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Numerical Simulation of the Solute Migration Regulated by Vertical Cutoff Wall based on FEFLOW

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Abstract: Cutoff wall has been widely used in desalination of coastal aquifers in many coastal regions and remediation of industrial waste water pollution. In recent years, the excessive exploitation of resources in the coastal brine distribution area leads to the salinization of deep soil. At the same time, the mine water pollution caused by improper discharge of industrial waste water into the abandoned mining area is a new form of pollution in Shandong, China. However, due to the complex geological conditions of abandoned mining areas, loose collapse of overlying strata in roadway and gob layer, it is difficult to prevent and control groundwater pollution in deep gob layer. It is a major difficulty in practical engineering to evaluate the cutoff interception performance of vertical cutoff wall on the pollution of gob layer in such mining areas and optimize cutoff interception measures. In this paper, a typical polluted abandoned mining area in Shandong, China is taken as an example, and COD is used as the main simulation factor for numerical simulation. The numerical simulation results show that in the process of groundwater pollution control, the cutoff wall with appropriate thickness and hydraulic conductivity can effectively block the diffusion of solute. The horizontal transport of solute can be significantly weakened when the thickness of the cutoff wall is 90 cm and the hydraulic conductivity is 1.0×10-4 m/d. Compared with increasing the thickness, reducing the hydraulic conductivity of the cutoff wall is more effective in controlling the migration of solute in the site. When the hydraulic conductivity is reduced by an order of magnitude, the diffusion range of solute is reduced by 19.74% compared to before. Therefore, priority should be given to reducing the hydraulic conductivity of the cutoff wall in order to optimize its influence on pollutant migration.

Keywords: Vertical Cutoff Wall; Solute Migration; Groundwater.

1. Introduction

In recent years, with the expansion of modern industry, the problem of water resource pollution in China is becoming more and more serious, many coastal areas are plagued by salinization and industrial wastewater and residue become one of the main sources of groundwater pollution. At present, there are a large number of contaminated sites, the formation system is complex, the pollution prevention and control are difficult, and the frequency of groundwater pollution by organic matter has increased significantly [1]. Organic solute will spread in aquifers due to improper disposal or accidental release into the ground, and the diffusion path is particularly complex[2]. Deep groundwater polluted by organic matter is difficult to be found in time, and it is difficult to treat and repair it, which often leads to the pollution of a wider range of groundwater systems, and the polluted groundwater will seriously endanger people's life and health [3].

In order to control or prevent the migration and diffusion of groundwater and solute, the existing treatment methods for contaminated sites mainly include thermal desorption, air injection, solidification stabilization and vertical cutoff wall, etc. [4]. Industrial practice has shown that cutoff walls with significant impermeable properties are ideal building types for use as contaminant control barriers [5]. Due to its strong impermeability, simple construction and low cost, vertical cutoff walls are widely used in the treatment and restoration measures of contaminated sites[6]. However, the hydrogeological conditions of the contaminated sites vary greatly, and the types of solute in the underground environment are complex. When designing the size and construction technology of the vertical cutoff wall, various factors, such as the nature of the formation, hydraulic gradient, and the type and concentration of solute, usually need to be considered[7].

At present, most researches mainly analyze the characteristics and rules of the migration and diffusion of organic solute, and there are few applied researches on the influence of cutoff interception measures on the diffusion of solute in groundwater. The effect of the cutoff wall on solute in groundwater is affected by its own characteristics (such as thickness, adsorption and hydraulic conductivity) and the physical and chemical properties of solute. In practical applications, it is necessary to consider these factors comprehensively, and select a cutoff wall with appropriate properties such as material and thickness to more effectively control the migration of organic solute. Therefore, according to the actual conditions of the site, it is of great practical significance to study the effect of pollution prevention and control of vertical cutoff wall in advance and select an economical and efficient pollution prevention and control scheme.

2. Pollution Characteristics of Abandoned Mining Site

The research area is located in an abandoned mine in Shanggao Village, Puji Town, Jinan City, Shandong Province, China. The site is located in the mid-latitude area, 200 m southeast of Shanggao Village, Puji Town, Zhangqiu City, 1.6 km south of provincial Highway 102, 1.7 km north of National Highway 309, 5.8 km northeast of Zhangqiu City, 4 km southwest of Puji Town. The study area is flat. The location of the research area is shown in Fig.1.

