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Experimental Study on Dispersion of Unconfined Aquifer in a Site of Jilin City

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ARTICLE INFO	ABSTRACT

Dispersion parameter is an important parameter for the establishment of groundwater solute transport model. The dispersion test uses sodium chloride as a tracer, which was conducted in a site in Jilin City. The standard curve comparison method was used to solve the dispersion parameters of the aquifer under the natural flow field. The test results show that under the natural flow field, the longitudinal dispersion of unconfined aquifer in Jilin City is 0.400m, and the transverse dispersion is $1.933 \times 10^{-5} \sim 6.557 \times 10^{-3}$m; while the longitudinal dispersion coefficient is 0.246m^2/d, the transverse dispersion coefficient is $1.191 \times 10^{-5} \sim 4.039 \times 10^{-3}$m^2/d. The above results can provide an important parameter basis for the establishment of groundwater solute transport model, the accurate prediction of temporal and spatial variation of pollutant concentration in groundwater and the formulation of groundwater pollution prevention and control scheme.

1. Introduction

When establishing a model of solute transport in groundwater to study the migration law of pollutants in groundwater, the accurate determination of dispersion parameters is one of the key links to ensure the reliability of the model, which directly affects the accuracy and accuracy of the model prediction results [1]. The current effective method for determining dispersion parameters is to conduct dispersion tests. Dispersion test is divided into indoor test and field test. Because of the scale effect of dispersion parameters [2], in order to ensure

the reliability of dispersion parameters, most scholars at home and abroad conduct field dispersion tests. For field dispersion tests, most of the domestic scholars focus on two-dimensional dispersion and radial hydrodynamic dispersion in one-dimensional flow field.

The two-dimensional dispersion test of one-dimensional flow field is generally carried out under natural flow field. This method can obtain more accurate dispersion parameters. For example, Wu Yaoguo and others carried out a two-dimensional dispersion test of one-dimensional flow field in Benxi City, and the dispersion parameters of unconfined aquifer in the test site were determined by linear

graphic method[3]; Jiang Xuemin, Shao Jingli, et al .conducted a 2D dispersion test of one-dimensional flow field in a mining area in Inner Mongolia, and solved dispersion parameters by correlation coefficient polar method[4]. A two-dimensional dispersion test of one-dimensional flow field was carried out in Kashi area by using different analytical methods to solve the dispersion parameters[5].

Radial hydrodynamic dispersion test is carried out under the artificial flow field formed by pumping or water injection. For such issues, Yu Hong, Yuan Wei, Li Shiyu, Mei Jie[6-9]and others conducted dispersion tests in different regions. Zhang Yinmei[10] showed through indoor reserch that the dispersion parameter increases with the increase of hydraulic gradient, and the radial hydrodynamic dispersion test artificially increases the velocity and hydraulic gradient of groundwater. In addition, the dispersion solution method commonly used in radial hydrodynamic dispersion test can not obtain the transverse dispersion parameters of water-bearing medium.

Based on this, in order to obtain the dispersion parameters of unconfined aquifer at a site in Jilin City, this paper selects a test site in Jilin City to carry out two-dimensional dispersion test of one-dimensional flow field under natural flow field, and use the standard curve comparison method to solve the field dispersion parameters.

2. Overview of the Study Area

The dispersion test site is located in Longtan District, Jilin City, and located in Songhua River secondary terrace. The groundwater type in the study area is loose rock pore phreatic water, which mainly occurs in the Quaternary Holocene gravel layer. The average buried depth of bottom plate of unconfined aquifer is 13m. The groundwater level varies greatly within a year, with the high water period of 4~7 m and the dry water period of 3~4 m. Groundwater flows are generally north-south, and the hydraulic gradient is about 2/1000. Based on site drilling data, the stratigraphic lithology of the study area from top to bottom is backfill (0~1.5 m), silty clay (1.5~4 m), fine sand (4~7 m), gravel (7~13m), fully weathered granite (below 13m). Based on the results of pumping tests conducted in the study area, the average permeability coefficient K of the aquifer in the study area is 77 m/d.This provides parameter basis for the establishment of groundwater solute transport model and the formulation of restoration plans in this area.

