

Simulation and Prediction of Groundwater Pollution based on Modflow Model in a Certain Landfill

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Abstract. Solid waste landfill will produce leachate during its landfill phase and after the closure. The pollutants will pollute the regional groundwater. A three-dimensional coupled numerical model of groundwater flow and solute transport was established based on Modflow by researching a solid landfill project to simulate the migration process and range of Cr^{6+} in leachate when both horizontal and vertical anti-seepage layers are damaged. The results show that the migration range of Cr^{6+} is small and the pollution on groundwater is weak. Therefore, the feasibility of landfill disposal of solid waste in this area is proposed, which provides a theoretical basis for landfill disposal.

1. Introduction

The municipal solid waste landfill will produce leachate during its landfill phase and after the closure. Once the seepage occurs, the leachate will enter the groundwater through the vadose zone, and the pollutants will inevitably cause pollution to the regional groundwater^{[1][2]}. Therefore, studying the migration laws and processes of pollutants in leachate is of great significance for evaluating the degree of pollution to groundwater environment. In this paper, the three-dimensional coupled numerical model of groundwater flow and solute transport is established based on Modflow^{[3][4]}, by researching a solid waste landfill project as an example to simulate the migration of landfill leachate pollutants and evaluate its impact on groundwater environment under the condition of horizontal anti-seepage and vertical anti-seepage layer damage.

2. Project Overview

The landfill project is located in the urban area of Taihe City, 10km north of the River Ying. The main river in the city is the River Ying, with a total length of 619.0km, flowing through Jieshou City, Fuyang City and other places. Its functions are mainly farmland irrigation, shipping and industrial water. The project will be constructed in two phases. The first phase covers an area of 45.5 acres with the landfill volume being 212,000 m³; The second phase covers an area of 29.8 acres with the landfill volume being 302,000 m³. After the project is completed, the service period is 13 years^[5]. The landfill is an incineration landfill for solid waste and its main pollution factors are Cr^{6+} , Pb, Cu, Zn, As, Cr, and Hg.

2.1. Hydrogeological conditions

According to the engineering measurement data, the stratum within the project depth of exploration can be divided into four layers, as follows:

- The first layer of filling (Q4^{ml}): variegated, loose, mainly composed of cohesive soil. The layer is distributed throughout the field and has a layer thickness from 0.2 to 2.5 meters.



- The second layer of silty clay (Q4al+pl): This layer is only distributed on the long-term landfill and the east side of the dike, with a layer thickness from 4.1 to 7.6 meters.
- The third layer of clay (Q4al): the layer is distributed throughout the field, the local section is not exposed, and the layer thickness is from 0.6 to 7.7 meters.
- The fourth layer of schist: grayish yellow, strong weathering, the upper part of the layer has been weathered into pieces, containing mica pieces, the lower part is blocky. The layer is distributed throughout the field and has a layer thickness from 2.8 to 3.7 meters.

2.2. Aquifer groups

The area belongs to the hydrogeological zone along the hilly plains. It can be divided into four groups: metamorphic rock bedrock fissure water-bearing rock group, clastic rock bedrock fissure water-bearing rock group, carbonate rock karst fissure water-bearing rock group and loose rock-like pore water-bearing rock group. In the central part of the land and river valley, there is a large area of loose aquifer-type aquifers in the Cenozoic with water depth from 2.0 to 6.0 meters, and the single-hole water inflow is generally less than 10m³/d. The average annual precipitation in the area is 1031.2mm, and the precipitation is mostly concentrated in June to August, accounting for about 48% of the annual precipitation. The source of groundwater recharge in the area is mainly atmospheric precipitation. Under natural conditions, the groundwater runoff direction of the project area is generally from west to east, and the drainage mode is mainly phreatic evaporation^[6].

3. Numerical model

At present, Modflow is a widely used visualized groundwater seepage model software package. It has been successfully applied to the evaluation of groundwater resources based on its numerical method and widely used visualized groundwater seepage model software in the world. Many scholars have carried out more in-depth analysis and research in this regard^[7]. This paper only introduced the hydrogeological conceptual model and the corresponding mathematical model in the numerical model to highlight the analysis focus.

