, the diffusion velocity of agents in the soil tends to increase and then decrease. The experimental results presented in this paper show that the diffusion velocity is the fastest when the confining pressure reaches about 15 kPa. That is to say, it exists a confining pressure value to optimize the diffusion velocity. Under the high confining pressure, due to the compaction of soil, non-uniform diffusion and accumulation of agents will occur, and the effect of remediation is highly uncertain.

In addition, water content curves were presented, fitting the FRE from the experimental data. The FRE model is quite effective for simulating the transport of agents in unsaturated soil column experiments in this paper. At the same time, the diffusion mechanism of agent solutions was explored through analyzing three parameters ($C_0$, $\alpha$ and $n$) of FRE model. Therefore, the FRE model can be considered to predict the transport of agent solutions in unsaturated soil, in the actual remediation project.

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Author Contributions

C.C. (Ph.D. student) conceived and designed the study, performed the experiments, wrote the paper, reviewed and edited the manuscript. D.Y. (Professor) conceived and designed the study, reviewed and edited the manuscript. H.G. (graduate student) performed the experiments. Y.C. (Ph.D. student) performed the experiments, reviewed and edited the manuscript. G.X. (Ph.D. student) reviewed and edited the manuscript. All authors read and approved the manuscript.

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Fig. 1. Schematic diagram of soil particle arrangement in cross section of consolidated body within effective range. (1-Agents and mud, 2-Mixing part, 3-Penetration part).

Fig. 2. Diagram of experimental apparatus. (1-The agent solution, 2-KCS PRO peristaltic pump, 3-Static strain gauge, 4-Air compression pump, 5-Air bag, 6-Earth pressure sensor and 7-Soil detectors for water contents and pH).
Fig. 3. Diagram of agents diffusion in the soil column: the time when the water contents of soil samples at each position reaches to (a) 20% and (b) 30%; the relative time when the water contents of soil samples at each position reaches to (c) 20% and (d) 30%.
Fig. 4. Water content curves of fitting the FRE to experimental data: (a) injection rate is 20 ml/min, (b) injection rate is 40 ml/min and (c) injection rate is 60 ml/min.

Fig. 5. The change curves of the parameter \( n \) in the three groups of experiments.
The time when the water contents of soil samples at each position reaches to 20% under different confining pressures and two groups of pressures: (a) low confining pressures and (b) high confining pressures.
Fig. 7. Water content curves of fitting the FRE to experimental data: (a) confining pressure is 5 kPa, (b) confining pressure is 10 kPa, (c) confining pressure is 15 kPa, (d) confining pressure is 20 kPa, (e) confining pressure is 30 kPa, (f) confining pressure is 40 kPa and (g) confining pressure is 50 kPa.
Fig. 8. The change curves of parameter $\alpha$, fitted by FRE in each group.