In 2015, a chemical enterprise illegally dumped a large amount of petrochemical waste liquid, waste gas residue and

other toxic and harmful substances in the shaft of the research site, causing serious pollution to the environment of the site. The length of the contaminated site is about 140 m from east to west, the width is about 100 m from north to south, and the total area of the contaminated site is about 14,000 m^2. The accident well where the waste liquid was dumped is located on the south side of the contaminated site area, with a wellhead diameter of about 3 m and a well depth of about 75 m. The chemical waste liquid flows into the underground environment of the mining area through the accident well, which causes direct pollution to the groundwater in the coal measure formation, affects the water supply safety of the surrounding residents, and causes irreversible damage to the groundwater environment. Fig.1b shows the location of the contaminated site. Immediately after the pollution incident, vertical cutoff walls were installed 100 m around the accident well to prevent further spread of pollution. At the same time, based on the ground distribution and groundwater flow direction of the site, groundwater monitoring wells with a depth of 70~110 m were set up in the site for sewage sampling and monitoring.

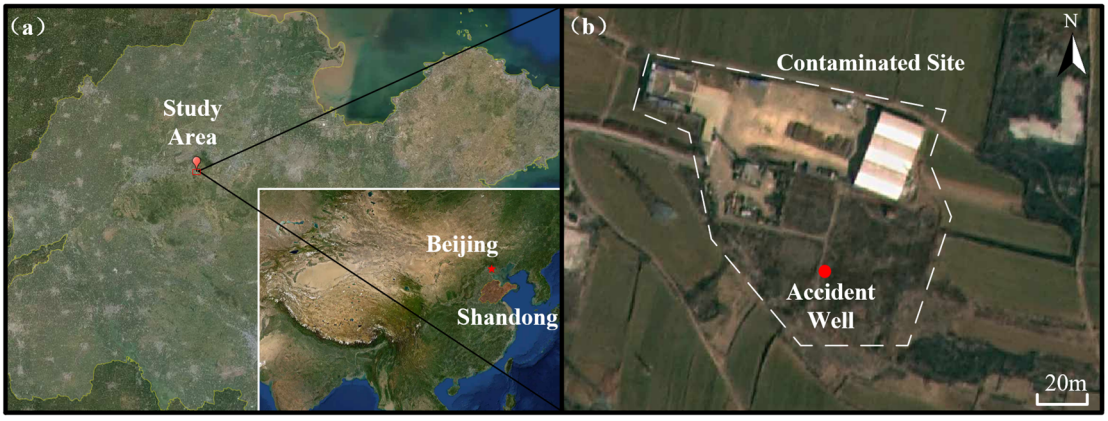


Fig 1. Geographical location of the study area

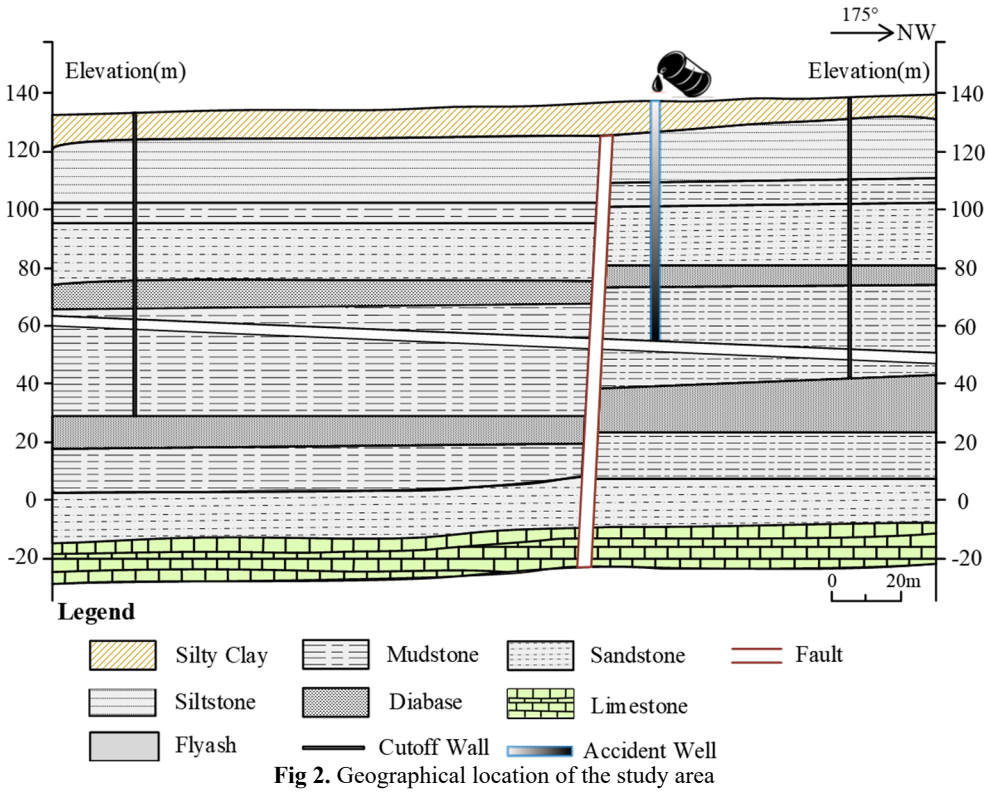


Fig 2. Geographical location of the study area

Samples of groundwater contaminated with waste liquid were taken in 2018. The sampling depth is below 0.5 m of the water table. The collected groundwater samples are stored in sealed dark glass bottles in accordance with China's national quality standard for groundwater and the solute and pollution concentrations in groundwater are measured. The chemical oxygen demand of groundwater was detected by dichromate method, and the volatile organic compounds and semi-volatile organic compounds were detected by gas chromatography-mass spectrometry. Among the groundwater indexes obtained by monitoring, the organic matter detection rate is higher in many sample points, and the dichloromethane content in some sample points is higher than the standard value of Class V groundwater. The underground water is mainly polluted by organic matter. In addition, it is also polluted by some inorganic substances with reducing properties such as ferrous ions. Since the chemical oxygen demand COD can effectively measure the content and pollution degree of reductive organic matter and inorganic matter in the water body[8], we chose the comprehensive

