

Article

Effect of Height Difference Between Adjacent Liquid Injection Holes on Wetting Body Evolution of Ion-Absorbed Rare Earth In Situ Leaching Ore

Qiang Huang ^{1,2,3} , Chunlei Zhang ^{1,2,3}, Yunzhang Rao ^{1,2,3,*}, Guozhu Rao ^{2,3,4}, Jiazheng Wan ^{1,2,3}, Yangjun Xie ^{1,2,3} and Qiande Lai ^{1,2,3}

¹ School of Mining Engineering, Jiangxi University of Science and Technology, Ganzhou 341000, China; 6120230014@mail.jxust.edu.cn (Q.H.)

² Jiangxi Provincial Key Laboratory of Low-Carbon Processing and Utilization of Strategic Metal Mineral Resources, Jiangxi University of Technology, Ganzhou 341000, China

³ Jiangxi Provincial Key Laboratory of Environmental Pollution Prevention and Control of Mining and Metallurgy, Jiangxi University of Technology, Ganzhou 341000, China

⁴ College of Emergency Management and Safety Engineering, Jiangxi University of Science and Technology, Ganzhou 341000, China

* Correspondence: raoyunzhang@jxust.edu.cn

Abstract

This study investigated wetting body migration and blind area distribution variations under different height differences (Δh) using indoor experiments and numerical simulations. Results show that the Δh of the injection hole shifts the wetting body intersection backward. Due to the increase in Δh , the vertical migration of the wetting peak at the No. 1 liquid injection hole accelerates, and the horizontal migration tends to be stable, which indicates that the Δh promotes the vertical seepage by changing the hydraulic gradient, which is beneficial to accelerate the leaching process. The migration of the wetting peak presents the characteristics of ‘fast first and then slow’, and it is easy to form a blind area in the later stage of leaching. When Δh is 0 and 3 cm, the blind area is concentrated between the two holes in the upper part of the ore heap. When Δh increases to 5 and 7 cm, the blind area expands to the top of the No. 1 hole. The simulation results show that although the increase in Δh can accelerate the recovery of water pressure in the near-end injection hole, it will increase the difference in leaching efficiency between ‘near-end’: when Δh is small, the wetting body diffuses symmetrically and the blind area is easy to eliminate; the increase in Δh leads to the asymmetric migration of the wetting body, and the remote area faces a significant risk of a blind area due to a low water pressure and low concentration.

Keywords: ionic rare earth; wetting body; in situ leaching; hole network parameters; COMSOL simulation



Academic Editor: Antoni Roca

Received: 12 January 2026

Revised: 3 February 2026

Accepted: 9 February 2026

Published: 19 February 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Ionic rare earth ore is a crucial strategic resource in China, with its reserves primarily concentrated in seven provinces, including Jiangxi and Guangdong [1–3]. Its efficient and sustainable mining methods have consistently attracted significant attention. At present, the in situ leaching process is widely used in ion-absorbed rare earth mines (see Figure 1 below). By arranging a liquid injection pore network on the surface of the mountain and injecting a leaching agent, the rare earth cations adsorbed on the mineral surface are replaced into the solution to form rare earth leachate, from which rare earth elements are

then extracted [4–6], achieving green mining. The advantage of this process is that it does not require the destruction of surface vegetation or the mountain structure. However, after more than 20 years of promotion, the in situ leaching process has gradually exposed its inherent defects. For example, the ore-forming lithology of ion-adsorption-type rare-earth ore is rich [7]. The internal conditions of the ore body during the mineralization process are complex, and there are cracks and extremely low-permeability areas, which seriously affect the leaching effect. Another major issue is that the layout of the liquid injection hole network parameters in the in situ leaching process largely relies on experience and lacks a scientific basis, which can lead to resource wastage and cause the intersection of wetting bodies during the leaching process. This, in turn, affects the stability of the rock and soil mass and may induce landslides [8]. Specifically, when the liquid injection strength is constant, the smaller pore sizes of the injection holes and larger hole spacing lead to incomplete leaching, the formation of blind areas in the leaching process, and resource wastage. Larger apertures and smaller hole spacing increase the leaching investment cost. At the same time, they are prone to causing ‘channeling holes’ between adjacent holes, leading to the overlap of adjacent leaching areas and causing local ore bodies to become supersaturated, which affects the stability of the slope [9–12]. Some scholars have shown that the wetting formed by adjacent liquid injection holes overlaps, a phenomenon known as the intersection of wetting bodies. The intersection effect causes changes in the moisture content of the wetting body. Different injection hole spacings significantly impact the intersection effect of the wetting body, and the influence on moisture content also varies [13–15], which, in turn, affects the strength of the slope soil during the leaching process.

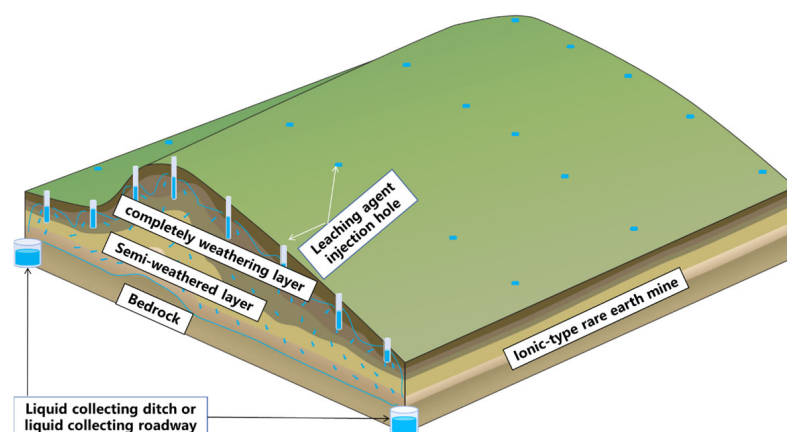


Figure 1. In situ leaching schematic diagram.

Studies have shown that injection parameters can be optimized by adjusting hole network parameters when using in situ leaching for ionic rare earth mining [16,17]. Currently, scholars both domestically and internationally mainly study the evolution and migration behavior of the wetting body during leaching under different pore network conditions in the investigation of liquid injection pore network parameter arrangement for the in situ leaching of ionic rare earth. Sepaskhah et al. [18] used the three-dimensional Green–Ampt model to calculate the radius and depth of the wetting body during surface infiltration. Based on the Green–Ampt model and the law of conservation of mass, Guo et al. [19] described the evolution process of wetting the body in the in situ leaching process by digital image technology, and established the empirical relationship between particle size and stable infiltration rate. Fan et al. [20] used a multivariate nonlinear model to predict the shape and size of the wetting body under moisture irrigation. Wu et al. [21] constructed an ionic rare earth digital model based on nuclear magnetic resonance imaging (NMRI) technology and analyzed the leaching effect of rare earth ions under different liquid in-

jection intensities and different leaching agent concentrations. Zhang et al. [22] studied the dynamic changes in the pore structure and permeability of ore bodies in the process of leaching in detail. The heterogeneity of ore body permeability is the key physical basis for determining whether the pore network layout can effectively infiltrate. Negash [23] pointed out that the expansion of clay in water is the main challenge in reducing the permeability in in situ leaching, which directly leads to the blockage and blind area of the seepage channel. Del et al. [24] established infiltration models for hemispherical and circular sources based on the Green–Ampt model, without considering the depth of surface water. Mehdi et al. [25] discussed a new deep learning method based on gradient boosting with multi-filtering to comprehensively study the wetting distribution pattern of sloping land under drip irrigation. The wetting front migration model of ion adsorption rare earth during the injection of porous unsaturated liquid was proposed by Yu Wang [26].

