Economic analysis of groundwater contamination control in landfills of coalmine subsidence area

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Abstract. There are a great number of irregular landfills in urban and rural areas, some of which have caused severe contamination in the soil environment. It has been of great practical significance to study the leachate migration with different control measures. From the perspective of technical feasibility and economic rationality, the coupling numerical model of groundwater seepage and solute transport is established and the migration processes of leachate are analyzed under different measures. In addition, the effectiveness of control measures and engineering cost are also comprehensively analyzed. The results show that the leachate has reached the downstream drinking wells which have caused the contamination risks after 15 years, while the combination of horizontal and vertical impervious measures can meet the design requirements for 30 years. Finally, the control effects and engineering cost of different measures can provide significant basic data for the seal design of irregular landfill site.

1. Introduction
In recent decades, the demand of energy leads to the extensive development of coal mining activities with the rapidly developing of community economy in China, resulting in a series of geological problems in coal mine subsidence area[1,2]. Some coal mining subsidence areas are set as irregular landfills due to the lack of laws and regulations and long-term development planning which are generally not taken control measures, and have become soil and groundwater potential contamination sources, especially the capacity of large-scale landfills are large, thus once the leachate infiltrates into underground which will cause huge contamination risks to the soil and groundwater. The contamination control measures of regular landfills have the characteristics of the long construction period, high cost[3], secondary contamination and other hidden dangers[4-10]. Therefore, it is of great practical significance to predict the process of groundwater contamination, and evaluate the control effect and economic cost with different control measures.

At present, the effectiveness and assessment of different measures have been discussed in some researches[11-14], but there is still lack of study on optimization of control measures and rationality of economic cost of researches in the coal mine subsidence area. In this paper the seal of landfill site in coal mine subsidence area is studied based on Groundwater modeling system in Huainan of Anhui province, and the groundwater seepage and solute transport model is established, the migration process of contaminant is simulated, furthermore, the control effect and economic cost with different measures are analyzed in order to provide the basic design of contamination control measures in the irregular landfill site.
2. Simulation methods

2.1. General situation of the study site

The study area is located in the middle reaches of Huaihe with three strata: (1) the thickness of first miscellaneous and garbage stratum is 0-19 m, (2) the thickness of second silty clay stratum is 0.7-15 m with partial vulnerable area, (3) the third stratum is the mixture of limestone and mudstone. The main groundwater types are unconsolidated rock pore water, clastic rock fissure water, and carbonate fracture karst water according to its occurrence condition and hydraulic characteristics. The porous aquifer is composed of Quaternary unconsolidated sediments, such as clay and silty clay. The fissured aquifer is mainly shale of Permian system, and karst aquifer mainly occurs in the limestone fractures of Cambrian, Ordovician, Carbonic.

The recharge of pore water is mainly atmospheric precipitation. Fissure water and karst water are recharged directly from the precipitation of bare carbonate rock area. The study area is located on the south bank of Huaihe and close to Wabulake, the connection between groundwater is intently and it composes a unified water-bearing formation. The buried depth of the groundwater table is about 0.5~11.7 m and monitoring data shows that the groundwater table has been decreasing due to the sewer drainage of the coal mining process.

The waste of irregular landfill is mainly municipal solid waste where leachate infiltrates directly into groundwater and contaminate the shallow seated groundwater without any anti-seepage treatment. Therefore, the rural drinking water wells in the downstream are regarded as the main sensitive targets.

2.2. Numerical model

2.2.1. Hydrogeological conceptional model. The study area is located in the eastern of Huainan city in China where the model range is about 5 km², and the south of landfill is surface watershed, the other three sides are the boundary of coal mine subsidence.

The stratum sequence is a porous aquifer, aquifuge, fissure aquifer and karst aquifer from top to bottom according to the water-bearing media, occurrence condition and recharge-runoff-discharge condition. The upper aquifer has been contaminated by the leachate of the landfill. Groundwater flow system is generalized into a heterogeneous anisotropic three-dimensional model.

The flow direction of groundwater is from south to north, the hydraulic gradient is about 0.01, and the seasonal variation of groundwater table is about 1.6 m. The north and south sides are set to fixed water level boundary. The east and west sides are set to zero flux boundary which is perpendicular to the contour of groundwater. The recharge of the upper side is atmospheric precipitation.

2.2.2. Mathematical models. The groundwater flow numerical model is established by GMS based on the hydrogeological conceptual model. The mesh is generated by finite difference discretization method, the upper and lower layers are aquifers and the middle layer is aquifuge. The model is identified and verified with the monitoring data combine the requirements of the seal of the landfill site, simulation time is set 30 years, in addition, the simulation and prediction of groundwater flow are established.

The range and boundary of the solute transport model are consistent with the flow model. As the target contaminant, chloride is used for the identification and calculation of the solute transport model based on the monitoring results. The migration of chloride is simulated and predicted by MT3DMS module under the non-point source continuous contamination with the most unfavourable condition.