index COD as the pollution simulation factor to complete the simulation of the discussion on the cutoff interception performance of the vertical cutoff wall, so as to reflect the pollution degree of groundwater more comprehensively.

3. Numerical Simulation Introduction on Calculation

According to the geological borehole data and hydrogeological conditions of the study area, a three-dimensional geological model of the site was constructed (Fig. 3). The size of the generalized hydrogeological unit is 176.455 m×139.898 m×164.929 m. According to the different hydraulic conductivity of the study site, the model can be generalized into three layers, the first layer is silty clay layer, the second layer is limestone layer, and the third layer is mudstone layer (including coal seam). The groundwater flow in the study area is in a natural stable state, the groundwater flow direction is northeast, and the seasonal groundwater level is measured by the groundwater observation well. The average water volume of a single hole of the aquifer in the polluted area is 5 m^3/d after the pumping test. The hydraulic conductivity of silty clay of quaternary system was determined by geotechnical test. The measured result is 6.68×10^{-6} cm/s, and the permeability rate of soil fracture in the field is 0.5~1.0 m/d.

FEFLOW7.0 is an internationally popular visualization professional software system used to simulate and evaluate three-dimensional groundwater flow and solute transport[9]. In this study, FEFLOW7.0 software was used to simulate the dynamic process of pollutant migration and diffusion. The mesh scale of the model in the study area was segmented according to the selected physical field as a whole. The mesh unit scale was about 1 m by triangle algorithm, and the mesh unit scale was about 0.4 m at the cutoff wall. The model of the study area is dispersed with 301505 triangular mesh elements and 182340 grid nodes. Set the diffusion time of solute in the model to the period from the occurrence of the accident to the detection of pollutant concentration, that is, the total time step is set to 873 d, and the initial time step is set to 0.001 d.

