Research Article

A New Method for Reducing Collapsibility of Loess Foundation with Thicker Deposit: The Borehole Preimmersion Method

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1. Introduction

Loess is a yellow sediment deposited during the transportation of Quaternary aeolian sand that is widely distributed in arid and semi-arid areas within the mainland. Chinese loess covers an area of $64 \times 10^4$ km$^2$, accounting for 6.6% of the total land area of China; collapsible loess accounts for approximately 60% of the total area of Chinese loess. Collapsible loess has a strong bearing capacity in its natural state from the soluble cement used to connect the soil particles. When saturated, the bonding materials in loess are easily decomposed and collapse under the joint action of chemical and physical changes, resulting in collapsible deformation of loess [1–4]. Due to this special nature, buildings in collapsible loess areas must consider the impact of subsidence and deformation of the ground. It is vital to reduce or eliminate the collapsibility of the ground.

Currently, the preimmersion method is widely used in the treatment of the collapsible loess ground. This method can effectively eliminate the collapsibility of the treated ground. However, there are some problems, such as the long immersion time, the soaked loess range, and the total water consumption, which are not conducive to effective control of the construction period and can easily affect the surrounding buildings and cause damage. In this study, these problems are studied in detail, and a new preimmersion method is...
proposed to ensure the immersion effect and shorten the construction period to reduce the impact on surrounding buildings.

Many studies have been conducted on reducing the collapsibility of the loess ground [5–14]. In 1958, American scholars first used the preimmersion method to treat the ground of earth dams; in 1963, Romanian scholars used this method to treat the collapsible loess grounds under industrial workshops; in 1964, the Soviet Institute of Building Structure began to use the preimmersion method to treat the collapsible loess ground [5]. Since the 1960s, Chinese scholars have completed many in situ immersion tests under different site conditions in combination with engineering construction. Liao et al. [6], from the 1960s onward, conducted presoaking water tests for pit flooding in collapsible loess sites. Li et al. [7] first conducted an in situ immersion test of collapsible loess for Q2 loess. Huang et al. [8–10] studied the collapsible law of the large-thickness collapsible loess ground under self-weight conditions and external load conditions through many test pit immersion tests. An et al. [14] studied the settlement characteristics of loess by conducting a field immersion test on collapsible loess with water injection holes. Meng et al. [15] studied the permeability law of water in unsaturated layered loess and backfill remolded loess by the in situ water immersion test, rainfall test, and water storage test.

Another focal point in the study of the preimmersion method is understanding the migration rule of soil water in the loess ground. Darcy’s law was developed by Henry Darcy in 1856 based on the seepage test, which is still an important theory for seepage characteristics. In 1931, Richards developed the Richards equation using Darcy’s law as the basic theoretical equation to determine the water infiltration in unsaturated soil. Conte [16] determined the influence of the ratio of air and water permeability coefficients on pore air pressure, pore pressure, and compression settlement deformation in soil over time through a 1D consolidation test. In recent years, many scholars have studied loess permeability characteristics [17–23]. Hong et al. [21] introduced the capillary model of multiporous media into the seepage model of loess permeability. Xu et al. [23] studied the microscopic mechanism of anisotropic saturated permeability and the infiltration process of undisturbed loess.

To effectively use the soil parameters of an engineering site to analyze the permeability of loess, scholars have introduced the finite element method. Neuman [24] first used numerical analysis software to solve the unsaturated seepage of loess. Sammori and Tsuboyama [25] used the finite element method to solve the problem of unsaturated loess infiltration caused by rainfall infiltration on slopes. The finite element method has gradually matured in the study of loess permeability; loess scholars have adopted finite element software to simulate different working conditions [26–30]. Li et al. [29] used the commercial software VADOSE/W to simulate the flow characteristics of unsaturated loess concerning environmental factors. Modano et al. [30] studied the nature of the forcing function applied by a Vibrodyne and its influence on the results of simulations on the dynamics of a single degree of freedom system by the Experimental Modal Analysis (EMA) dynamic tests.

However, research on the physical mechanism of the preimmersion method in reducing loess ground collapsibility remains to be studied further; there are few research results from the perspective of a long immersion period, the soaked loess range, and the total water consumption. Moreover, few research results have been reported concerning calculation of the soaked loess volume and the total water consumption in the study of water infiltration characteristics in the loess ground.

These problems are discussed in detail and solved in this study, and new ideas and methods are presented. A new ground treatment method, the borehole preimmersion method, is proposed. Using theoretical analysis and numerical calculation, the theoretical design framework is proposed, and the diffusion form and mechanism of moisture in this method are discussed. The treatment effect and applicability of this method are evaluated using an in situ immersion test.