3. Test Methods

3.1 Tracer Selection

Ideal tracers used in field dispersion tests should be less toxic, less easily adsorbed by solid particles in aquifers, more

sensitive and less expensive[11]. At present, the main tracers used at home and abroad can be divided into four categories: ionic compounds, artificial radioisotopes, organic dyes and fluoride[12]. Considering that artificial radioisotope is known as radioactive hazard and that organic dyes are easily adsorbed by solid particles in the aquifer, in this experiment, sodium chloride (NaCl), which is less toxic, cheap and easy to monitor, is selected as tracer for field dispersion tests.

3.2 Placement of Test Wells

In general, monitoring wells in field dispersion tests are arranged along both sides of the main groundwater line[13]. In this test, the test wells respectively arranged along the main groundwater line in a circular arc with a radius of 2m, 4m and 6 m from the tracer injection well. The test wells include 1 tracer injection well ,3 rows (12) tracer monitoring wells, all of which are complete wells, with well edpth of 13m; design dispersion angles of 10° and 20°, respectively, as shown in Figure 1.
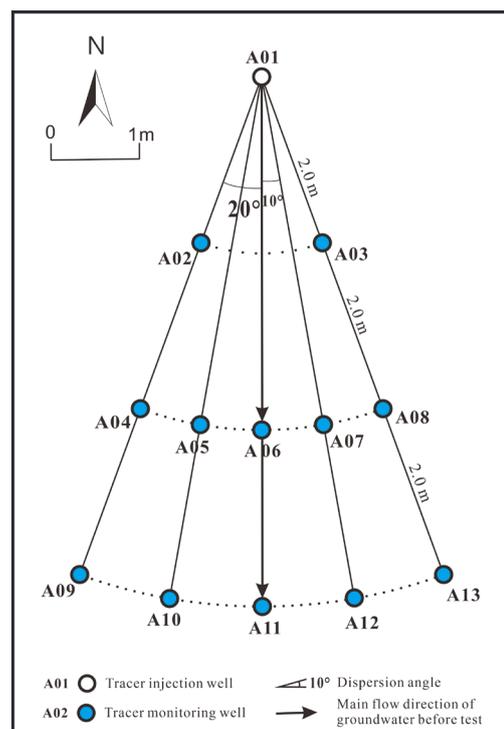

Figure 1. Plan of well for dispersion test

4. Test Process

4.1 Trial Preparation

(1) Monitoring of the initial groundwater level and monitoring of the water level before each sampling after the start of the test to correct the groundwater mainstream.

(2) The background concentration of chloride ions in each test well is measured, and the average background

value of groundwater chloride ions in this test area is 29.24 mg/L.

(3) Each monitoring well is equipped with a water level meter, a sampler and a test data monitoring record sheet.

(4) A solution of silver nitrate with known concentrations to be used for titration to test chloride concentration in groundwater.

(5) Preparation of tracer solution. The dispersion test added 60 kg of iodine-free edible salt to a plastic container containing 450 L of pure water and stirred to accelerate dissolution until the excess salt at the bottom was no longer dissolved. The concentration of chloride ion in tracer solution was 129.42 g/L.

4.2 Tracer Delivery

When the test begins, the tracer solution is injected into the well (A01), and the tracer time is used as the starting time of the dispersion test. Do not make the injection well water level too high (generally above the initial water level within 50 cm) to avoid the formation of groundwater mound, which has a significant impact on the water movement of the test site.