2.2.3. Identification of model. Firstly, the numerical model is established based on groundwater flow and solute transport parameters. The source-sink terms are mainly the upstream recharging, precipitation infiltration, and the downstream discharge, and precipitation infiltration is set based on actual meteorological data. Finally, the actual groundwater level is used for the model calibration, the model parameters are shown in Table 1.
Table 1. Model parameters.

| Strata      | HC  | Porosity | Lithology               |
|-------------|-----|----------|-------------------------|
| First layer | 0.61| 0.41     | Municipal solid waste   |
| Second layer| 0.01| 0.42     | Silty clay              |
| Third layer | 0.22| 0.25     | Mudstone with sandstone |

After the identification of the flow model, the groundwater flow field and calibration targets are shown in Figure 1 (a), the solute transport parameters are input the migration model, the dispersion is about 20 m according to the model scale[15] and the actual groundwater quality monitoring data are used for the model calibration. Parts indicators are relatively steady at the beginning of leachate formation in a landfill[16], therefore the identification of chloride concentration is determined by monitoring date (2012-2015) in the upstream, downstream and east side observation wells. The non-point chloride concentration is about 25000 mg L⁻¹ ultimately by the running of a model for 20 years as shown in Figure 1 (b).

![Figure 1](image1.png)

Figure 1. (a) Groundwater level calibration (b) Contaminant concentration fitted curve.

2.3. Scheme comparison of prediction and control of contaminant migration

2.3.1. The simulation prediction without measures. The migration process of chloride is simulated by an identified model under the condition of no measures. The average monthly rainfall is used for simulated calculation[17] based on the statistical of long-term (1985-2009 yrs) rainfall data according to Anhui provincial hydrographic office as shown in Figure 2 (a). Effective rainfall infiltration coefficient is set to 0.14 according to Chinese water resources bulletin[18] and the hydrogeological condition of the study area.

The simulation results show that chloride migration distance is about 600 m after 45 years which is twice as much as that after 15 years, and the contaminant has arrived the rural drinking wells without measures as shown in Figure 2 (b).

![Figure 2](image2.png)

Figure 2. (a) Average monthly rainfall of annual (b) Simulation results under natural conditions.
2.3.2. **Contaminant control schemes.** In order to prevent the leachate infiltrating into the groundwater system resulting in the contamination of rural drinking wells and other sensitive targets, engineering measures should be applied to control the contamination sources and cut off the contamination pathway. The horizontal impervious materials can transform the rainfall into surface runoff which can reduce the quantity of leachate[19]. The vertical impervious curtain can prevent the leachate from infiltrating into the downstream groundwater system[11,20].

2.3.3. **Horizontal impervious materials (HIB).** The main engineering measures to reduce contamination sources is building the impervious barrier on the top of the landfill. In addition, the runoff coefficient is about 0.4–0.9 based on general empirical value[21] according to the impervious materials. Compacted clay(CC)[22] and HDPE geomembrane(HDPE)(CC)[23,24] a which are two common kinds impervious materials are discussed as below in Table 2.

| Type   | HC     | Thickness (m) | Surface runoff |
|--------|--------|---------------|----------------|
| CC     | 1.E-04 | 0.3–0.6       | 0.6            |
| HDPE   | 1.E-07 | 0.001–0.003   | 0.9            |

Table 2. Horizontal impervious materials.

2.3.4. **Vertical impervious curtain (VIC).** The vertical impervious curtain is one of the common methods used for preventing the continuous contamination of leachate infiltrating into groundwater. And the primary function of a landfill liner is obviously the blockage of the movement of leachate, the contaminant migration path can be cut off with a vertical curtain when considering the actual hydrogeological conditions. Three kinds of commonly impervious materials: plastic concrete (PC), cement-bentonite (CB)[25] and HDPE geomembrane-bentonite composite material (HDPE-B) are discussed and the empirical thickness are shown in Table 3.

| Type   | HC     | Thickness (m) | HC coefficient |
|--------|--------|---------------|----------------|
| PC     | 1.E-03 | 0.6–1.0       | 1.4E-03        |
| CB     | 1.E-04 | 0.6–1.0       | 1.4E-04        |
| HDPE-B | 1.E-05 | 0.6–1.0       | 1.4E-05        |

Table 3. Vertical impervious curtain materials.

3. **Results**

3.1. **Comparison of contamination control measures**
Horizontal impervious, vertical impervious and the combination of two measures are considered with the effect of contaminant migration in different combination measures. The sealing area is about 126538 m² and an average depth of vertical curtain is about 13 m which achieve the top of the second layer.

3.2. **The prediction results of horizontal impervious materials**
The horizontal impervious control measures are applied at the top of solid waste in measure 1 and 2 which increase the surface runoff coefficient and reduces the leachate. The prediction results of two kinds of compacted clay and HDPE geomembrane are shown in Figure 3 (a) and (b).