## 2. Basic Principle and Theoretical Model of the Borehole Preimmersion Method

### 2.1. Principle of the Method

There are three steps in the traditional preimmersion method for reducing the collapsibility of the loess ground [14]. First, a large immersion pit is excavated, slightly larger than the ground area at the site, and water is used to immerse the entire area of collapse. The saturated soil collapses under the effect of self-weight. The self-weight collapsibility of the entire loess stratum is reduced (full collapsibility is eliminated under additional loads). This method requires a long immersion period and a large amount of construction; controlling the scope of soaking and the total water consumption is difficult during the immersion process, which affects the surrounding buildings.

In view of these problems, based on the Standard for Building Construction in Collapsible Loess Regions [1], released jointly by the Ministry of Housing and Urban-Rural Development, PRC, and State Administration for Market Regulation in 2018, and the idea of borehole immersion, the borehole preimmersion method is proposed. In contrast to previous in situ immersion tests, the immersion pit used in the borehole preimmersion method consists of several water injection holes with diameters not less than 400 mm. Using water injection holes to immerse the site effectively shortens the immersion period, controls the immersion range, and reduces the impact of water immersion on surrounding buildings.

The basic steps of the method are shown in Figure 1.

#### 2.1.1. Determining the Design Parameters

To determine the basic physical and mechanical parameters such as dry density \( \rho_d \), void ratio \( e \), permeability coefficients \( K_x \) and \( K_y \), and the expected elimination range of the ground collapsibility, the immersion conditions of the site are numerically simulated, and the water injection hole diameter, hole depth, hole spacing, and immersion period are determined using ABAQUS finite element simulation software.
2.1.2. Determining the Volumes of the Soaked Loess and the Total Water Consumption. The volumes of soaked loess and the total water consumption calculation model of the impregnated loess presented in this study are used to estimate the water influence range and the total water consumption. If the water influence range is too large, the surrounding buildings are affected; the layout plan of the water injection holes should be optimized.

2.1.3. Site Construction and Follow-Up Evaluation. After site leveling, water injection holes are excavated according to the layout of the holes. The holes are filled with 1 m of sand and gravel as buffer materials to prevent water erosion of loess and collapse of the holes.

During the immersion process, the water head in the water injection hole should be maintained at the orifice position to ensure that the water is soaked in constant head infiltration. The water consumption was accurately measured using a water meter.

2.2. Immersion Calculation Model. Considering the engineering requirements, the calculation model of the borehole preimmersion method is presented here, including the calculation model of the volumes of soaked loess within a single water injection hole and group water injection holes and the calculation model of the total water consumption.

2.2.1. Calculation Model for Immersion with Single Water Injection Hole. The following assumptions should be made when calculating the volume of the soaked loess for a single water injection hole:

(i) In the test, the water head height is constant
(ii) Collapsible loess is heterogeneous and anisotropic
(iii) The flow of water in the saturated loess ground is laminar flow with uniform velocity

Figure 2(a) presents the hypothesis of the water infiltration lengths in different directions during the period \( t \). Point \( A \) is the infiltration point; \( AB = x \) is the seepage length of seepage water in the horizontal direction from point \( A \) in period \( t \); \( AC = h \) is the seepage length of seepage water in the vertical direction from point \( A \) in the period \( t \); \( AD = l_a \) is the seepage length of seepage water from point \( A \) in period \( t \) along any direction with an angle of \( \alpha \) from the vertical direction.

For any direction \( AD \) with an angle of \( \alpha \) from the vertical, the infiltration velocity is expressed as follows:

\[
v_a = \frac{k_x l_a \sin \alpha}{\Delta l_a} + \frac{k_y l_a \cos \alpha}{\Delta l_a}.
\]

where \( k_x \) is the horizontal equivalent permeability coefficient of the site and \( k_y \) is the vertical equivalent permeability coefficient of the site.

Taking the infiltration point as the starting point, the penetration velocity of each point in the same vector direction remains constant. In the horizontal direction, \( v_x = k_x l_a / \Delta l_a = k_x \); in the vertical direction, \( v_y = k_y l_a / \Delta l_a = k_y \). The seepage velocity in any direction with an angle of \( \alpha \) from the vertical direction can be expressed as follows:

\[
v_a = k_x \sin \alpha + k_y \cos \alpha.
\]

The relationship between the flow velocity of water in the loess pores and the seepage velocity is expressed as follows:

\[
u = \frac{v}{n}
\]

where \( u \) is the actual velocity of water seepage in soil, \( v \) is the Darcy penetration rate, and \( n \) is the porosity of the soil.