4.3 Data Monitoring

After the tracer solution is injected into the well (A01) of the test area, the sampling in the monitoring well of the test area is started immediately, and the buried depth of the groundwater level is determined before each sampling. At the beginning of the experiment, samples were taken every 1 hour and the groundwater level was measured. After sampling, the Cl⁻ in water samples were determined by silver nitrate titration concentration when the concentration of Cl⁻ was greater than the background value, the sampling time was encrypted for 30 minutes, when the Cl⁻ Concentration restored to the background value of Cl⁻ concentration in groundwater, returned to sampling every 1 hour and the monitoring stopped when Cl⁻ concentration in groundwater is basically stable as the background valu. Through continuous sampling and chloride ion concentration measurement, the Cl⁻ concentration curve of each tracer monitoring well can be obtained with time.

5. Calculation of Dispersion Parameters and Results Analysis

5.1 Calculation Method of Dispersion Parameters

There are two methods for calculating dispersion parameters in field dispersion test: analytical method and numerical method. The dispersion parameters of this experiment are calculated by the standard curve comparison method in the analytical method.

5.1.1 Calculation Method of Dispersion

The groundwater field in the test site is composed of loose rock type pore phreatic water. Because the hydraulic gradient of the ground water is small (about 2/1000;), the groundwater flow field in the test area is generalized into one-dimensional groundwater flow field with horizontal infinite extension and equal thickness. The tracer migration in groundwater conforms to the two-dimensional hydrodynamic dispersion equation of diving, and its mathematical model such as formula (1)[14] as shown:

$$\begin{pmatrix} \dfrac{\partial C}{\partial t} = D_L \dfrac{\partial^2 C}{\partial x^2} + D_T \dfrac{\partial^2 C}{\partial y^2} - V\dfrac{\partial C}{\partial x}; \\ C(x,y,0) = C_0, x, y \neq 0; \\ C(\pm\infty, y, t) = C_0, \\ C(x, \pm\infty, t) = C_0; t \geq 0; \\ \int\limits_{-\infty}^{\infty}\int\limits_{-\infty}^{\infty} n_e(C - C_0)\ dxdy = M; \end{pmatrix} \quad (1)$$

In the formula: C is the concentration of tracer in groundwater(g/L); C_0 is the tracer background concentrationin the groundwater in the test area(g/L); x and y are the longitudinal and transverse migration distances of the tracer(m) ; D_L and D_T are vertical and horizontal dispersion coefficients(m²/d); V is the actual average flow rate of groundwater(m/d); n_e is the effective porosity; M is the amount of tracer injection per unit thickness of aquifer(kg/m); T is time (d).

Analytical solution of mathematical model (formula (1)) for two-dimensional dispersion instantaneous injection of tracer in one-dimensional flow field[15]To:

$$C(x, y, t) = \frac{M/n}{4\pi t(D_L D_T)^{-\frac{1}{2}}} \exp\left[-\frac{(x-Vt)^2}{4D_L t} - \frac{y^2}{4D_T t} \right] \quad (2)$$

If we ignore molecular diffusion to $D_L = \alpha_L V$, $D_T = \alpha_T V$ replaced by the above formula:

$$C(x, y, t) = \frac{M/n}{4\pi Vt(\alpha_L \alpha_T)^{-\frac{1}{2}}} \exp\left[-\frac{(x-Vt)^2}{4\alpha_L Vt} - \frac{y^2}{4\alpha_T Vt} \right] \quad (3)$$

In the formula: α_L, α_T are longitudinal and transverse dispersion (m).