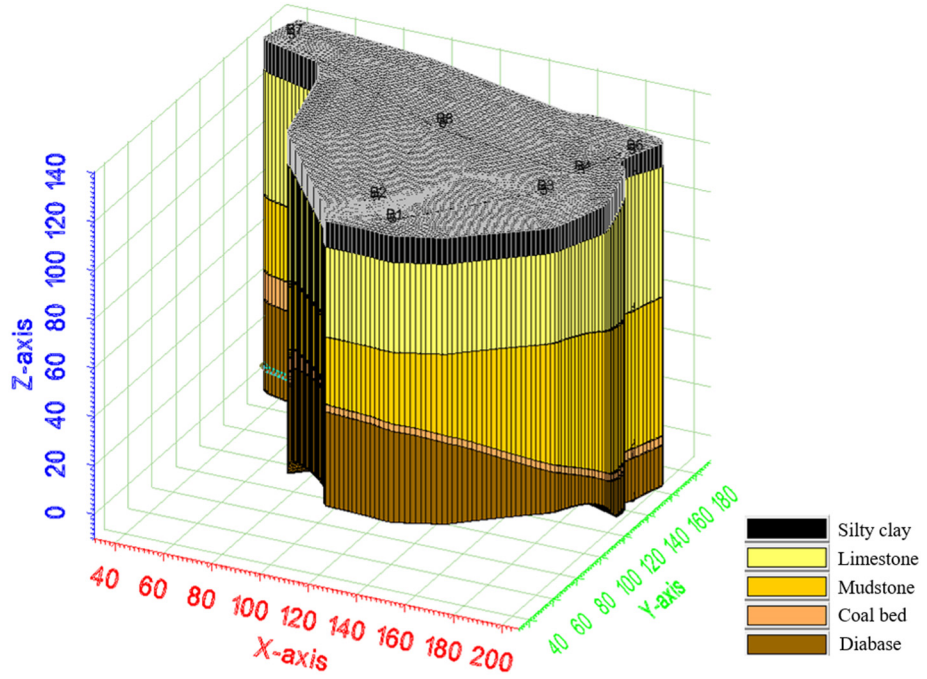


Fig 3. 3-Dimensional geological conceptual model

The main parameters of the model are set according to the results of soil test and permeability test. For some parameters that cannot be measured by geotechnical tests, initial settings are mainly made by referring to parameters of relevant engineering cases [10]. The specific parameter settings of the numerical model in the research area are shown in Table 1.

Table 1. Parameters of the calculation model

Parameters	Silty clay	Limestone	Mudstone	Vertical cutoff wall
Horizontal hydraulic conductivity (m/d)	0.58×10^{-2}	0.50	1×10^{-4}	1×10^{-3}
Longitudinal hydraulic conductivity (m/d)	0.78×10^{-3}	0.08	5×10^{-5}	1×10^{-3}
Porosity	0.20	0.25	0.18	0.10
Diffusion coefficient (10^{-9} m^2/s)	200	200	200	100
Longitudinal dispersivity (m)	10	10	1	1
Horizontal dispersivity (m)	2	2	0.2	0.2

4. Numerical Calculation Results Analysis

The simulation results of the numerical model are shown in Fig.4. The results show that after the solute are artificially injected into the accident well, the solute spread around the accident well, the pollution concentration in the accident well is gradually reduced, and the pollution range is gradually expanded. About 50 days after the accident occurred (Fig. 4a), the solute had completely dispersed in the high-permeability

roadway area around the accident well. At this time, the pollution diffusion characteristics were mainly centered around the accident well, and the contaminated area was about 2807 m^2. Fig. 4b showed that the solute diffused to the cutoff wall are obviously blocked, and the cutoff wall prevents the solute from diffusing to the outside wall to a certain extent. However, at this time, some of the solute in the southwest side still leaked outside the wall. We speculated that the main reason was the insufficient anti-cutoff effect of the cutoff wall itself, or the leakage occurred during the construction of the cutoff wall due to the existence of karst areas, karst caves, large areas of goaf and other areas in the underground medium of the mining area. About 600 days after the accident (Fig. 4c), the solute continued to diffuse. Although the solute outside the cutoff wall continued to diffuse with the direction of water flow, it was obvious that the concentration of solute outside the cutoff wall changed little. In addition, the diffusion rate of solute is also reduced due to the presence of low permeability areas. With the passage of time, the solute spread further until 873 days (Fig.4d), the solute have basically spread to all areas within the cutoff wall, and the low-permeability area is gradually slightly polluted. The solute that penetrate the cutoff wall spread slowly around, with a small diffusion rate. At this time, the cutoff wall plays the main control role, but the wall is insufficient to stop the cutoff, resulting in part of the pollution plume spread outside the walls, if not controlled, solute will continue to spread, resulting in pollution of downstream wells.