In the seepage calculation model with a period of \( t \), the seepage lengths in the horizontal direction, the vertical direction, and any direction with the included angle \( \alpha \) are expressed as follows:

\[
x = u_xt, \\
h = u_yt, \\
l_a = \frac{h(k_x^2 \sin \alpha + k_y k_x \cos \alpha)}{2k_x k_y} + \frac{x(k_y^2 \cos \alpha + k_x k_y \sin \alpha)}{2k_x k_y}
\]

The diameter of the water injection hole is assumed to be \( D_1 \), the depth of the water injection hole is \( Z \), and the vertical infiltration depth after immersion is \( h \). The shape of the soaked soil on any horizontal plane is assumed to be circular, and its diameter is \( D \). The relationship between \( D \) and \( D_1 \) is shown in equation (5); the calculation diagram of the soaked soil passing through the center of the circle is shown in Figure 2(b):

\[
D = D_1 + 2l_a \sin \alpha.
\]

The relationship between the depth of the water injection hole \( Z \) and \( l_a \) is expressed as follows:

\[
z = l_a \cos \alpha.
\]

According to equations (4) and (6), (7) can be obtained as follows:

\[
dz = m \cos 2\alpha + n \sin 2\alpha \, d\alpha,
\]
where \( m = (hk_xk_y + xk_y^2) \) and \( n = (xk_xk_y + hk_x^2) \), and according to \( dV = \left( nD^2/4 \right) dz \), the calculation formula for the volume of loess soaked through the water injection hole with diameter \( D_1 \) is expressed as follows:

\[
V = \frac{\pi}{12} m^2 n + \left( \frac{\pi^2}{4} - \frac{\pi}{24} \right) \frac{m^3 n}{D_1 n^2} + \frac{3\pi^2}{16} \frac{D_1 m n}{n^3}
\]  

(8)

2.2.2. Calculation Model for Immersion with Group Water Injection Holes. The following two assumptions should be made when calculating the volume of soaked loess saturated by immersion through multiple water injection holes:

(i) The single-hole immersion model for each water injection hole is the same. When using the same two water injection holes to immerse simultaneously, the hole spacing \( S \) must satisfy \( D_1 \leq S \leq D \) to achieve the expected treatment effect. The two water injection holes form a seepage confluence area along the vertical control section at the axis of symmetry.

(ii) The volume of soaked loess in each hole is not affected by the simultaneous infiltration through multiple water injection holes. For soaking with multiple water injection holes, the intersection area of the soaked soil between two adjacent holes is the area formed by the intersection of the immersing saturated front of the respective single-hole immersion areas and is not affected by other factors.

The depths of the two water injection holes are the same, both assumed to be \( Z \), with diameters of \( D_1 \) and a hole spacing of \( S \). During simultaneous soaking, the infiltration condition is shown in Figure 3(a). The depth of the upper intersection of the soaked soil is \( h_1 \); the depth of the lower intersection is \( h_2 \). At the two intersections, the diameter of the infiltration circle is equal to the distance between the water injection holes, expressed as \( D = S \).

The horizontal profile at the intersection of the soaked saturated soil is shuttle-shaped, and its area can be expressed as follows:

\[
S_j = \frac{1}{4} \left[ D^2 \arcsin \left( \frac{S}{D} \right) - DS \right].
\]

(9)

The depth of the upper intersection of the soaked soil is \( h_1 \); at this intersection point, the angle of the vertical direction from the seepage direction is \( \beta \). The depth of the lower intersection is \( h_2 \); at this intersection point, the angle of the vertical direction from the seepage direction is \( \gamma \). From equation (7), when \( Z \) changes from \( h_1 \) to \( h_2 \), \( \alpha \) changes from \( \beta \) to \( \gamma \).

From Figure 3 and equation (7), the height of the intersection of soaked saturated soil is expressed as equation (10), and the volume of the soaked loess at the intersection is expressed as equation (11). From the upper and lower limit expressions at the intersection of the soaked soil mass \( h_1 = l_\beta \sin \beta \) and \( h_2 = l_\gamma \sin \gamma \), the volume of the soaked loess at the intersection can be calculated using the following equation:

\[
dh_j = d(h_2 - h_1)
\]

\[
= \int_{\beta}^{\gamma} \left( \frac{hk_xk_y + xk_y^2}{2k_xk_y} \right) \cos 2\alpha + \left( \frac{hk_xk_y + hk_x^2}{2k_xk_y} \right) \sin 2\alpha \, d\alpha,
\]

(10)

\[
V_j = \frac{1}{4} \int_{\beta}^{\gamma} \left[ D^2 \arcsin \left( \frac{S}{D} \right) - DS \right] (m \cos 2\alpha + n \sin 2\alpha) \, d\alpha,
\]