In summary, the parameters of the liquid injection hole network (refer to the spatial layout scheme of the liquid injection hole and the liquid receiving hole designed for the implementation of the in situ leaching project and the collective name of the specific geometric parameters, such as the diameter of the liquid injection hole, the spacing of the liquid injection hole, etc.) are the key indicators in the process of ionic rare earth mining, which directly affect the migration law of the wetting body and the stability of the rare earth ore body. It is not difficult to find from Figure 1 that there is a height difference between the same row of liquid injection holes, which may affect the in situ leaching effect. This phenomenon stems from the difference between the row spacing of the liquid injection hole and the natural slope of the rare earth slope in the actual production of the mine, which leads to the inevitable existence of the height difference between the adjacent liquid injection holes. By adjusting the row spacing of the injection holes and the natural slope of the slope, the height difference of the adjacent injection holes can be optimized to improve the leaching effect. Through experiments and model simulations, the above scholars have conducted in-depth research on the evolution and migration law of the wet body under different conditions, but they have not considered the influence of the height difference of adjacent liquid injection holes on its evolution process. As one of the parameters of the liquid injection pore network for the in situ leaching of ionic rare earth, how the height difference of adjacent liquid injection pores affects the evolution and migration law of the wet body is still an urgent problem to be explored.

Based on research on the evolution law of the wetting body in the seepage characteristics of ionic rare earth by other scholars, this paper studies the influence of the height difference of adjacent liquid injection holes on the in situ leaching of ionic rare earth through two-dimensional box leaching experiments. The shape and cross-section changes of the wetting body and the migration speed of the wetting peak (a relatively clear boundary moving interface between dry and wet areas formed during water infiltration in unsaturated soil) are selected as the investigation objects. Finally, the numerical software is used to simulate and verify the experimental results. Finally, the influence of the height difference of adjacent liquid injection holes on the evolution of the wetting body is reflected.

2. Experiments and Methods

2.1. Experimental Apparatus and Materials

The experimental materials were selected from an ionic rare earth mine in Gannan, Jiangxi Province. The main test equipment includes a 30 cm × 15 cm × 30 cm transparent soil box made of a 5 mm thick acrylic plate, a peristaltic pump, a liquid injection hole, an overflow pipe, a measuring cylinder, and a camera. The experimental reagent used was a 2% MgSO₄ solution [27]. The experimental apparatus is shown in Figures 2 and 3.

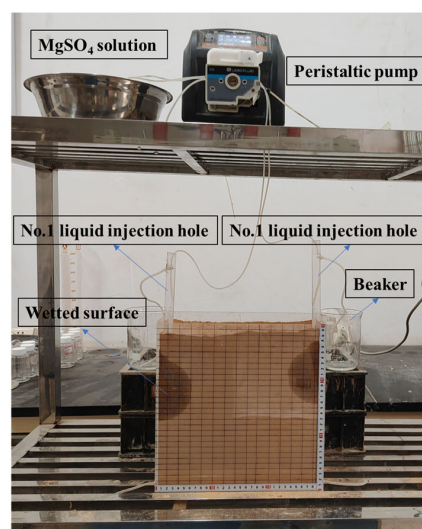


Figure 2. Experimental site device diagram.

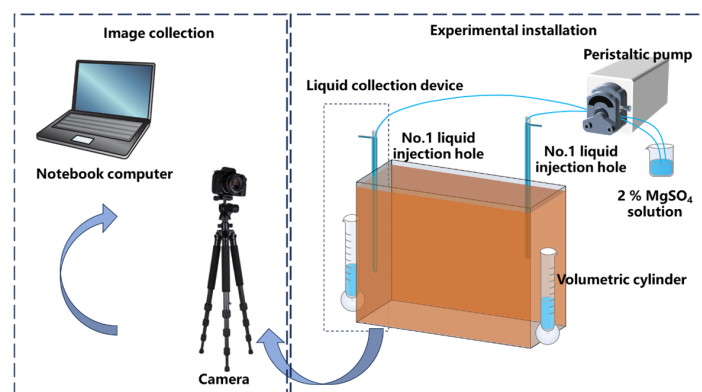


Figure 3. The schematic diagram of experimental device.

2.2. Experimental Design

Before the experiment, the soil samples taken from the rare earth mines were dried for at least eight hours in a drying oven at 105 degrees Celsius. At the same time, the physical parameters of the undisturbed soil were measured according to the experimental procedures (referring to the natural structure, density, water content, and other physical and mechanical properties during the collection or preparation process). The particle size screening experiment was carried out on the dried soil to measure the particle size distribution of the rare earth ore sample, and the remolded soil after screening was matched to obtain the experimental soil. The experimental soil samples were layered and loaded into the soil box made of acrylic plates. For convenient observation, the outer wall of the soil box was painted with grid lines. In order to ensure the uniform distribution of particles, the soil was divided into four layers, and each layer was loaded into the soil box three times, with a soil thickness of 5 cm. In order to avoid the phenomenon of stratification, according to the standard of rare earth to make undisturbed soil samples, it is necessary to roughen the stratification of each layer and leave the filled soil for one night to allow it naturally settle and reduce pores. In order to ensure the consistency of the liquid injection head during the experiment, a set of liquid collection devices was set up in the experiment, which was composed of a beaker, overflow pipe, and bracket. The excessive leaching agent solution was collected during the liquid injection process, and the height of the liquid injection head was selected as 26 cm. In the experiment, the height difference group is set: according to the specification [28], the depth of the injection hole is generally 0.5~1 m, and the height difference of the injection hole is set to 3 cm, 5 cm, and 7 cm according to the depth of

one-fifth of the hole. At the same time, a control group without a height difference was set up, and the injection hole spacing was 29 cm. The experiment uses double-hole liquid injection, with No. 1 and No. 2 liquid injection holes (In order to facilitate the observation of the wet body, two liquid injection holes are close to the experimental box. The depth of the No. 2 liquid injection hole is 7 cm, and the depth of the No. 1 liquid injection hole is 7 cm, 10 cm, 12 cm, 14 cm, respectively. The diameter of the liquid injection hole is 1 cm.). The experimental process clock fixes the depth of the No. 2 liquid injection hole and sets the height difference of the liquid injection hole by changing the depth of the No. 1 liquid injection hole. Before the experiment, the basic parameters of rare earth ore samples were measured as follows: Table 1. The mass of ore samples before and after drying was measured by an indoor constant temperature drying oven, and the dry density, wet density, and water content were measured. The porosity of the ore sample in the saturated state was measured by a nuclear magnetic resonance instrument.

Table 1. Basic physical properties.

Dry Density (g/cm ³)	Wet Density (g/cm ³)	Water Content (%)	Percentage of Saturated Water Content (%)	Porosity (%)
1.4787	1.5847	11.14	22.65	37.3575

The screening method is used to select the vibrating screen machine to screen the rare earth ore sample, and the particle gradation of the rare earth ore sample is measured as follows: Table 2.

Table 2. Particle gradation of ionic rare earth ore sample.

Particle Size	>5 mm	>2 mm	>1 mm	>0.25 mm	>0.075 mm	<0.075 mm
weight percentage	6.39%	16.91%	18.01%	28.77%	18.09%	11.83%

The XRD composition analysis of the rare earth ore samples obtained from the mine is shown in Figure 4. XRD analysis shows that the primary minerals in the ore samples are mainly quartz, orthoclase, albite, and muscovite, which are directly inherited from the parent rock (such as granite), and their crystal structure and chemical composition remain relatively stable. In terms of engineering geological properties, these minerals usually show low compressibility, a high permeability coefficient, and weak cohesion, and are generally in a relatively stable physical state.