In a dimensionless form:

$$C_R(a, t_R) = kt_R^{-1} \exp\left(-\frac{a^2 + t_R^2}{4t_R} \right) \quad (4)$$

Among them:

$$c_R = \frac{c - c_0}{c_{max} - c_0} \tag{5}$$

$$a = (x_R^2 + y_R^2)^{\frac{1}{2}} \tag{6}$$

$$x_R = x / \alpha_L \tag{7}$$

$$y_R = y / (\alpha_L \alpha_T)^{\frac{1}{2}} \tag{8}$$

$$t_R = Vt / \alpha_L \tag{9}$$

$$k = t_{R\max} \exp\left(\frac{a^2 + t_{R\max}}{4 t_{R\max}} \right) \tag{10}$$

$$t_{R\max} = (a^2 + 4)^{\frac{1}{2}} - 2 \tag{11}$$

According to formula (4), when the value of a is constant, the relationship curve of $c_R \sim t_R$ can be obtained. After assigning a series of values to 'a', a series of relationship curve clusters of $c_R \sim t_R$ can be obtained, and the $c_R \sim t_R$ measuring plate curve (figure 2).

A series of relational curve clusters to obtain $c_R \sim t_R$ Measuring plate curve (Figure 2).
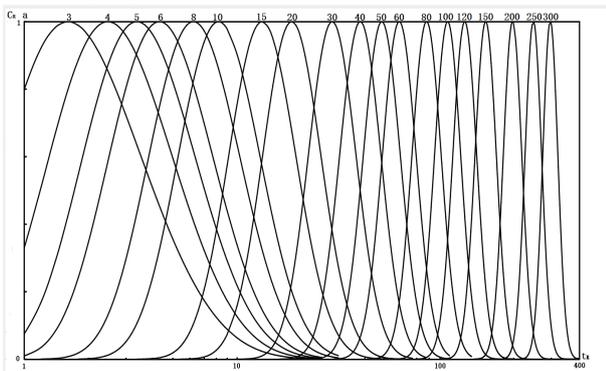

Figure 2. $c_R \sim t_R$ Standard gauge plate

Finally, the formula of dispersion degree can be obtained by the transformation of formula (6),(7),(8) and (9):

$$\acute{a}_L = x_i / a_i \tag{12}$$

$$\acute{a}_T = \frac{y_i^2}{\acute{a}_L (a_i^2 - x_i^2 / \acute{a}_L^2)} \tag{13}$$

Among them: x_i and y_i are the vertical and horizontal coordinates of the i well (m); a_i is the a value of matching the observation curve of i well with the curve of measuring plate.

Convert the measured concentration values of each monitoring well into dimensionless concentration C_R. Then, the measured chloride concentration curve obtained from the groundwater mainstream upward monitoring well (y=0) is matched with the measuring plate curve (the vertical and horizontal coordinate scale of the two is the same), and the corresponding a value is obtained. According to formula (12), the longitudinal dispersion α_L is calculated. The measured curve obtained from the monitoring well (y≠0) deviating from the mainstream of groundwater is matched with the measuring plate curve (the vertical and horizontal coordinate scale of the two is the same), and the corresponding a value is obtained, and then calculate the transverse dispersion α_T according to the α_T value and formula (13).

5.1.2 Calculation Method of Dispersion Coefficient

The longitudinal dispersion α_L and the lateral dispersion α_T of the phreatic aquifer calculated from equations (12) and (13) are substituted into the following equations:

$$D_L = \alpha_L V \tag{14}$$

$$D_T = \alpha_T V \tag{15}$$

The longitudinal dispersion coefficient D_L and the lateral dispersion coefficient D_T of the site diving aquifer can be obtained.

V in formula (14) and formula (15) is the actual average velocity of groundwater, which can be calculated according to Darcy's law. The formula is as follows:

$$V = KI / n_e \tag{16}$$

In the formula: K is the permeability coefficient (m/d); I is the hydraulic gradient; n_e is the effective porosity.