(11)

\[
V_j = \frac{\pi}{12} \left( \frac{m}{n} - \frac{1}{2n} \right) (D_1 + m + n - 3\sqrt{3}S)^3.
\]

(12)

In summary, when immersing loess through two identical water injection holes, the calculation formula for the soaked loess is expressed as follows:

\[
V' = 2V - V_j.
\]

(13)
The calculation diagram for soaked loess volume when a group of water injection holes in a rectangular hole layout are immersing simultaneously is shown in Figure 4. To ensure the treatment effect when immersing through a group of holes, the spacing between adjacent holes and the spacing between diagonal holes must be considered. When the distances between adjacent holes and diagonal holes meet the design requirements, the loess layers in the pre-treatment area can be treated to achieve the desired effect.

The distances between adjacent holes $S_1$ and $S_2$ and diagonal hole spacing $S'$ satisfy the following equation:

$$S' = \sqrt{S_1^2 + S_2^2}. \quad (14)$$

The calculation formula for the soil volume at the soaked intersection of diagonal holes is expressed as follows:

$$V'_j = \frac{\pi}{12} \left( \frac{m}{n} - \frac{1}{2n} \right) (D_1 + m + n - 3\sqrt{3} S')^3. \quad (15)$$

From equations (14) and (15), the calculation formula for the soaked loess immersed through four rectangular water injection holes is expressed as follows:

$$V' = 4V - 4V_j + 2V'_j. \quad (16)$$

The volume of the soaked loess obtained from the calculation formula is slightly larger than the actual soaking volume, which meets the conditions of water savings and water control and also meets the minimum soaking volume requirements in engineering construction.

When the rectangular hole layout method is used to treat the collapsible loess ground, the number of vertical and horizontal single holes affects the calculation formula for soil volume. The number of horizontal single holes is assumed as $M$, and the number of vertical single holes is assumed as $N$; the number of intersections of soaked loess for adjacent hole spacing $S$ and diagonal hole spacing $S'$ is expressed as follows:

$$a_{M\times N} = 2(M \cdot N - N),$$

$$a_{M\times N} = 2(M \cdot N - M - N - 1). \quad (17)$$

The intersection area of the soaked soil slightly overlaps in the center of the rectangle; the overlapping volume has little influence on the total volume of the soaked loess and can be ignored. Substituting equation (17) into (16), when a rectangular hole arrangement is used, the number of horizontal single holes is $M$ and the number of vertical single holes is $N$; the formula for calculating the volume of soaked loess is expressed as follows:

$$V' = (MN)V - 2(MN - N)V_j + 2(MN - M - N + 1)V'_j. \quad (18)$$

2.2.3. Calculation Model for Total Water Consumption. In the actual project, soil with saturation $S_r \geq 85\%$ is considered as saturated soil. Assuming that the soil saturation in the saturated area reaches $S_r = 85\%$ at the end of soaking, the saturation density of the soil is expressed as follows:
3. Field Immersion Test

3.1. Background. An in situ immersion test was conducted on an engineering construction site in Tongchuan city, Shaanxi Province. Tongchuan city is located in the central part of Shaanxi Province, in the north of the Guanzhong Plain and in the south of the Loess Plateau. In terms of the regional structure, Tongchuan city is located in the Tongchuan fold in the source region of Shaanxi-Gansu-Ningxia Basin and in the south of the Weihe Loess Tableland with relatively flat strata.

The elevation of the test site is 721.35–724.32 m according to geological survey data; the collapsibility grade of the site is grade IV, and the thickness of self-weight collapsible loess is greater than 15 m. The strata information from top to bottom is characterized in Tables 1 and 2. The specific gravity of the loess on the site is 2.7; the horizontal equivalent permeability coefficient is $0.751 \times 10^{-3}$ cm/s, and the vertical permeability coefficient is $1.840 \times 10^{-3}$ cm/s. No underground water was found at the 15-m-deep test site. Thus, it is not necessary to consider the impact of groundwater on the test and sampling; the field is suitable for site testing and sampling. The test pit range is $10 \times 12$ m, and the proposed treatment depth is 14 m.