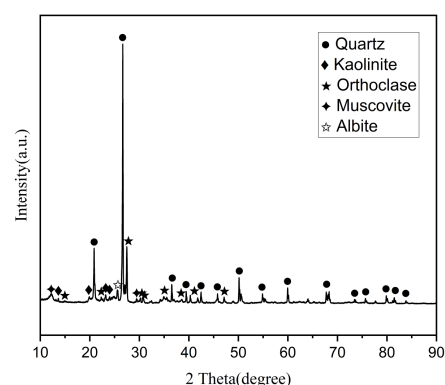


Figure 4. XRD analysis results.

The secondary minerals are mainly layered silicate clay minerals, such as kaolinite, which belong to the alteration products of primary silicate minerals, such as feldspar, under the action of weathering, leaching, and topsoil. Compared with primary minerals, secondary clay minerals have significant hydrophilicity and physical and chemical activity, and are prone to reciprocating the deformation of hydration expansion and dehydration shrinkage, resulting in poor engineering geological stability, which has a significant impact on the strength, deformation, and permeability of soil. According to the mineral assemblage shown by XRD analysis, the sample belongs to granite weathering sedimentary rare earth, which is classified as sandy clay.

2.3. Experimental Content

Before starting the test, the required instruments and solvents were prepared in advance, and the peristaltic pump was adjusted to a predetermined flow rate of 2 mL/min to maintain the head height of the liquid injection hole. Once the experiment began, the indoor simulated leaching infiltration process was recorded using a timer according to the set time intervals, following the principle of starting dense and transitioning to sparse intervals. During the first 80 min, data were recorded every 10 min using a camera. For the subsequent 30 to 360 min, data were recorded every 20 min, and the interval gradually increased to 30 min thereafter. The experiment was stopped when the vertical wetting front displacement was less than 0.1 cm per hour. To ensure the accuracy of the experimental results, the area of the wetted surface was calculated using PS 2024 repair software and the artificial number lattice method, with the average value taken from three repetitions of each experiment. The position of the wetting peak directly below the liquid injection hole, the position of the wetting peak at the intersection, and the shape of the wetting body were primarily observed and recorded. The position of the wetting peak can be determined using the scale on the acrylic soil box to characterize the evolution and migration of the wetting body.

3. Results and Discussion

3.1. The Influence of the Height Difference Between Adjacent Liquid Injection Holes on the Shape Change of the Wetting Body

During the experiment, the camera was used to record the changes in the wetting body over time. Figure 5 is a partial experimental result diagram that reflects the evolution of the wetting body during the leaching process. By analyzing the evolution and migration of the wetting body in the main view (Figure 5a) and the side view (Figure 5b), the changes in the wetting body before and after the intersection of single-hole injection and multi-hole injection can be compared. It can be seen from the main view that, with the leaching process, the migration trajectory of the wetting body before the intersection can be approximated as an ellipsoid, similar to that in the side view. It shows that in the process of single-hole and multi-hole liquid injection, the migration pattern of the wetting body before intersection is essentially the same, which aligns with the research of Guo et al. [19].

The results in Figure 6 show that an increase in the height difference between adjacent liquid injection holes significantly prolongs the lateral migration distance of the wetting peak and causes the intersection point of the wetting body to shift backward. This phenomenon can be explained by the geometric characteristics of the wetting body migration path: when ignoring the intersection, the wetting body migration path follows an ellipsoidal distribution. The change in the height difference between adjacent liquid injection holes causes the center of the ellipsoid to deviate from the same horizontal line, altering the position of the tangent point between the two ellipsoids, which ultimately increases the horizontal migration distance of the wetting peak.

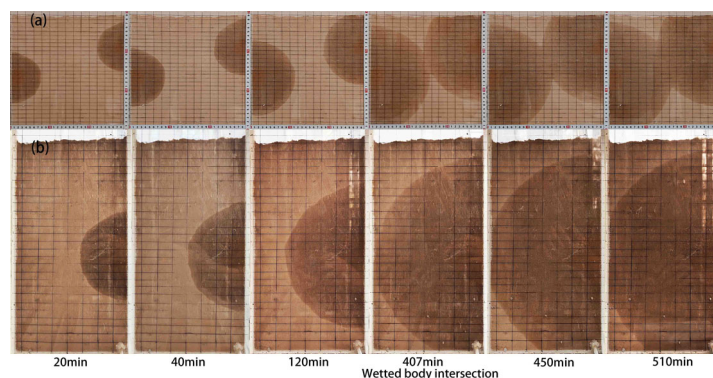


Figure 5. The experimental results of wetting body evolution at some time nodes, (a) Main view (b) Right view.

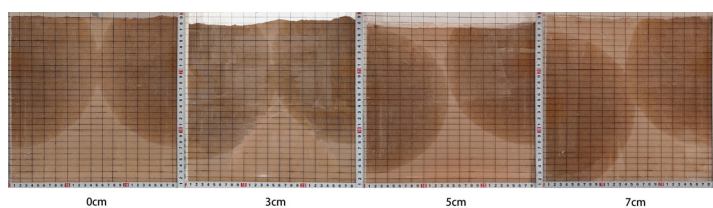


Figure 6. Photos of wetted body intersection under different liquid injection hole height difference conditions.

The experimental results show that the height difference between adjacent liquid injection holes has a minimal effect on the morphological evolution of the wetting body. However, the significant influence of the height difference on the intersection point of the wetting body cannot be overlooked. This provides a new approach for optimizing the layout of the liquid injection holes: by adjusting the height difference appropriately, the efficient distribution of the solution can be achieved, thereby improving leaching efficiency and reducing resource waste.

3.2. The Influence of the Height Difference of Adjacent Liquid Injection Holes on the Wetting Peak Migration Distance

The migration distance of the wetting peak refers to the horizontal and vertical migration distance of the wetting peak. The vertical displacement and horizontal displacement of the wetting peak per unit time during the experiment can be analyzed to reflect the migration speed of the wetting peak. The specific results are as follows. Figures 7 and 8.

It can be seen from the figure that the wetting peak migration distance per unit time continues to decrease and tends to be stable with the leaching activity. This is because the infiltration process of the solution is affected by capillary force and gravity. Initially, the solution flows between the particles of the ore body, and the infiltration rate is fast. However, there are pores in the ore body particles. The solution is sucked into the pores in the particles through capillary action, and the solution flow between the particles is relatively reduced, resulting in a slower infiltration rate [29]. At the same time, it can be obviously noted that under the condition of the height difference of the liquid injection hole, the vertical migration distance of the No. 1 liquid injection hole at the same time is slightly larger than that of the No. 2 liquid injection hole when the wetting peak migrates to the later stage, and there is no obvious difference in the migration of the wetting peak in the horizontal direction. The buried depth of the liquid injection hole has a certain influence on the vertical migration of the wetting peak, and the experimental design belongs to the point source infiltration problem. Studies have shown that the movement of the leaching solution in the ore soil follows Darcy's law [30] and the principle of mass conservation.

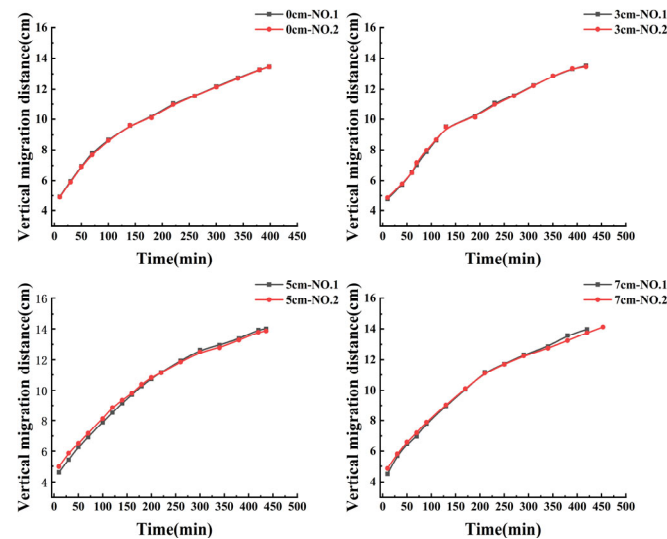


Figure 7. The relationship between the vertical migration distance of the wetting peak and time.