5.2 Calculation of Dispersion Parameters for Unconfined Aquifer

According to the groundwater flow field diagram (Fig .3) drawn from the groundwater level in the test period, the actual groundwater mainstream direction is A01-A07-A12 direction. Therefore, the vertical dispersion of the diving aquifer in the site is calculated according to the method in 5.1.1, and the other monitoring wells are used to calculate the transverse dispersion of the groundwater aquifer.
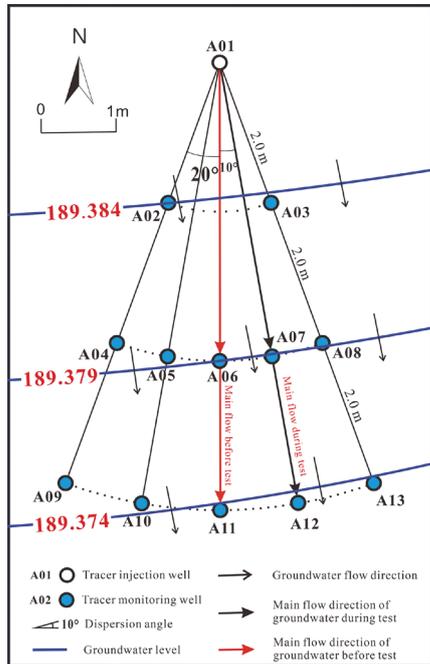
Figure 3. Field flow pattern of the site during the test

A04, A05, A06, A08, A09, A13 measured chlorine ion concentration diachronic curve of the monitoring well is fitted to the standard plate, and the fitting result diagram is shown in figure 4.
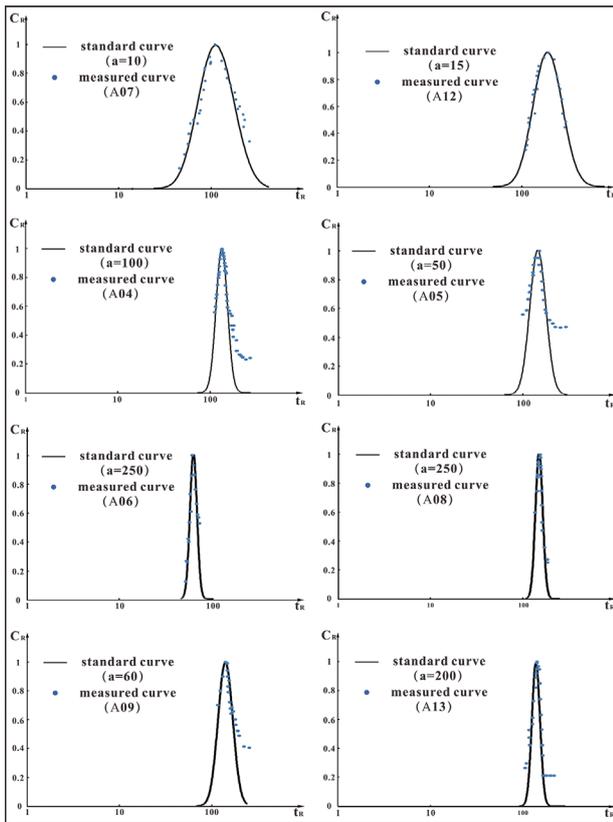

Figure 4. Matching diagram of measured concentration curve and plate curve of each monitoring well

5.3 Results and Analysis

5.3.1 Calculation of Dispersion

The a values and vertical and horizontal coordinates (x_i, y_i) of each monitoring well were substituted into equations (12) and (13) by fitting the measured chloride ion concentration of each monitoring well in 5.2 and the plate curve, and the dispersion results of the site unconfined aquifer were calculated respectively, as shown in Table 1.

Table 1. Summary of calculated results of aquifer dispersion

Well No	A07	A12	A04	A05	A06	A08	A09	A13
Longitudinal dispersion(α_L/m)	0.400	0.400	\	\	\	\	\	\
Transverse dispersion (α_T/m)	\	\	1.008×10^{-3}	1.940×10^{-3}	1.933×10^{-5}	1.933×10^{-5}	6.557×10^{-3}	6.822×10^{-5}

Table 1 shows that the longitudinal dispersion of unconfined aquifer in Jilin site is 0.400 m, the transverse dispersion is $1.933 \times 10^{-5} \sim 6.557 \times 10^{-3}$ m. The lateral dispersion obtained from the monitoring well (A04, A05, A09) on the west side of the A01-A07-A12 is generally greater than that obtained from the monitoring well (A08, A13) on the east side, which is inferred to be caused by the heterogeneity of the diving aquifer in the site.