3.2. Selection of Design Parameters. Before immersion treatment of the site, the ABAQUS finite element simulation software was used to simulate the immersion conditions of the site to determine the diameter, depth, spacing, and number of water injection holes. The finite element method solves the seepage problem using the variational principle to transform the seepage differential equation and the relative boundary conditions into a linear equation system to find its functional extremum and obtain a solution. The seepage differential equation is expressed as follows:

$$I(h) = \frac{1}{2} \left[ k_x \left( \frac{\partial h}{\partial x} \right)^2 + k_v \left( \frac{\partial h}{\partial y} \right)^2 \right] dxdy. \quad (22)$$

The minimum value of the functional $I(h)$ is obtained using the variational principle, as shown in the following equation:

$$\left[ \frac{\partial I(h)}{\partial h} \right] = [K]^e [h]^e + [P]^e \frac{\partial (\bar{h})}{\partial t} \right]^e = 0, \quad (23)$$

where $\bar{h}$ is the water head whose boundary condition is the free water surface boundary, $k_x$ is the horizontal permeability coefficient, $k_v$ is the vertical permeability coefficient, and $[P]^e \frac{\partial (\bar{h})}{\partial t} \right]^e$ is a function of free head height with time in the boundary conditions.

The functional differentials of all elements of the calculation model $\Sigma I(h_i)$ are added to find the extreme value, $\Sigma \partial I(h_i)/\partial h = 0$. The equation group requires solving the functional of the regional seepage field and differentiating the node value between each element, known as the seepage balance equation, as shown in the following equation:

$$[K][h] + [P] \frac{\partial (\bar{h})}{\partial t} + [F] = 0, \quad (24)$$

where $[F]$ is the known node, added to equation (24) as a free term. The known node is a free term because it cannot be varied in the form of a seepage differential equation, and the head of each element node must be solved by simultaneous equations to obtain the solution.

To study the law of water infiltration under different working conditions (immersion within a single water injection hole or immersion within two identical water injection holes), this study establishes different seepage models. The models do not consider the influence of the fracture and water-barrier layer, and assume that the loess stratum is uniformly distributed. The single-hole seepage model uses a two-dimensional axisymmetric model; the double-hole seepage model uses a two-dimensional plane model. The shape of the model is a square with a length of 30 m. The horizontal direction is the diameter direction of the circular water injection hole; the vertical direction is the hole depth direction; the lower left corner of the model is the coordinate zero point. To the left of the model, there is a water injection hole; the depth and aperture of this hole adopt different parameters according to different working conditions. The water head in the water injection hole is maintained at the opening of the hole. The seepage model is presented in Figures 5(a) and 5(b).

The area adjacent to the water injection hole is the main immersion infiltration area. To make the calculation result convergent and accurate, the grid is divided into quadrilateral elements of $0.2 \times 0.2$ m and $0.4 \times 0.2$ m. The specific grid division is shown in Figures 5(a) and 5(b).

The left side of the model is an infiltration boundary; the bottom is a 10 m pressure head boundary; the side wall of the hole is a pressure head boundary varying with the hole depth; the top, sides, and bottom of the model are set with impermeable boundary conditions. The model mainly studies the law of water infiltration; thus, it does not consider the overall strain of the model, and the boundary of
constrained displacement and angular deformation is applied to the entire model.

The initial saturation of the soil layer in the unsaturated soil seepage model has a significant influence on the calculation results. The calculation parameters of the model in this study are based on the actual measured values. The average initial void ratio is 0.95, and the average dry density is 1.3 g/cm³; the initial saturation of each formation is calculated from data in Table 1. The soil-water characteristic curve must be analyzed to express the relationship between water content and matrix suction in the relationship between pore pressure and saturation. The moisture absorption curve and corresponding parameters are shown in Figure 5(c).

ABAQUS finite element simulation software was used to set a single water injection hole with a hole depth of 10 m and

### Table 1: Physical parameters of loess.

| Soil thickness | Collapsibility coefficient $\delta_S$ | Self-weight collapsibility coefficient $\delta_{ZS}$ |
|----------------|---------------------------------------|-----------------------------------------------|
|                | Maximum | Minimum | Average | Maximum | Minimum | Average |
| 0–15 m         | 0.103    | 0.005    | 0.034    | 0.05    | 0.002    | 0.020 |

### Table 2: Physical and mechanical properties of loess in the test field.

| Stratigraphic name | Water content (%) | Weight kN/m³ | Dry weight kN/m³ | Saturation $S_r$ (%) | Void ratio $(e)$ |
|--------------------|-------------------|--------------|------------------|--------------------|-----------------|
| Loess $Q_{el}^1$   | 15.1              | 14.7         | 12.7             | 36                 | 1.134           |
| The ancient soil $Q_{el}^1$ | 17.8 | 16.4 | 13.8 | 51 | 0.963 |
| Loess $Q_{el}^2$   | 14.8              | 15.0         | 13.1             | 38                 | 1.068           |
| The ancient soil $Q_{el}^2$ | 17.7 | 16.4 | 13.9 | 61 | 0.953 |

Figure 5: (a) Calculation model of the single water injection hole. (b) Calculation model of double water injection holes. (c) Moisture absorption curve.
Immersion holes were excavated, with a diameter of 0.4 m. The saturation distribution cloud diagram over time is shown in Figure 6. The relationship curve between the vertical depth and the horizontal radius of the saturated area and the immersion period is shown in Figure 7.