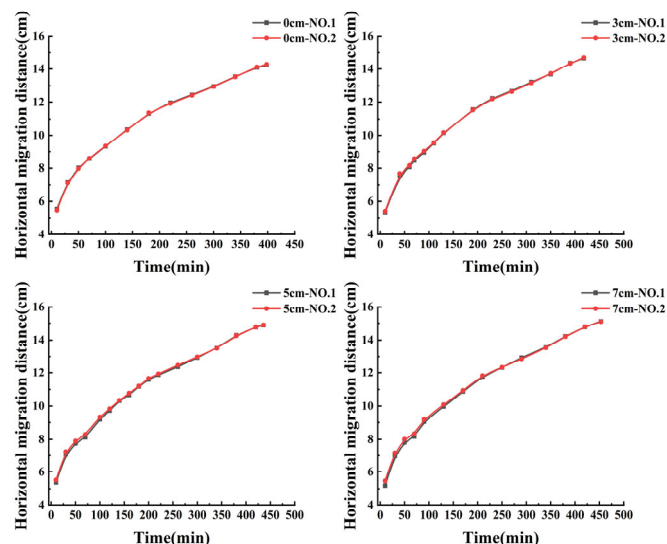


Figure 8. The relationship between the horizontal migration distance of the wetting peak and time.

Based on Darcy's law equation, we know that:

$$q = -K \cdot \nabla H K_s \quad (1)$$

Among them, q is the Darcy flow rate (which can be approximated as the permeation rate); K is the hydraulic conductivity (K_s at saturation); and ∇H is the hydraulic gradient, that is, the change rate of the total water potential H along the flow.

Ignoring the solute and temperature potentials, for the vertical one-dimensional flow:

$$H = \psi + z \quad (2)$$

Among them, ψ is the matrix potential (pressure potential), which is generated by soil capillary action and adsorption. In the saturation band, $\psi \geq 0$; in the unsaturated zone, $\psi < 0$. z is the gravity potential, usually taken as the vertical coordinates; the direction downward is positive, taking the topsoil as the coordinate starting point, the gravity potential increases with the increase in buried depth, which is an important factor affecting vertical infiltration. Therefore, the buried depth of the liquid outlet directly changes the boundary conditions at the bottom of the system, thus affecting the entire soil profile,

especially the distribution of water potential ψ near the bottom, and ultimately changing the hydraulic gradient ∇H . This also shows that the greater the buried depth of the liquid injection hole, the greater the role in promoting the vertical migration of the wetting peak.

3.3. Influence of the Height Difference of Adjacent Liquid Injection Holes on the Blind Zone of In Situ Leaching

The blind area of the ion-type rare earth in situ leaching process is the retention ore body area where the rare earth ions are not exchanged and leached due to the non-uniform seepage of the leaching agent in the ore layer, which cannot be effectively contacted. Its essence is a complex problem involving seepage mechanics, surface chemistry, and geological structure. In this paper, this problem is simplified and analyzed through laboratory tests. The influence of the height difference of adjacent liquid injection holes on the blind area of in situ leaching is preliminarily discussed by observing the morphological law of the wet body and the area change of the wet surface in the later stage of leaching. In Figure 9 below, photos of the wetted body of the experimental leaching for 8 h were selected. By observing the evolution of the wet body, the approximate location of the blind area in the process of in situ leaching can be roughly inferred. When the height difference between adjacent liquid injection holes is 0 cm and 3 cm, it can be roughly considered that the blind area is basically concentrated in the upper part of the ore soil, and the middle of the two liquid injection holes. With the height difference between adjacent liquid injection holes reaching 5 cm and 7 cm, the blind area in the upper part of the ore soil can be seen to be expanding, and it is concentrated above the No. 1 liquid injection hole (left side in the picture).

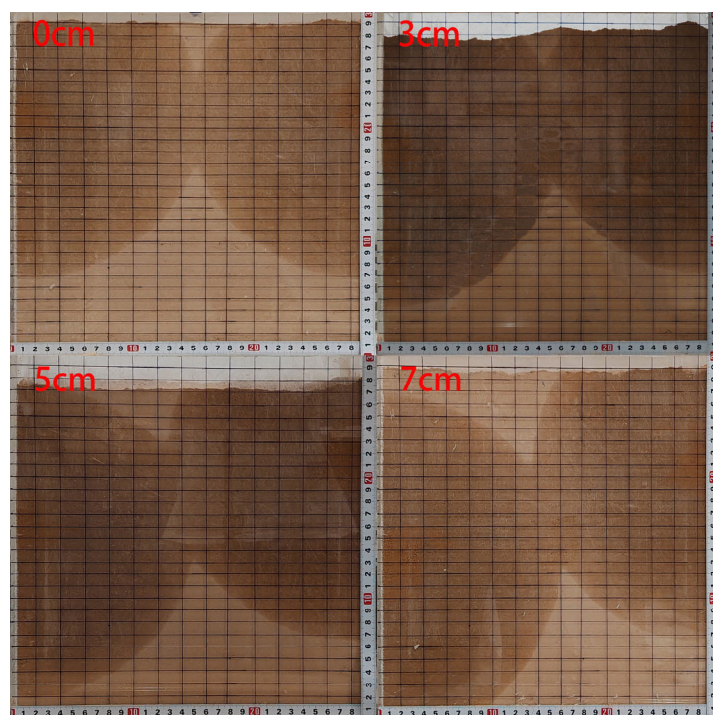


Figure 9. Morphological photos of wetted body in the later stage of the experiment under different height differences for the liquid injection hole.

At the same time, the area of the wet surface during the experiment was analyzed (Figure 10 below is the change trend of the wet surface area with the leaching time. The root mean square error (RMSE) under different liquid injection hole height differences is 6.97, 7.78, 5.66, 7.14). It can also be seen that with the progress of leaching, the migration rate of the wet peak is first fast and then slow, and the speed is slower and slower in the later stage of leaching. As a result, there will be a part of the upper part of the ore body

that is difficult to reach by the leaching solution, thus forming a blind area for leaching. At the same time, with the progress of leaching, there is no obvious distinction between the wetting surface area in the early stage of leaching, and it gradually increases with the increase in the height difference of adjacent liquid injection holes in the later stage. It can also be seen from the above diagram that the evolution of the wetting body in the lower part of the experimental mine soil is obviously different, forming a large dislocation. At the same time, the increase in the buried depth of the liquid injection hole is different and the vertical migration of the wetting peak has a certain role in promotion.

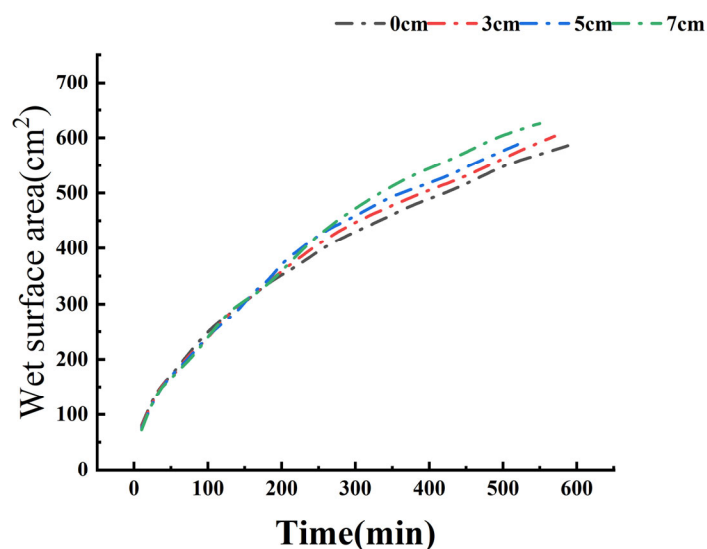


Figure 10. The change in wetted area with time under different height differences for the liquid injection hole.