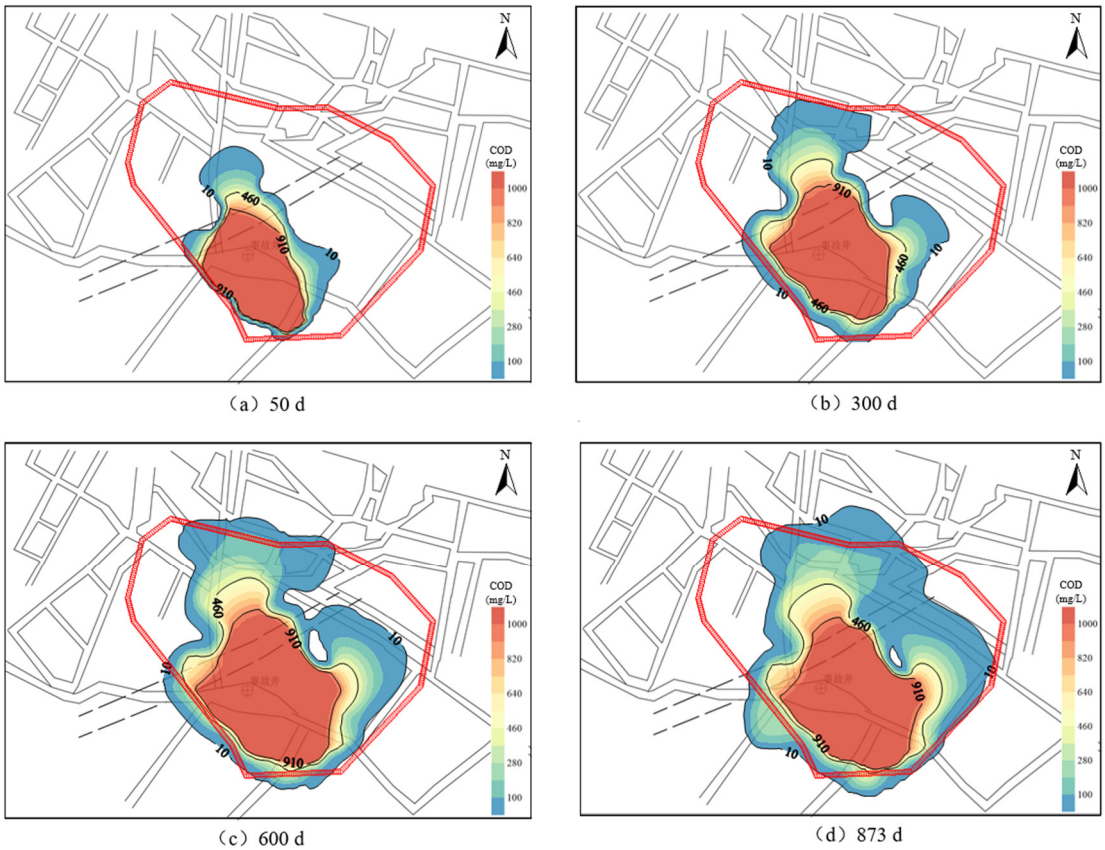


Fig 4. Pollution migration at different periods under the control of cutoff wall

The numerical simulation results show that the vertical cutoff wall can effectively control the diffusion of pollution, mainly because the installation of the vertical cutoff wall greatly changes the groundwater flow field of the polluted site, and the change of the groundwater flow field greatly affects the diffusion path of solute. However, the cutoff walls in different states have different control effects on the pollution plume, and the main parameters controlling the cutoff wall effect are the thickness and hydraulic conductivity[11]. In the process of groundwater pollution prevention and control, cutoff wall with appropriate thickness and hydraulic conductivity can effectively block the diffusion of solute[11]. In the above engineering cases, when the thickness of the cutoff wall is 60 cm, the hydraulic conductivity is 1×10^{-3} m/d, and some solute in the contaminated site diffuse and migrate outside the cutoff wall. In order to evaluate the influence of the hydraulic conductivity of the cutoff wall on pollutant migration and set up efficient pollutant prevention and control measures, we expanded the thickness of the cutoff wall and set its thickness to 90 cm and 120 cm respectively, and set the hydraulic conductivity of the cutoff wall to 1×10^{-4} m/d and 1×10^{-5} m/d respectively (Table 2). The variation of pollutant diffusion range under different thicknesses and hydraulic conductivity was calculated.

Table 2. Parameters of cutoff wall

Thickness / (cm)	Hydraulic conductivity / (m/d)
60	1×10^{-3}
90	1×10^{-3}
120	1×10^{-3}
60	1×10^{-3}
60	1×10^{-4}
60	1×10^{-5}

As shown in Fig.5, the diffusion process of solute is significantly affected by the thickness and hydraulic conductivity of the intercepting wall. With the passage of time, the diffusion rate of solute was observed to slow down gradually, which was mainly due to the blocking effect of the

cutoff wall. Increasing the thickness of the cutoff wall will affect the horizontal diffusion range of solute. When the thickness of cutoff wall is increased from 60 cm to 90 cm, the diffusion range of COD is reduced by 0.8%. When the thickness increased from 90 cm to 120 cm, the diffusion range of COD was reduced by 7.7%.