It is observed in Figures 6 and 7 that, in the initial stage of water immersion, the diffusion rate in the saturated area is high due to the unsaturated state of the loess ground, and the vertical infiltration speed is greater than the horizontal infiltration speed. After 3 d of immersion, the vertical and horizontal diffusion rates of the saturated range decrease, and the infiltration radius is essentially stable. However, the depth of infiltration still changes greatly with time. When the flooding period reaches 7 d, the vertical infiltration rate slows and the infiltration depth tends to stabilize. In this study, the immersion period in the in situ immersion test is selected as 7 d.

With an immersion period of 7 d and a water injection hole diameter of 0.4 m, the immersion conditions of a single water injection hole with different hole depths (2.5 m, 5 m, 7.5 m, 10 m, 12.5 m, and 15 m) were simulated. The relationship between the infiltration depth, the infiltration radius, and the immersion period is obtained, as shown in Figure 8. According to the proposed treatment range of the test, it is observed that water injection holes with a depth of 10 m are more suitable in the in situ immersion test. The simulation results assuming two identical water injection holes (hole diameter of 0.4 m and hole depth of 10 m) are shown in Figure 9 for a hole spacing of 2 m and an immersion period of 7 d. The soaked loess was evenly distributed, and the soil between the holes was completely saturated. According to the results of the numerical simulation, preliminary design can be conducted for the layout of water injection holes at the site.

The water injection holes were arranged in a rectangular shape in a 3 × 3 formation (nine holes). The hole spacing was 2 m, the hole diameter was 0.4 m, and the hole depth was 10 m.

### 3.3. In Situ Immersion Test

The design of the water injection holes was adjusted according to the site conditions, and a 10 m × 12 m rectangular immersion pit with a depth of 2 m was formed after excavation and site leveling. Nine identical immersion holes were excavated, with a diameter of 400 mm and a hole depth of 10 m, arranged in a 3 × 3 rectangle, and evenly distributed on the bottom of the ground pit. The detailed arrangement method is shown in Figure 10. During the immersion process, the water head in the water injection holes should be kept at the orifice position to ensure that the water is soaked through constant head infiltration. The water consumption was accurately measured using a water meter. The total immersion period for the in situ immersion test was 7 d. After the in situ immersion test, the soil 1–15 m below the surface was divided into 15 layers with a thickness of 1 m. The exploration holes a, b, and c are shown in Figure 10(a). The exploration holes a, b, and c were used to sample from each soil layer; the water content, collapsibility coefficient, and self-weight collapsibility coefficient were measured, and the treatment effect of the borehole immersion method was evaluated.

### 4. Evaluation of the Treatment Effect of the Immersion Method and Verification of the Theoretical Model

#### 4.1. Variation Law of the Moisture Content in the In Situ Soil Layer

Through the in situ immersion test and boring sampling, the variation law of the moisture content was obtained; the treatment range and effect of this method are discussed. The moisture content of the soil at different depths and different saturations can be calculated based on the basic physical indicators of the formation in Table 1 and the moisture content calculation formula $\omega = \left(\\frac{(d_s + S_r e)\rho_w(1 + e)\rho_s}{\rho_w}\right) - 1$. When the saturation $S_r = 85\%$, the calculated moisture contents at different depths are evenly distributed between 27% and 38%; when the saturation $S_r = 100\%$, the calculated moisture contents at different depths are evenly distributed between 32% and 44%. A comparison of the measured moisture content variation curve for each exploration hole and the calculated saturated moisture content at different depths is shown in Figure 11.

Figure 11 indicates that the moisture content measured in each exploration hole changes suddenly between 7–8 m. The soil depth was divided into greater than 7 m and less than 7 m for analysis. The average moisture content in exploration holes a, b, and c above and below 7 m was compared with the calculated moisture content of the formation when $S_r = 85\%$ and $S_r = 100\%$, respectively. The comparison is presented in Table 3.

After immersion, the moisture content distribution of exploration hole a was uniform and close to the calculated moisture content with a saturation of 85%; the moisture content below 7 m was higher than the calculated moisture content with a saturation of 85%. The moisture content of exploration hole b changed greatly with the depth of the soil layer, and the sudden increase in the moisture content at 7 m was most obvious. The change in the moisture content of the formation above 7 m was less than that of the natural moisture content of the soil layer, and the effect of soil immersion was poor; the moisture content below 7 m was approximately equal to the calculated moisture content with a saturation of 85%. The moisture content distribution of exploration hole c was relatively uniform, with an average increase of 2.305% compared with the natural moisture content; at a depth of 8 m, the increase in moisture content reached its maximum, 5.395%.