3.1. Hydrogeological conceptual model

Considering the recharge, runoff and discharge conditions of the landfill site in the district, the calculation scope is based on the administrative areas of the townships and towns near the district. Because the research area is relatively flat and there are reservoirs around the selected simulation area, Therefore, the simulated boundaries are generalized to the fixed head boundary^{[8][9]}. A hydraulic connection occurs between the aquifers and is generalized to heterogeneous anisotropy. At the top of the simulated area, the recharge of atmospheric rainfall and agricultural irrigation infiltration is generalized to the recharge boundary, and the groundwater is evaporated through it, which is generalized as the discharge boundary. A thick layer of cohesive soil is distributed at the bottom, and the water permeability is weak, which is generalized to a water-blocking boundary. According to the hydrogeological conditions in the evaluation area, the scope of the simulation area is shown in **Figure 1**, and the calculated area is 36,000 m². The simulation zone profile is divided into top-down:

- loose layer weak aquifer (group), consisting of the upper layer of the Holocene Fengle town formation (Q4) and the Upper Pleistocene and lower Shu formation (Q3), with a layer thickness from 4.8 to 12.6 meters;
- The confined aquifer (group), mainly composed of metamorphic rock series such as quartz schist, and the controlled thickness of this layer is about 9 meters.

Due to the small scale of groundwater exploitation in the simulation area, the groundwater flow field is basically in a natural state, and the various elements of the water flow change with time^[10]. The seepage is basically in accordance with Darcy's law^{[11][12]}, and the groundwater flow in the simulated area is generalized into a heterogeneous isotropic three-dimensional groundwater flow system^{[13][14]}.

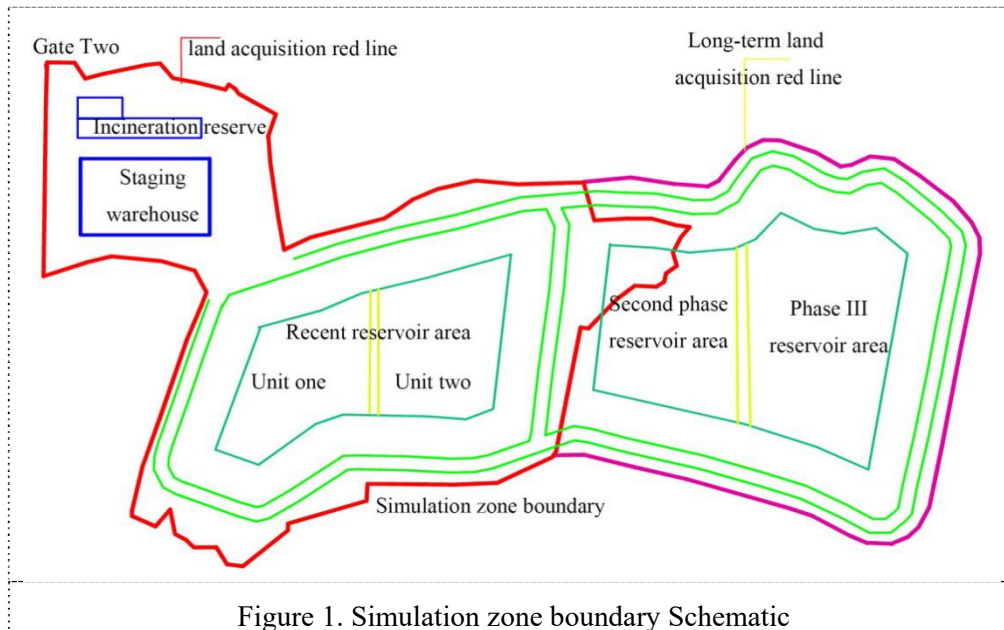


Figure 1. Simulation zone boundary Schematic

3.2. mathematical model

According to the hydrogeological model of the generalization of the simulation area, the corresponding mathematical model is established:

$$\frac{\partial}{\partial x} \left(k_{xx} \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_{yy} \frac{\partial H}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_{zz} \frac{\partial H}{\partial z} \right) + w = \mu_s \frac{\partial H}{\partial t} \quad (x, y, z) \in \Omega, t > 0 \quad (1)$$

$$H(x, y, z, t)|_{t=0} = H_0(x, y, z) \quad (x, y, z) \in \Omega \quad (2)$$

$$H(x, y, z, t)|_{s_1} = H_1(x, y, z) \quad (x, y, z) \in S_1, t > 0 \quad (3)$$

$$k_n \frac{\partial H}{\partial n} |_{s_2} = q(x, y, z, t) \quad (x, y, z) \in S_1, t > 0 \quad (4)$$