4. Numerical Model Validation Analysis

4.1. Theory and Modeling

COMSOL Multiphysics® 6.2 is an advanced numerical simulation software based on the finite element method. Its core advantage is that it can easily couple multiple physical fields to simulate complex engineering and scientific problems that are affected by multiple physical effects in the real world [31–33]. The coupling process of ‘fluid flow in porous media–solute diffusion–chemical reaction’ can be simulated in detail. In this simulation, the Richards equation built in COMSOL is used to describe the water movement in unsaturated porous media. It combines the law of conservation of mass with Darcy’s law and takes the soil water pressure head (ψ , matrix potential) as the dependent variable, which can clearly reveal the water movement.

$$C(\psi) \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial Z} \left[K(\psi) \left(\frac{\partial \psi}{\partial Z} - 1 \right) \right] - S \quad (3)$$

In the formula:

— $C(\psi) \frac{\partial \psi}{\partial t}$ represents the change rate of water content in unit volume of soil with time;

— $\frac{\partial}{\partial Z} \left[K(\psi) \left(\frac{\partial \psi}{\partial Z} - 1 \right) \right] - S$ represents the spatial variation in water flux per unit volume;

— $K(\psi)$ represents the unsaturated hydraulic conductivity, which is a function of pressure head ψ . Because the soil used in the experiment is sandy clay, its value is generally 10^{-5} ;

— $\left(\frac{\partial \psi}{\partial Z} - 1 \right)$ is the total water potential gradient, which is the driving force of water flow;

— S is the source and sink term, representing the process of plant root water absorption.

In the simulation process, the constant water head is 0.26 m, the porosity is 0.374, the van Genuchten water holding model is used, and the porous material properties are the basic physical parameters of the rare earth ore sample.

The size of the model was 30 cm $\times$ 30 cm. Four cases were simulated by adjusting the position of the No. 1 injection hole (height difference of adjacent injection holes: 0 cm/3 cm/5 cm/7 cm). In the simulation process, the constant water head is 0.26 m, the porosity is 0.374, the Van Genuchten water holding model is used, and the porous material properties are the basic physical parameters of the rare earth ore sample. The main boundary conditions of the model are as follows in Figure 11:

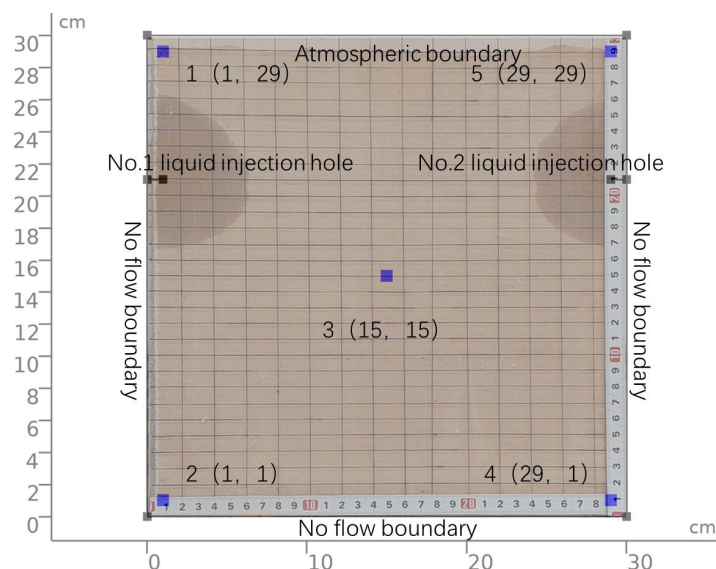


Figure 11. Model boundary conditions and monitoring point settings.

(1) Inflow boundary (No. 1 and No. 2 injection holes)

The boundary is the input port of the fluid (magnesium sulfate solution), and the fluid is injected into the porous medium, which is the mass input source of the system. The water head is set to 0.26 m, and the concentration of the magnesium sulfate solution is 0.166 mol/m³. By adjusting the depth of the No. 1 injection hole, the four conditions set by the simulation experiment are simulated.

(2) No flow boundary

It is only used as the 'closed boundary' of the model to limit mass exchange and simulate the area of 'no fluid/solute in and out' in the actual scene. There is no flow boundary around the model.

(3) Atmospheric boundary

It is the upper boundary of the model. In the process of liquid injection infiltration, the exchange between the solution and the external atmosphere is very small, which can be ignored. In order to simplify the calculation, the atmospheric boundary is set according to the non-flow boundary.

4.2. Simulation Reliability and Result Analysis

Before the analysis of the simulation results, the reliability of the simulation needs to be demonstrated. The primary basis for reliability is the direct matching degree between the experimental results and the simulation results, as shown in Figure 12 below. It can be seen that the simulated water pressure distribution pattern is consistent with the experimental results, and the time evolution trend maintains synchronization. The matching degree between the experimental and simulated water pressure distribution pattern, high water

pressure range, and time evolution trend (from local to global) is better. In a short time (20 min/40 min), both the experiment and simulation showed that the water pressure was only concentrated near the liquid injection hole, and there was no significant diffusion. The long-term (407 min/450 min) experiment and simulation show that the water pressure is globally homogenized, the high-water-pressure area disappears, and the time nodes for the two to reach the ‘near-homogeneous state’ are close. It is proven that the model is reliable in predicting the steady-state trend, and the evolution rhythm is not offset due to numerical dispersion or parameter error.

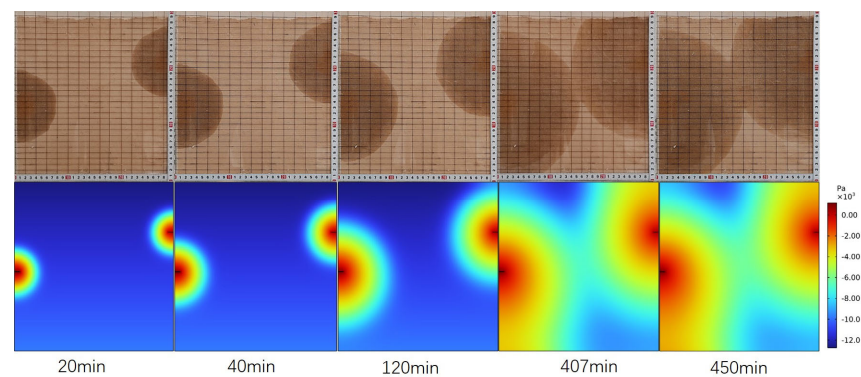


Figure 12. Comparison of experimental results and simulation results.

The simulation results are as follows in Figure 13. They reflect the spatial distribution of water pressure inside the mine soil with the increase in the height difference of adjacent liquid injection holes. Through the analysis of the internal water pressure of the ore soil, we can understand the influence of the height difference between adjacent liquid injection holes on the migration of the wetting body in in situ leaching and further analyze the generation of the blind area in the leaching process.