According to the change in the formation moisture content measured by each exploration hole after immersion in water, the saturation of soil in each layer was calculated, and the distribution curve of formation saturation was drawn, as shown in Figure 12. Figure 12 shows that, after water immersion treatment, each stratum in exploration hole a tends to almost complete saturation; the saturation changes little with the depth of hole a formation, and the distribution is uniform. The saturation distribution of the stratum above 7 m in exploration hole b is approximately 40%, which is an unsaturated state. Above 7 m, the soil...
Figure 6: Saturation distribution nephogram of a single water injection hole at different time points: (a) 1 h; (b) 12 h; (c) 1 d; (d) 3 d; (e) 5 d; (f) 7 d.
saturation distribution is approximately 80%, which can be regarded as near-saturation. The soil mass in each layer in exploration hole $c$ was not saturated, and the soil was not within the scope of immersion treatment.

Figure 13 shows a cloud chart of the saturation distribution of ground soil with single-hole soaking; the variation in saturation at exploration holes $a$, $b$, and $c$ is shown.

With a continuous increase in stratum depth, the void ratio $e$ of loess decreases gradually; with a gradual increase in the dry density $\rho_d$, the permeability coefficient of the soil layers gradually decreases; with a decrease in water head and an increase in seepage path, the seepage force decreases. Thus, after immersion treatment, the moisture content of the slightly deeper soil layers changes significantly; the moisture content of deeper soil layers changes less, and the saturation gradually approaches that of the natural soil layer. According to the change rule of the moisture content, the diffusion pattern of water is similar to a mushroom shape.

![Figure 7: Relation curve of infiltration depth, infiltration radius, and infiltration time.](image)

![Figure 8: (a) Change curve of infiltration depth with immersion time. (b) Infiltration radius change curve with immersion time.](image)

![Figure 9: Cloud map of saturation distribution for double water injection holes.](image)
Figure 10: (a) Layout of water injection holes (unit: mm and scale: 1:100). (b) Immersion field.

Figure 11: Comparison of moisture contents.

Table 3: Average differences in moisture content.

| Exploratory point | Moisture content range (%) | Depth (m) | Moisture content increment |
|-------------------|----------------------------|-----------|---------------------------|
|                   |                            | ≤7        | ΔωO (%)                  | ΔωS=85% (%) | ΔωS=100% (%) |
| a                 | 28–34                      | ≤7        | 15.723                   | −0.503      | −11.061       |
|                   |                             | >7        | 14.975                   | 0.078       | −5.441        |
| b                 | 15–32                      | ≤7        | 2.380                    | −18.377     | −24.404       |
|                   |                             | >7        | 13.987                   | −0.909      | −6.428        |
| c                 | 14–21                      | ≤7        | 2.223                    | −18.534     | −24.5561      |
|                   |                             | >7        | 2.387                    | −12.509     | −18.028       |

ΔωO is the average value of the difference in the site’s original moisture content; ΔωS=85% is the average value of the difference between the calculated values with a saturation of 85%; ΔωS=100% is the average value of the difference between the calculated values with a saturation of 100%.
According to the Standard for Building Construction in Collapsible Loess Regions, loess with a saturation of 85% is regarded as saturated loess. It is assumed that only the saturated loess is subject to the effect of eliminating collapsibility. From Figure 13, the effective treatment range of the in situ immersion test can be obtained. The range is 14.5 m in depth, 8.25 m in length, 7.8 m in width, and the effective immersion radius of a single water injection hole is 2.1 m.

4.2. Evaluation of the Collapsibility Treatment Effect on Loess. The change data of the self-weight collapsibility coefficient and the collapsibility coefficient of each exploration hole after immersion treatment were analyzed, and the changes in collapsibility coefficient before and after water immersion were compared; the variation trend of collapsibility characteristics is shown in Figure 14.

Figure 14(a) shows the variation curves of self-weight collapsibility with layer depth in different exploration holes; the comparison results are as follows: (1) the self-weight collapsibility of exploration hole a is completely eliminated, and the collapsibility coefficient changes uniformly with the depth of the soil layers. The collapsibility coefficient is distributed around 0.005, and the maximum value is 0.006; (2) exploration hole b only eliminates the self-weight collapsibility of the surface and below the boundary line. The distribution of the collapsibility coefficient varies greatly with the depth of the soil layers. The minimum value is 0.003 for the soil sample at 15 m; the maximum value is 0.03 for the soil samples at 4 m and 7 m; and, (3) because exploratory hole c is not within the range of immersion treatment, the test results show that the soil samples with depths of 1 m and 2 m have no self-weight collapse deformation; the soil samples at other depths have collapsible deformation.