Where, Ω is the groundwater seepage zone; H is the groundwater head (m); S_1 is the Dirichlet boundary, S_2 is the second type boundary; k_{xx} , k_{yy} and k_{zz} are respectively the permeability coefficients (m/d) of the main directions of x , y and z , and w is the source and sink term, including precipitation infiltration replenishment, river infiltration replenishment, pump output replenishment, etc. (m^3/d).

μ_s is the water storage rate (1/m); $H_0(x, y, z)$ is the initial head (m), $H_1(x, y, z)$ is the initial head (m) of the Dirichlet boundary, and $q(x, y, z)$ is the second type of boundary unit area flow function (m^3/d). n is the outer normal direction on the boundary S_2 .

The mathematical model of groundwater solute transport established this time:

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial x_i} \left(\theta D_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_i} (\theta v_i C) + q_s C_s + \sum R_n \quad (5)$$

Where, C is the dissolved phase concentration of the components in groundwater, ML^{-3} ; θ is the porosity of the formation medium, dimensionless; t stands for time, T ; x_i is the distance along the axial direction of the Cartesian coordinate system, L ; D_{ij} is hydrodynamic dispersion Coefficient tensor, $L^2 T^{-1}$; V_i is the actual flow velocity of pore water, LT^{-1} ; q_s is the flow rate per unit volume of aquifer, representing source and sink, $L^3 T^{-1}$; C_s is the concentration of components in the source or sink stream, ML^{-3} ; $\sum R_n$ is a chemical reaction term, $\text{ML}^{-3} T^{-1}$.

(1) Initial conditions

The initial concentration at the supply concentration boundary is set to C_0 , and the rest is 0 mg/L. The expression is as follows:

$$\begin{cases} C(x_i, y_j, z_k, 0) = C_0 \\ C(x, y, z, 0) = 0 \end{cases} \quad (6)$$

(2) Boundary conditions

The boundary of the aquifer is used as the second type of boundary condition, and the layers do not cross. As follows (Γ_2 is the Neumann boundary):

$$-D_{ij} \frac{\partial C}{\partial x_j} = 0 \quad (\Gamma_2, t > 0) \quad (7)$$