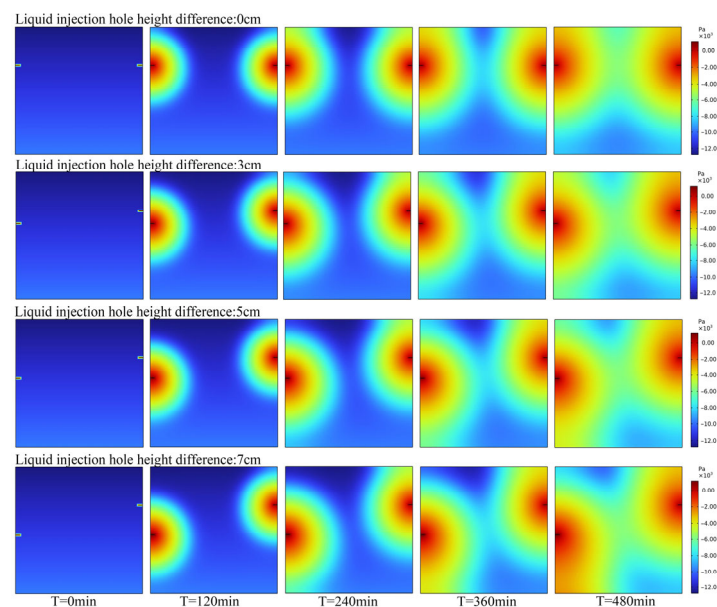


Figure 13. Simulation results at different moments under different injection hole height difference conditions.

Through the spatial distribution evolution of the internal water pressure of the mine soil with time under different adjacent liquid injection hole heights, the variation law of water pressure, the migration characteristics of the wetting body, and the risk of a blind area can be analyzed. In the initial stage (0 min), the water pressure of the mine soil under all

working conditions is at the lowest level; only the position of the liquid injection hole has a weak disturbance, and the liquid injection has not yet started. With the passage of time (120~480 min), the water pressure around the liquid injection hole gradually increases, and the larger the height difference of the liquid injection hole, the wider the range and the faster the water pressure increases. At the same time, there is a certain spatial difference, that is, there is a high-value area of water pressure (red/yellow) near the injection hole, and the water pressure gradually decreases in the area far from the injection hole. When the height difference increases, the 'asymmetry' of the high-water-pressure area is more obvious (the water pressure diffusion range in the direction of the height difference of the injection hole is larger). The migration of the wetting body is directly related to the distribution of water pressure. When the height difference between adjacent liquid injection holes is small, the wetting body diffuses approximately symmetrically with the liquid injection hole as the center. When the height difference increases, the diffusion direction of the wetting body is inclined to the direction of 'high liquid injection hole to low liquid injection hole', and the overall wetting range expands with the increase in the height difference.

At the same time, the area where the water pressure is low for a long time and the wet body is not covered can be considered as a 'leaching blind area'. When the height difference between adjacent liquid injection holes is small, the blind area is mainly distributed in the edge area away from the liquid injection hole, and it is gradually covered by the wetting body over time. When the height difference of adjacent injection holes increases, although the overall wetting range is expanded, the 'asymmetric diffusion' in the direction of the height difference of the injection holes may lead to a slow recovery of water pressure in local areas (such as the upper left edge of the model range), but it is easy to form a new blind area. The increase in the height difference between adjacent liquid injection holes will accelerate the diffusion of the wetting body and expand the overall wetting range, but it will also enhance the asymmetric migration characteristics of the wetting body and increase the risk of local blind areas.

4.3. Local Feature Analysis

In order to further analyze the 'asymmetry' of the solution diffusion motion during the experiment, monitoring points (symmetrical distribution, upper left, upper right, middle, lower left, lower right) were added to the model, as shown in Figure 11 above. Through the real-time analysis of the water pressure and magnesium ion concentration at the monitoring point, the influence of the height difference of different injection holes on the water pressure and magnesium sulfate solution concentration distribution inside the model is reflected. See Figures 14 and 15 below.

In order to understand the change mechanism of water pressure and concentration in the above figures, it is necessary to analyze the two core dimensions of the strong coupling relationship between seepage and mass transfer and the gravity driving effect caused by the height difference of liquid injection holes. Firstly, the height difference of the injection hole leads to the chain effect of asymmetric seepage and asymmetric mass transfer. In the experiment, the height difference is introduced by adjusting the buried depth of No. 1 liquid injection hole. The essence is to apply the gravitational potential energy difference. The potential energy difference further affects the mass transfer field through the seepage field and changes the water and solute distribution inside the ore soil. When the height difference of the liquid injection hole is 0 cm, the buried depth of the two liquid injection holes is the same, the gravitational potential energy is symmetrical, the seepage field is dominated by the liquid injection pressure and the medium resistance, and the water pressure distribution is relatively uniform. It can be seen from the figure that the water pressure of the monitoring point rises from the initial negative pressure

(about $-14,000$ Pa) with high synchronization, and the later curve gradually approaches. With the increase in the height difference of the injection hole and the introduction of the gravitational potential energy difference, the water pressure gradient near the low injection hole increases significantly, and the water flow velocity is faster. It can be seen from the figure that at the monitoring point near the low injection hole (such as monitoring point 2), the water pressure rebounds faster; at the monitoring points in the high area (such as monitoring point 1), the water pressure changes more gently. Finally, the water pressure curves of each monitoring point are gradually separated. The larger the height difference is, the more obvious the separation is. Material transfer is determined by molecular diffusion and convection diffusion, in which convection diffusion is determined by seepage velocity (Darcy's law). Therefore, when the height difference of the liquid injection hole is 0 cm, the seepage velocity is uniform and the convection diffusion is symmetrical. With the uniform migration of water flow, the concentration of each monitoring point rises synchronously, and the curve is highly concentrated. As the height difference of the liquid injection hole increases, the seepage velocity is non-uniform, and the convection velocity near the low liquid injection hole is faster, and the solute is transported to the monitoring point in the area faster by the water flow. The concentration of monitoring points near the low area (such as monitoring point 2) increased significantly; the concentration of the high monitoring point (such as monitoring point 1) rises slowly, and the curve is gradually dispersed. The larger the height difference of the liquid injection hole, the higher the degree of dispersion.

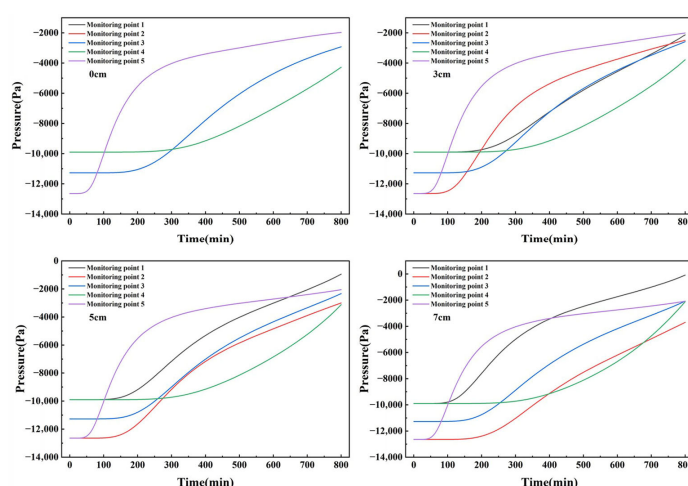


Figure 14. The change in water pressure at each monitoring point under different height differences of the liquid injection hole.

It can be known from the above that the height difference of the liquid injection hole is the driving force of asymmetric seepage and mass transfer. When there is no height difference in the liquid injection hole, the distribution of seepage and mass transfer is symmetrical and uniform. The larger the height difference of the liquid injection hole is, the more significant the spatial distribution difference of water pressure and concentration is. At the same time, there is a strong coupling relationship between seepage and mass transfer. The non-uniform distribution of water pressure directly determines the non-uniformity of convection and diffusion, and the change trend of the two is highly synchronized.