5.3.2 Calculation of Dispersion Coefficient

According to formula (14) and formula (15), we can calculate the dispersion coefficient D_L and D_T of unconfined aquifer.

The permeability coefficient (K) of unconfined aquifer in this dispersion test site is 77 m/d, the hydraulic gradient (I)is 2/1000; according to the hydrogeological manual, the effective porosity n_e of sand gravel unconfined aquifer has an empirical value of 0.25; substituting K, I and n_e into equation (16), the actual average velocity V of groundwater in the unconfined aquifer is 0.616 m/d.

Substituting the actual average velocity V of groundwater in the phreatic aquifer of the site into equations (14) and (15),the longitudinal dispersion coefficient D_L and the lateral dispersion coefficient D_T of the site can be calculated respectively.The results are shown in Table 2.

Table 2. Summary of calculations of the dispersion coefficient of the unconfined aquifer

Well No	A07	A12	A04	A05	A06	A08	A09	A13
Longitudinal dispersion coefficient (D_L/m· d^{-1})	0.246	0.246	\	\	\	\	\	\
Transverse dispersion coefficient (D_T/m·d^{-1})	\	\	6.209×10^{-4}	1.195×10^{-3}	1.191×10^{-5}	1.191×10^{-5}	4.039×10^{-3}	4.202×10^{-5}

According to Table 2, the longitudinal dispersion coefficient of diving aquifer in Jilin site is 0.246 m^2/d, and ransverse dispersion coefficient is 1.191×10^{-5} ~4.039×10^{-3}m^2/d.

5.3.3 Scale Effect of Dispersion

By comparing the dispersion of monitoring wells with 4 m, 6m distance tracer injection wells, the effect of scale effect on dispersion is discussed.

Table 3. Comparison of Dispersion Size at Different Migration Distance

Dispersion angle	Monitoring well distance from tracer injection well (m)	α_T of transverse dispersion (m)
30°	4	1.008×10^{-3}
	6	6.557×10^{-3}
10°	4	1.933×10^{-5}
	6	6.822×10^{-5}

Table 3 shows that, when the dispersion angle is 10°, the transverse dispersion of the sand-gravel aquifer in the study area calculated by the monitoring well at 6m distance from the injection well is 3.5 times larger than that calculated by the tracer concentration in the monitoring well at 4m distance from the injection well;when the dispersion angle is 30°, this value is expanded to 6.6 times. The results show that the transverse dispersion of sand and gravel aquifer increases with the increase of tracer migration distance, and the larger the dispersion angle, the greater the transverse dispersion. The studies of Domenico(1984) and Gelhar (1992) also have come to a similar conclusion: in the same aquifer, the dispersion increases with the increase of solute migration distance[16-17].

6. Conclusion

(1) The dispersion parameters of the unconfined aquifer at the site were obtained by field dispersion tests :the longitudinal dispersion is 0.400 m,and the transverse dispersion is 1.933×10^{-5}~6.557×10^{-3}m; the longitudinal dispersion coefficient is 0.300 m^2/d, and the transverse dispersion coefficient is 1.450×10^{-5} ~4.918×10^{-3}m^2/d.

(2) This field dispersion test confirms the existence of diffusion parameter scale effects in field tests. In the same aquifer, the transverse dispersion increases with the increase of tracer migration distance, and the larger the dispersion angle, the greater the dispersion.

(3) The method of using standard curve comparison method to solve dispersion parameters of unconfined aquifer is simple and quick, the result of calculation is more accurate and the applicability is wide, but there are some subjective errors when the measured curve and standard curve fit in the calculation process.

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