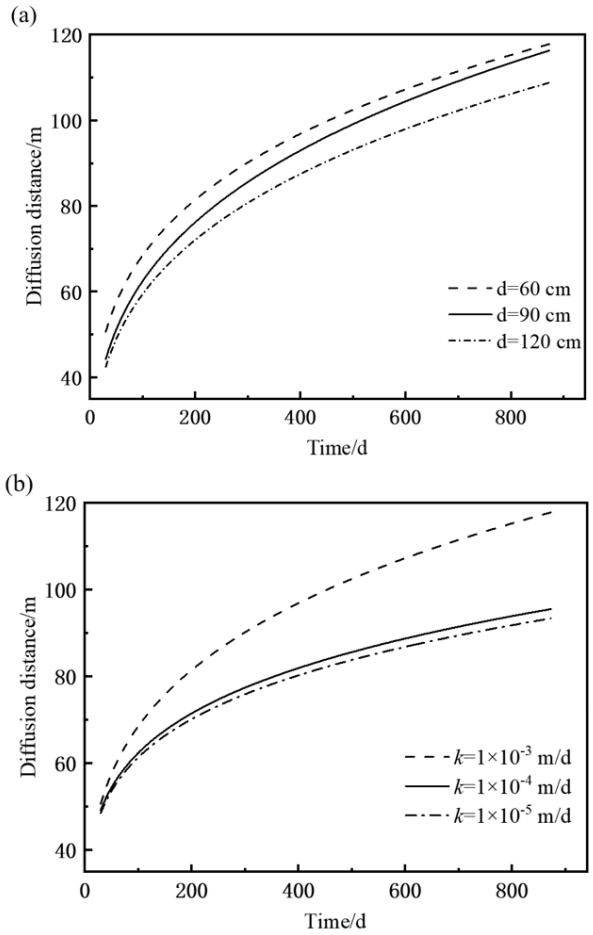


Fig 5. Effects of cutoff wall parameters on pollutant migration and diffusion (a) Effects of cutoff wall thickness. (b) Effects of the hydraulic conductivity of the cutoff wall.

The results show that increasing the thickness of the cutoff wall can effectively slow down the diffusion of COD solute, although the effect is relatively limited. In addition, the reduction of hydraulic conductivity in the cutoff wall plays a significant role in preventing the diffusion of solute. When hydraulic conductivity of the cutoff wall was reduced from 1×10^{-3} m/d to 1×10^{-4} m/d, the diffusion range of solute was reduced to 80.26% of the initial range. With the continuous decrease of hydraulic conductivity of the cutoff wall, although the diffusion range of solute is still decreasing, the reduction rate is relatively slow. The simulated results show that reducing the hydraulic conductivity of the cutoff wall can more effectively control the diffusion of solute in the polluted site, and reduce the migration speed of solute. When setting the cutoff wall in the in-situ site, the cutoff wall parameter with a thickness of 90 cm and hydraulic conductivity of 1×10^{-4} m/d can effectively prevent the diffusion of COD solute to the outside of the cutoff wall, thus polluting the drinking water of nearby residents. In order to reduce the hydraulic conductivity of the cutoff wall, measures such as changing the cutoff wall material and increasing the degree of compaction can be adopted. At the same time, combined with increasing the thickness of the cutoff wall with low construction difficulty, the diffusion of solute can be more economically and efficiently blocked.

5. Conclusion

The pollution characteristics of an abandoned mining area in China were discussed, and the effect of cutoff wall on pollution control was investigated. The influence of different parameters (i.e. thickness, hydraulic conductivity) of vertical cutoff wall on solute transport and diffusion was analyzed. Vertical cutoff walls in polluted abandoned mining areas can effectively control the diffusion of contaminated groundwater. In order to improve the blocking effect of the cutoff wall, the hydraulic conductivity or the thickness of the cutoff wall should be increased by improving the grouting material. However, when the hydraulic conductivity of the cutoff wall increases to a certain value, the permeating strength will not increase significantly. Compared with increasing the thickness, reducing the hydraulic conductivity of the cutoff wall is more effective in controlling the migration of solute in the site. In the practical engineering, in the case of ensuring safety, economic benefits should be comprehensively considered to set a reasonable thickness and hydraulic conductivity of the cutoff wall.

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