![Figure 3. Simulation results of (a) CC layer and (b) HDPE layer.](image)
3.3. The prediction results of the vertical impervious curtain
The only vertical impervious curtain is set up along the solid waste boundary in measure 3, 4 and 5. The sealing area is about 20267 m² and the length of the vertical curtain is about 1500 m. The prediction results of different materials are shown in Figure 4 (a), (b) and (c).

The simulation results show that the vertical impervious curtain which is set up along the solid waste boundary have the significant controlling effect of chloride migration. The vertical impervious curtain can delay the time of chloride reaching to rural drinking wells up to about 35 years. Control effect of various impervious materials: HDPE-B > CB > PC.

![Figure 4. Simulation results of (a) PC curtain, (b) CB curtain and (c) HDPE-B curtain.](image)

3.4. The prediction results of the combination of horizontal impervious materials and vertical impervious curtain
The compacted clay layer is used in the horizontal impervious layer and parts (750m) of cement-bentonite (P-CB) wall is used in the vertical impervious curtain in measure 6, the prediction results are shown in Figure 5 (a). Part (750 m) or whole (1500 m) vertical HDPE geomembrane-bentonite (P/W-HDPE-B) curtain is set along landfill boundary combined with compacted clay horizontal impervious materials in measure 7 and 8, the prediction results are shown in Figure 5 (b) and (c).

![Figure 5. Simulation results of CC with (a) P-CB, (b) P-HDPE-B and (c) W-HDPE-B.](image)

The combination of horizontal and vertical impervious curtain has great control effect on chloride migration, and the vertical impervious curtain can maintain the quality of groundwater within III standard up to 40 years.

Horizontal materials and vertical impervious curtain can control the migration range of contaminant in a landfill and the combination of horizontal and vertical impervious curtain can be more effective to protect the quality of groundwater in 40 years according to simulation result of different engineering measures.

3.5. Cost-effectiveness analysis
The cost of various contamination prevention and control measures are compared and analyzed based on the actual situation of the landfill. The construction technology of horizontal impervious engineering is earth backfill and tamp which area is about 126538 m² and thickness is about 0.45 m. The construction technology of vertical impervious curtain is drilling and grouting which depth is about 7 m-19 m and thickness is about 0.8 m. The area of the whole impervious curtain is 20267 m² and the length is 1500 m which are twice as much as those of the part impervious curtain respectively. The fixed price is computed, including labor cost, material cost and machinery cost according to the
budget quota of water resources and architectural engineering, construction machinery time fee of water conservancy project and the local price of construction material. Due to the engineering cost(EC), sensitive time(ST) and design requirement(DR) as the significant reference index in the practical engineering, the results of eight measures are shown in Table 4.

| Measures | HIB  | VIC  | EC (million) | ST (yr) | DR  |
|----------|------|------|--------------|---------|-----|
| 1        | CC   | —    | 537          | 20      | x   |
| 2        | HDPE | —    | 1790         | 40      | √   |
| 3        | —    | PC   | 1840         | 28      | x   |
| 4        | —    | CB   | 1610         | 32      | √   |
| 5        | —    | HDPE-B | 1810        | 35      | √   |
| 6        | CC   | P-CB | 1340         | 40      | √   |
| 7        | CC   | P-HDPE-B | 1440       | >40     | √   |
| 8        | CC   | W-HDPE-B | 2350       | >40     | √   |

The engineering measures except measure 1 and 3 can satisfy the design requirements which lag the migration time of contaminant to downstream sensitive targets up to 30 years. measure 6 and 7 have the advantage of engineering cost and control effect of contaminant migration range. The engineering cost of measure 8 is the highest among measure 2, 4, 5 and 8 which has caused over designed. Considering the characteristics of engineering construction and the comprehensive utilization of landfill site, the measure 7 has a great advantage.

4. Discussion and conclusions
(1) The migration range of contaminant is about hundreds of meters in groundwater once the leakage occurs in an irregular landfill. Engineering measures must be applied to preventing contaminant infiltrating into the downstream sensitive targets due to persistent potential contamination source.

(2) The horizontal and vertical impervious measures can be used to control the migration of contaminant to a certain extent. The horizontal impervious materials can reduce the amount of rainfall infiltration and control the landfill leachate amount, the vertical impervious curtain can effectively delay the time of contaminant migration and diffusion, and both of measures can effectively protect the downstream sensitive targets.

(3) The combination measures of clay or geomembrane as horizontal impervious materials and parts of the vertical impervious curtain can meet the design requirements which has considerable advantages and low cost according to the control effect of contaminant diffusion and engineering cost.

(4) The numerical simulation of groundwater is a very effective technique in the design of the enclosure of the irregular landfill. Contamination control effect of different engineering measures can be mastered based on the simulation results and the lack of engineering measures or excessive design can be avoided by combining a comprehensive analysis of engineering cost. Finally, these results can provide the accurate design basis for the irregular landfill.

Up to now, the design and construction of irregular waste landfill site with complex hydrogeological conditions in mining area are less. The numerical simulation of groundwater can provide a more accurate basis for the engineering design, and monitoring wells will be set to verify the effectiveness of numerical simulation and the effect of practical measures.

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