Figure 14(b) shows the variation curve of the collapsible coefficient with layer depth of soil samples from different exploratory holes. Compared with the variation curve of the self-weight collapsibility coefficient with layer depth of soil samples in Figure 14(a), the results are as follows. (1) There is no significant difference between the curves of the collapsibility coefficient for exploration hole a with the depth of the soil layer in the two figures; there is no significant difference between the two curves of the soil sample in
The exploration of hole b below a layer depth of 8 m; (2) both have collapsible deformation, and the curves at 1–2 m are significantly different. In Figure 14(b), the collapsibility coefficients of the soil samples at 1–2 m are 0.092 and 0.089; those in Figure 14(a) do not reach 0.015. The difference is large, which indicates that the saturated self-weight stress of the soil sample does not reach the initial collapsibility pressure; thus, the collapsibility of this part of the soil is not eliminated; (3) collapsible deformation occurred in the soil samples at 3–7 m in the two exploration holes b, the difference in the collapsibility coefficient between these holes. The test results show that the borehole preimmersion method can effectively eliminate the self-weight collapsibility and external load collapsibility of the soil within the treatment range.

4.3. Validation of Model Rationality. The effectiveness of the proposed method is demonstrated in the results of the in situ immersion tests. Based on the results, this study compares the calculation results of the theoretical model with the results obtained from in situ immersion tests to demonstrate the rationality of the established calculation model and provide a basis for subsequent application of the model. In this study, the method of hole arrangement was rectangular and the number of horizontal and longitudinal single holes was three; the horizontal hole spacing was 1.8 m, and the longitudinal hole spacing was 2.025 m; the equivalent soaked depth h of a single water injection hole was 14.5 m, and the equivalent soaked radius x was 2.1 m. The permeability coefficient of loess is the equivalent permeability coefficient; the horizontal equivalent permeability coefficient is $0.751 \times 10^{-3}$ cm/s, and the vertical permeability coefficient is $1.840 \times 10^{-3}$ cm/s. Substituting the field-measured data, parameters m and n can be calculated as $m = (hk_xk_y + xk_y^2)/2k_xk_y = 9.82$ and $n = (xk_xk_y + hk_x^2)/2k_xk_y = 4.01$.

Substituting the field-measured data into equation (18), the volume of the soaked loess can be obtained as 4442 m$^3$. The specific gravity of loess on the site is $d_s = 2.7$, the equivalent dry density is $\rho_d = 1.318$ g/cm$^3$, and the equivalent void ratio $e = 1.069$. Substituting these into equation (20), the moisture content in the saturated state $\omega_{sat}$ can be obtained as $\omega_{sat} = 32.3\%$.

Substituting $\rho_d = 1.318$ g/cm$^3$ and $\omega_{sat} = 32.3\%$ into equation (21), the total water consumption can be calculated as $Q = \rho_d\omega_{sat}$ and $V' = 1434.766$ m$^3$.

In summary, when using the borehole preimmersion method with a $3 \times 3$ rectangular hole layout to treat the collapsible loess site with an equivalent range of $8.25 \times 7.8 \times 14.5$ m, the calculated total water consumption is 1434.766 m$^3$. The actual total water consumption in the in situ immersion test pit was 1250 m$^3$, with an error of 14.8%. The calculation parameters selected by the model are conservative values, and the error is within an acceptable range. Thus, the calculation models of the volume of soaked loess and the total water consumption using the rectangular layout proposed in this study are feasible.

5. Conclusions

Based on the traditional presoaking water method, the following research results are obtained using theoretical analysis, numerical calculation, and field tests:

(1) The borehole preimmersion method is proposed to effectively reduce the collapsibility of the loess ground. The mechanism and law of water diffusion in the loess ground were discussed in detail, and a calculation model was developed to obtain the volume of soaked loess and the total water consumption for single holes and group holes.
(2) Through engineering applications, this method can effectively reduce the self-weight collapsibility of loess. The error between the model calculation and the test results of water immersion is small, which indicates the reliability of the model.

(3) The water injection holes can be backfilled with cement soil or lime soil after the immersion is completed, or filled with sand and gravel for grouting to form a plain concrete pile. The new methods proposed in this study can provide a new perspective and theoretical framework and can be successfully applied in engineering to effectively reduce the collapsibility of the loess ground.

Data Availability
No data were used to support this study.

Conflicts of Interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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