The increase in the height difference between adjacent liquid injection holes will accelerate the recovery of water pressure and magnesium ion leaching in the area near the liquid injection hole, but will delay the response in the remote area (see Table 3), and expand the difference in leaching efficiency within the ore soil, which also explains the

source of the previous ‘blind zone risk’ (long-term low water pressure and concentration in the remote area).

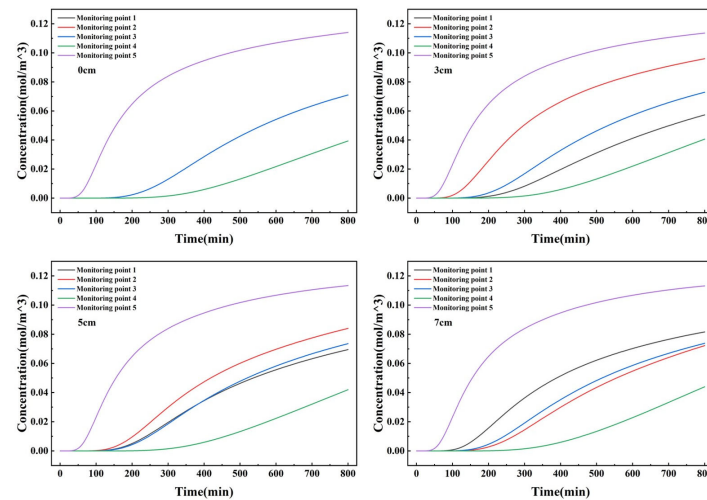


Figure 15. The change in concentration at each monitoring point under different height differences of the liquid injection hole.

Table 3. Comparison table of ‘water pressure–concentration’ response time of each monitoring point under different injection hole height differences.

Hole Height Difference	Monitoring Point	Time for Water Pressure to Rise Back to −5000 Pa (min)	The Time When the Concentration Reached 0.05 mol/m ³ (min)	Final Water Pressure (Pa, 800 min)	Final Concentration (mol/m ³ , 800 min)
0	1	100	150	−2000	0.12
	2	200	250	−4000	0.08
	3	300	400	−6000	0.05
	4	200	250	−4000	0.08
	5	100	150	−2000	0.12
3	1	80	120	−2000	0.10
	2	180	220	−4000	0.07
	3	350	450	−6500	0.04
	4	190	230	−4200	0.07
	5	90	130	−2200	0.09
5	1	70	100	−2500	0.09
	2	150	200	−4500	0.07
	3	400	500	−7000	0.04
	4	170	210	−4700	0.06
	5	80	110	−2700	0.08
7	1	60	90	−3000	0.08
	2	200	250	−5000	0.07
	3	450	550	−7500	0.03
	4	220	270	−5200	0.06
	5	70	100	−3200	0.07

5. Conclusions

Through laboratory experiments and numerical analysis software, this paper explores the influence of the height difference of adjacent liquid injection holes on the evolution of the wetting body in the in situ leaching of ionic rare earth ore, hoping to provide suggestions for mines to deal with related problems. The main research results are as follows:

(1) Compared with the traditional liquid injection method, the height difference between adjacent liquid injection holes will cause the intersection point of the wetting body to move backward during the leaching process. With the increase in the height difference between adjacent liquid injection holes, the vertical migration rate of the wetting peak at the No. 1 liquid injection hole will gradually accelerate, while the horizontal migration is basically the same. This shows that the larger the buried depth of the liquid injection hole, the hydraulic gradient under the height difference of different adjacent liquid injection holes changes, so as to promote the vertical migration of the wetting peak. At the same time, the observed cross-sectional area of the wet body gradually increases, indicating that there is a height difference between the two liquid injection holes, which can accelerate the in situ leaching process.

(2) The migration rate of the wetting peak is fast at first and then slow, and the speed is slower and slower in the later stage of leaching, resulting in a part of the upper part of the ore body being difficult to reach by the leaching solution, thus forming a blind area for leaching. When the height difference between adjacent liquid injection holes is 0 cm and 3 cm, it can be roughly considered that the blind area is basically concentrated in the upper part of the ore soil, between the two liquid injection holes. With the height difference between adjacent liquid injection holes reaching 5 cm and 7 cm, the blind area in the upper part of the ore soil can be seen to be expanding, and it is concentrated above the No. 1 liquid injection hole.

(3) By simulating the distribution of water pressure and the magnesium ion concentration in the soil under different height differences of adjacent liquid injection holes, the core influence of the height difference of liquid injection holes on the in situ leaching process was clarified. The height difference of the liquid injection hole is the asymmetric driving force of seepage and mass transfer. When there is no height difference in the liquid injection hole, the distribution of seepage and mass transfer is symmetrical and uniform. The larger the height difference of the liquid injection hole, the more significant the spatial distribution difference in water pressure and concentration. When the height difference between adjacent liquid injection holes is small, the wetting body is approximately symmetrically diffused with the liquid injection hole as the center, and the blind area is only distributed on the edge and is easily covered. After the height difference increases, the wetting body migrates asymmetrically, the water pressure and concentration in the distal area are low for a long time, and the risk of a local blind area is significantly increased.