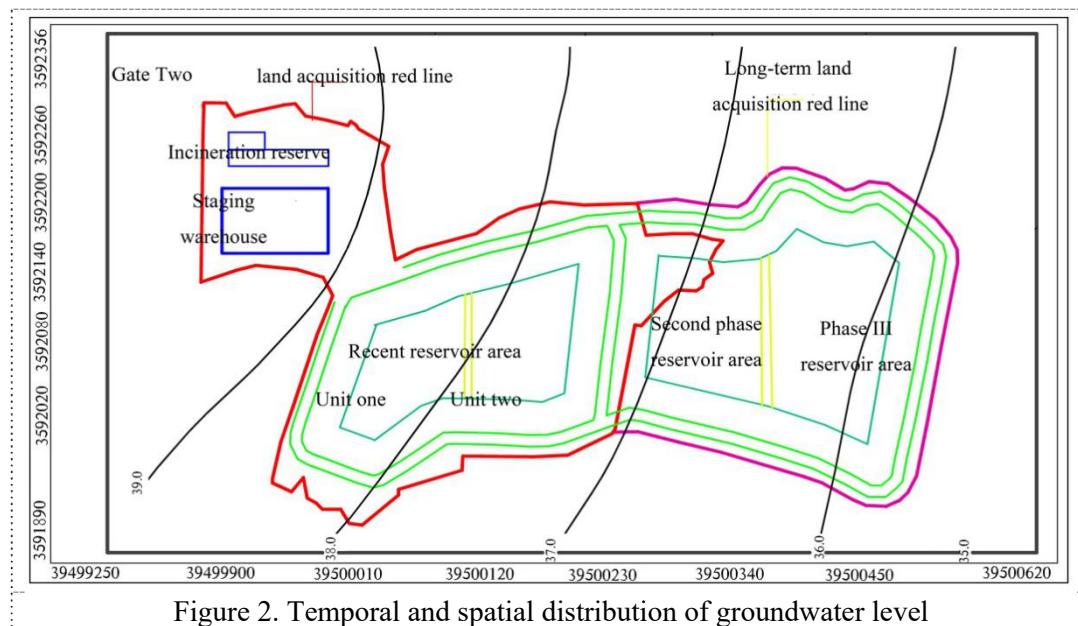


Figure 2. Temporal and spatial distribution of groundwater level

3.2.1. Model identification

(1) Groundwater level fitting

The time-space distribution of the groundwater level is obtained after solving the model (As shown in **Figure 2**). In addition, due to the parameter partition and the initial value of the parameters, the actual hydrogeological conditions of the simulation area are objectively reflected. After repeated adjustments, the model identification has achieved ideal results.

(2) Hydrogeological parameters

In order to accurately describe the hydrogeological conditions of the evaluation area, the model partitioned the simulated area according to the hydrogeological map and the results of the drilling materials, and finally obtained the aquifer parameters. Referring to the drilling data of the simulation area and its hydrogeological conditions, the parameters of the simulation area are obtained, as shown in **Table 1**.

Table 1. Simulation area parameter value.

Stratum	Permeability coefficient (m/d)	Specific yield	Degree of porosity	Dispersion degree (m)
First Aquifer	0.033	0.02	0.15	10
Second Aquifer	0.0006	5E-6	0.05	10

3.2.2. Generalization of model conditions

In this simulation, the concentration boundary of pollutants is set in the form of surface source, and the location of pollutants is generalized according to the actual design, focusing on the diffusion of pollutants under convection and dispersion. In order to analyze the impact of the pollutants in the leachate on the surrounding groundwater environment, the corrected water flow model is used to select the pollution factors in the landfill that have a great impact on water quality and may lead to drinking water safety problems^[15]. As a representative pollutant, Cr^{6+} is used to predict the process of pollutants entering groundwater in the case of damage to both horizontal and vertical impermeable layers. The simulation prediction time is set to a maximum of 20 years (including service period of 13 years, 7 years after service period). The simulation shows the time-space variation process of the pollutant concentration to determine the scope and extent of the groundwater environment in this area. In the process of predictive calculation, the impact of pollutant migration on the downstream is considered, that is, considering the pollution range and pollution degree of pollutants downstream, the temporal and spatial distribution of pollutants is expressed. The determination of the initial concentration value is determined by reference to the water quality monitoring results of the previous landfill sampling.

4. Model calculation

(1) The landfill has horizontal and vertical impermeable layers. The composite liner adopts a high-density polyethylene anti-seepage film with a thickness of 1.0 mm and a permeability coefficient, $k \leq 1 \times 10^{-7}$ cm/s; the bottom of the landfill uses natural silty clay as a horizontal anti-seepage layer; the vertical anti-seepage layer adopts a layer of high-density polyethylene film having a thickness of 600 mm and a permeability coefficient, $k \leq 1 \times 10^{-7}$ cm/s. Add a layer of bentonite waterproof blanket extending underneath to the clay layer for 3 meters. The vertical impermeable layer has an area of about 18,000 m². This time, it is assumed that the landfill has a leak, and the location is on the east side of the most dangerous plant area that is most likely to affect other downstream water users. Cr^{6+} pollutants migrate as ground source pollution with groundwater. According to the engineering analysis report, the concentration flux of the upper boundary of Cr^{6+} contaminants is 3 mg/l.

(2) The water flow and solute models were combined to obtain the predicted results of Cr^{6+} contaminant transport by the Modflow software^[16]. The operation period of the landfill is 13 years, and the transport situation of the 13th year of the pollutant leakage and the end of the 20th year are shown in **Figure 3** to **Figure 6**, respectively.

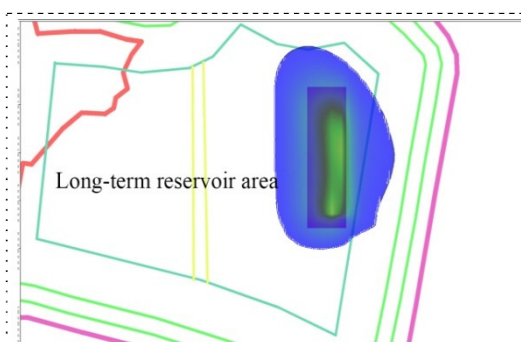


Figure 3. Distribution of Cr^{6+} concentration at the end of 13 years in the horizontal direction.

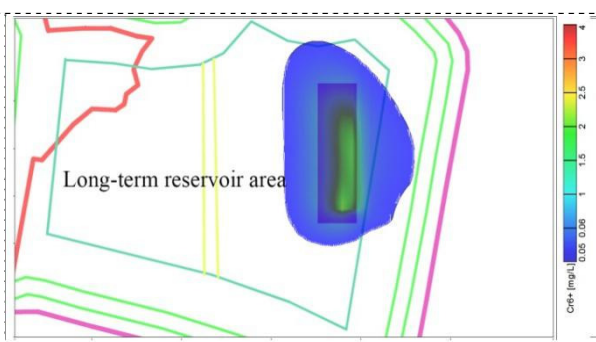


Figure 4. Distribution of Cr^{6+} concentration at the end of 20 years in the horizontal direction.

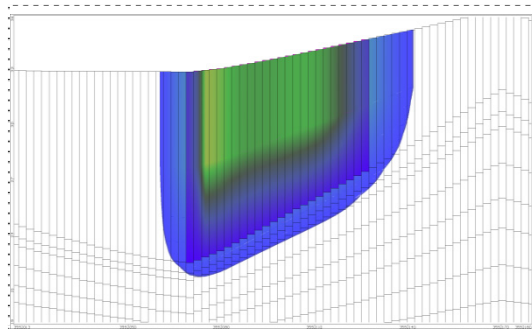


Figure 5. Distribution of Cr^{6+} concentration at the end of 13 years in the vertical direction.

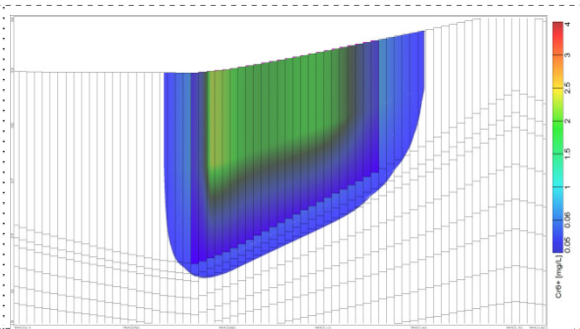


Figure 6. Distribution of Cr^{6+} concentration at the end of 20 years in the vertical direction.

We can analyze it from the above figures:

- At the end of the 13th year, the maximum migration distance of the pollution factor Cr^{6+} will be 30.2m, the maximum migration distance in the vertical direction will be 8.3m, and the concentration at the center point will be 5mg/l.
- At the end of the 20th year, the maximum migration distance of the pollution factor Cr^{6+} will be 41.1m, the maximum migration distance in the vertical direction will be 10.2m, and the concentration at the center point will be 3mg/l.

5. Conclusion

(3) After the leak, the landfill leachate mainly diffuses to the surrounding area in the weak aquifer, and then slowly leaks downward. In the case of damage of the anti-seepage layer, since the anti-fouling performance of the clay layer at the bottom is medium, the pollutants will slowly infiltrate into the karst aquifer after the leakage. But the simulation results show that the concentration value of the pollutants can still meet the Class III standard of the Groundwater Quality Standard after the end of the simulation period;

(4) The horizontal migration range of leachate pollutants in the landfill after the expiration of the service period is still small and does not exceed the long-term planning scope of the plant;

(5) The relevant parameters of this simulation calculation are conservative, and factors such as soil block and biodegradation are not considered. Therefore, the predicted results are theoretically too large. In the case of damage to the impermeable layer, the leachate pollutant level and vertical migration range are small. As a result, the leachate produced at the landfill has less impact on the local groundwater environment.

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