Author Contributions: Conceptualization, Y.R., Q.H., C.Z. and G.R.; methodology, Y.R., G.R. and Q.H.; software, Y.X. and Q.H.; validation, Y.R., Q.H., G.R., J.W., Y.X. and Q.L.; investigation, C.Z. and Q.H.; resources, Y.R., Q.H., C.Z. and J.W.; data curation, Q.H., J.W., Y.X. and Q.L.; writing-original draft, Q.H.; writing-review and editing, Y.R., Q.H., C.Z. and G.R.; visualization, Q.H. and G.R.; supervision, Y.R. and C.Z.; project administration, J.W., Y.X. and Q.L.; funding acquisition, Y.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 51964014.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Xiao, Y.F.; Feng, Z.Y.; Hu, G.H.; Huang, L.; Huang, X.W.; Chen, Y.Y.; Li, M.L. Leaching and mass transfer characteristics of elements from ion-adsorption type rare earth ore. *Rare Met.* **2015**, *34*, 357–365. [\[CrossRef\]](#)
2. Feng, C.; Bi, X.; Liu, S.; Hu, R. Fluid inclusion, rare earth element geochemistry, and isotopic characteristics of the eastern ore zone of the Baiyangping polymetallic Ore district, northwestern Yunnan Province, China. *J. Asian Earth Sci.* **2014**, *85*, 140–153. [\[CrossRef\]](#)
3. Chen, Z. Global rare earth resources and scenarios of future rare earth industry. *J. Rare Earths* **2011**, *29*, 1–6. [\[CrossRef\]](#)
4. Zhang, Z.; He, Z.; Yu, J.; Xu, Z.; Chi, R. Novel solution injection technology for in-situ leaching of weathered crust elution-deposited rare earth ores. *Hydrometallurgy* **2016**, *164*, 248–256. [\[CrossRef\]](#)
5. Crespo, Ó.; Hermassi, M.; Gibert, O.; Cama, J.; Cortina, J.L. Optimizing the recovery of rare earth elements from acid mine water: A sustainable approach using selective precipitation. *Clean. Eng. Technol.* **2025**, *30*, 101123. [\[CrossRef\]](#)
6. Yang, X.; Zhang, J. Recovery of rare earth from ion-adsorption rare earth ores with a compound lixiviant. *Sep. Purif. Technol.* **2015**, *142*, 203–208. [\[CrossRef\]](#)
7. Li, Y.H.M.; Zhao, W.W.; Zhou, M.F. Nature of parent rocks, mineralization styles and ore genesis of regolith-hosted REE deposits in South China: An integrated genetic model. *J. Asian Earth Sci.* **2017**, *148*, 65–95. [\[CrossRef\]](#)
8. Yuan, W.; Wang, H.; Sun, D.; Yan, F.; Liu, C.; Zhang, X.; Dong, L. Analysis of Slope Stability in Ion-Adsorption Rare Earth Mine Under In Situ Leaching Condition. *Appl. Sci* **2025**, *15*, 6677. [\[CrossRef\]](#)
9. Cao, W.; Yan, G.; Hofmann, H.; Scheuermann, A. A Novel Permeability–Tortuosity–Porosity Model for Evolving Pore Space and Mineral-Induced Clogging in Porous Medium. *Geotechnics* **2025**, *5*, 2. [\[CrossRef\]](#)
10. Pham, K.; Kim, D.; Choi, H.J.; Lee, I.M.; Choi, H. A numerical framework for infinite slope stability analysis under transient unsaturated seepage conditions. *Eng. Geol.* **2018**, *243*, 36–49. [\[CrossRef\]](#)
11. Yang, X.J.; Lin, A.; Li, X.L.; Wu, Y.; Zhou, W.; Chen, Z. China’s ion-adsorption rare earth resources, mining consequences and preservation. *Environ. Dev.* **2013**, *8*, 131–136. [\[CrossRef\]](#)
12. Jia, M.; Luo, B.; Lu, F.; Yang, Y.; Chen, M.; Zhang, C.; Xu, Q. Improved FMM for well locations optimization in in-situ leaching areas of sandstone uranium mines. *Nucl. Eng. Technol.* **2024**, *56*, 3750–3757. [\[CrossRef\]](#)
13. Girardi, V.; Yerro, A.; Simonini, P.; Gabrieli, F.; Ceccato, F. Wetting induced instabilities in layered slopes: A Material Point Method analysis. *Eng. Geol.* **2023**, *313*, 106978. [\[CrossRef\]](#)
14. Yang, S.R.; Chen, X.R. Assessing rainfall-induced wetting band depth for stability analysis of unsaturated soil slopes. *Case Stud. Constr. Mat.* **2023**, *18*, e02180. [\[CrossRef\]](#)
15. Bentz, J.; Patel, R.A.; Benard, P.; Lieu, A.; Haupenthal, A.; Kroener, E. How Heterogeneous Pore Scale Distributions of Wettability Affect Infiltration into Porous Media. *Water* **2022**, *14*, 1110. [\[CrossRef\]](#)
16. Guo, K.S.; Zhuang, Y.F. A reactive transport model for in-situ leaching of weathered crust elution-deposited rare earth ores using ammonium sulfate. *Hydrometallurgy* **2023**, *222*, 106191. [\[CrossRef\]](#)
17. Sanematsu, K.; Kon, Y.; Imai, A.; Watanabe, K.; Watanabe, Y. Geochemical and mineralogical characteristics of ion-adsorption type REE mineralization in Phuket, Thailand. *Min. Depos.* **2011**, *48*, 437–451. [\[CrossRef\]](#)
18. Sepaskhah, A.R.; Chitsaz, H. Validating the Green-Ampt Analysis of Wetted Radius and Depth in Trickle Irrigation. *Biosyst. Eng.* **2004**, *89*, 231–236. [\[CrossRef\]](#)
19. Guo, Z.Q.; Lai, Y.M.; Jin, J.F.; Zhou, J.R.; Zhao, K.; Sun, Z. Effect of particle size and grain composition on two-dimensional infiltration process of weathered crust elution-deposited rare earth ores. *Trans. Nonferrous Met. Soc. China* **2020**, *30*, 1647–1661. [\[CrossRef\]](#)
20. Fan, Y.W.; Ren, C.; Yang, Z.W.; Zhang, C.Y.; Yin, W.F. Prediction of wetting pattern dimensions under moistube irrigation with a multivariate nonlinear model. *Water Sci. Eng.* **2023**, *17*, 217–225. [\[CrossRef\]](#)
21. Wu, F.; Wang, D.; Rao, Y.; Zhang, M.; Shi, L.; Han, M.; Xu, W. Mesoscopic Process Simulation of In Situ Leaching of Ionic Rare Earth Based on NMRI Technology. *Adsorpt. Sci. Technol.* **2023**, *2023*, 8348431. [\[CrossRef\]](#)
22. Zhang, L.; Wen, B.; Chen, L.; Chen, H.; Wu, K. Variations in pore structures and permeabilities of ion adsorption rare earth ores during simulated in-situ leaching: Effect of newly formed clay particles and their swelling. *Hydrometallurgy* **2024**, *228*, 106357. [\[CrossRef\]](#)
23. Negash, B.M.; Effiong, A.J.; Khan, H.W.; Zulkifli, N.I. Ion-adsorbed REE clays: Swelling challenges and future solutions. *J. Mol. Liq.* **2024**, *403*, 124849. [\[CrossRef\]](#)
24. Vigo, Á.D.; Zubelzu, S.; Juana, L. Infiltration models and soil characterisation for hemispherical and disc sources based on Green-Ampt assumptions. *J. Hydrol.* **2021**, *595*, 125966. [\[CrossRef\]](#)
25. Jamei, M.; Karimi, B.; Ali, M.; Alinazari, F.; Karbasi, M.; Maroufpoor, E.; Chu, X. A comprehensive investigation of wetting distribution pattern on sloping lands under drip irrigation: A new gradient boosting multi-filtering-based deep learning approach. *J. Hydrol.* **2023**, *620*, 129402. [\[CrossRef\]](#)

26. Wang, Y.; Wang, X.; Qiu, Y.; Wang, H.; Li, G.; Hu, K.; Zhong, W.; Guo, Z.; Li, B.; Zhang, C.; et al. Wetting front migration model of ion-adsorption rare earth during the multi-hole unsaturated liquid injection. *J. Rock Mech. Geotech. Eng.* **2024**, *16*, 483–496. [[CrossRef](#)]
27. Wang, Y.; Gao, F.; Sun, B.; Chen, W.; Nie, Z. Life cycle assessment for rare earth production from ion-adsorption deposits: A comparative study of magnesium sulfate and ammonium sulfate leaching techniques. *J. Environ. Manag.* **2025**, *385*, 125627. [[CrossRef](#)]
28. 20140025-Q-469; Technical specification for in-situ leaching mining of ionic rare earth ore (Chinese). Ministry of Industry and Information Technology: Beijing, China, 2014.
29. Ilankoon, I.M.S.K.; Neethling, S.J. Liquid spread mechanisms in packed beds and heaps. The separation of length and time scales due to particle porosity. *Miner. Eng.* **2016**, *86*, 130–139. [[CrossRef](#)]
30. Dianyu, E.; Su, Z.; Zeng, J.; Yang, L.; Li, J.; Xu, Q.; Wang, L.; Cui, J. Numerical Study of Percolation and Seepage Behaviors in Ion-Adsorption-Type Rare Earth Ore Leaching Process. *Math. Probl. Eng.* **2023**, *2023*, 5916294. [[CrossRef](#)]
31. Wang, D.; Wu, F.; Rao, Y.; Zhao, Z.; Xu, W.; Han, M. Microscopic Simulation of RE3+ Migration in Ion-Type Rare Earth Ores Based on Navier–Stokes Equation—Exchange Reaction—Ion Migration Coupling. *Metals* **2024**, *14*, 1130. [[CrossRef](#)]
32. Zhu, X.; Zhang, Q.; Liang, M.; Zhang, W. Mining-induced damage evolution and infiltration failure in deep mudstone-sandstone interbedded strata. *Results Eng.* **2025**, *28*, 107095. [[CrossRef](#)]
33. Zhang, J.; Wen, N.; Sun, Q.; Horton, R.; Liu, G. The effect of macropore morphology of actual anecic earthworm burrows on water infiltration: A COMSOL simulation. *J. Hydrol.* **2023**, *618*, 129261. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.