Prediction of Permeability Coefficient of Unsaturated Loess in Dry-Wet Cycle based on Thermodynamics and Microstructure Evolution Law

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Abstract

soil-water characteristic curve describes the relationship between matrix suction and soil saturation (or water content). It affects the shear strength, deformation and seepage behavior of unsaturated soil, and is a very important research content in unsaturated soil mechanics. Based on the internal variable theory of thermodynamics, a soil-water characteristic curve model is proposed, which can comprehensively consider the capillary hysteresis effect and the influence of unsaturated soil volume deformation. Based on the evolution law of microstructure, the moisture distribution in loess under natural humidity was analyzed, and the relationship among pore fractal dimension, unsaturated pore porosity and collapsibility was analyzed by regression analysis. The results show that the larger the pore fractal dimension is, the more complex the pore structure is. The collapsibility coefficient of loess increases with the increase of pore fractal dimension and unsaturated pore porosity, which is the main cause of loess collapsibility. By comparing with the existing test results, it is shown that the model can well predict the change of scanning line of soil in different processes of drying and wetting.

Keywords: Soil-water characteristic curve; Thermodynamics; Microstructure; Unsaturated loess; pPermeability coefficient

1. Introduction

Loess is widely distributed in northwest China, and most of it is above the groundwater level, which is a typical unsaturated soil. Studies have shown that the permeability coefficient is an important material parameter reflecting unsaturated soil [1]. Because of the concentrated rainfall and high environmental temperature in northwest China in summer, the loess is constantly in the cyclic process of rainfall infiltration and evaporation of water vapor, which leads to changes in the internal structure of loess and ultimately affects its permeability and mechanical properties [2]. Unsaturated permeability coefficient is a function of volume water content of rock and soil or matrix suction. Direct testing of unsaturated permeability coefficient is time-consuming and labor-intensive, and the testing cost is high. At present, the widely used method is to predict and analyze the unsaturated permeability coefficient based on the soil-water characteristic curve of rock and soil. Water is one of the external causes of loess collapsibility. Loess with obvious high strength and low compressibility under natural low humidity, once soaked in water or even humidified, will have a sharp drop in strength and sharp increase in deformation [3]. There have been systematic experimental studies on the water sensitivity of loess, and the results have been obtained [4-5].

The microstructure of loess is a spatial concept, and its composition depends on the shape and contact relationship of coarse mineral particles, pore size and distribution, type and occurrence state of cement and degree of cement [6]. Through the joint efforts of several generations of scholars in the past century, classical soil mechanics has made great progress and brilliant achievements, and established an independent and perfect theoretical system. The test shows that the effective stress formula of unsaturated soil is not a single-valued function, but is related to the stress path, and its relationship with saturation is not unique [7-8]. Literature [9] tests unsaturated soil by consolidation test, and the results show that all unsaturated soil samples collapse with the decrease of suction. Literature [110] found that temperature has a certain influence on unsaturated permeability coefficient. Literature

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[11] proposed a method to obtain unsaturated permeability coefficient based on electronic analysis table. Literature [12] puts forward three basic indexes to characterize the function of soil permeability coefficient: shrinkage curve, volumetric water content and saturated permeability coefficient. Literature [13] The permeability function of unsaturated loess is obtained by using the joint test method of unsaturated soil moisture movement, considering the comprehensive influence of humidity and density on the permeability function. Literature [14] based on the continuum theory and the characteristics of unsaturated soil, the effective stress which is dual with the deformation of solid skeleton is derived, and the generalized effective stress principle of unsaturated soil is obtained by the deformation work.

Different mineral compositions determine different loess microstructures, and loess microstructures directly affect and determine the physical and mechanical properties of loess, and then affect the stability of loess [15-16]. Under natural low humidity, some pores may be completely saturated, while others are unsaturated, and the saturated pores are less likely to be damaged by water immersion. From the microscopic point of view, this paper reveals the evolution law of microstructure of unsaturated soil when suction changes. Based on the internal variable theory of thermodynamics, a soil-water characteristic curve model is established, which can simultaneously consider the influence of unsaturated soil volume deformation and capillary hysteresis effect. By establishing the relationship between the pore distribution curve and the pore ratio, a mathematical model that can predict the permeability coefficient of unsaturated loess in dry-wet cycle is derived.

2. Factors affecting soil-water characteristic curve

There are many factors affecting the soil-water characteristic curve, such as mineral composition and pore structure, compacted water content, compactness, stress history, temperature and so on. On the whole, the mineral composition and pore structure of soil are the decisive factors to determine the position and shape of soil-water characteristic curve, and both of them indirectly change the soil-water characteristic curve by influencing these two basic factors. When these factors change, the change of soil-water characteristic curve is mainly reflected in three key parameters: air intake value, dehydration rate and water content.

Particle size distribution is usually used to characterize the proportion of particle sizes of different grades in the mixture of different particle sizes. Gradation is often expressed as a percentage of the total. Reasonable particle size distribution is an important way to prepare low porosity samples. The particle size of soil is mainly determined by the mineral composition of soil, and gradation is one of the important basis for judging the soil type. Generally speaking, the smaller the particle size, the greater the viscosity. However, for the soil samples with initial water content higher than the optimal water content, the pore size in the soil samples is uniform, and the lack of macropores leads to higher air intake value, so it is difficult to discharge pore water. Therefore, the increase of initial water content will lead to the increase of air intake value and dehumidification rate of soil.

A large number of test results show that [17-18], the degree of soil deformation or compactness has a great influence on the soil-water characteristic curve. In addition, the deformation of soil skeleton is also influenced and restricted by the change of suction. Most of the soil-water characteristic curve models can't consider the influence of soil structure changes, so they will produce large errors when predicting the hydraulic-mechanical coupling behavior of unsaturated soil. Therefore, when establishing the equation of soil-water characteristic curve, the influence of soil elastic-plastic deformation on soil-water characteristic curve should be considered.

3. Research method

3.1. Evolution law of microstructure of unsaturated soil

Unsaturated soil is a porous medium composed of water, gas and solid particles. Because of the existence of

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gas interface in unsaturated soil, its permeability characteristics are very complex, and the permeability coefficient can not be determined by conventional test methods [19]. The indirect measurement test of unsaturated soil permeability coefficient is to measure the water content and matrix suction of unsaturated soil under different confining pressures, and draw the corresponding soil-water characteristic curve, and then deduce the permeability coefficient of unsaturated soil according to the soil-water characteristic curve. The soil sample in this laboratory is the fill of a highway embankment, and its physical and mechanical properties are shown in Table 1.

Table 1 Basic physical and mechanical indexes of test loess samples

Index	numerical value
Effective particle size d_{10} / mm	0.0008
Continuous particle size d_{30} / mm	0.0033
Constrained grain size d_{60} / mm	0.0115
Uneven coefficient C_u	11.87
Curvature coefficient	1.28
Wet density ρ /(g/cm^3)	2.14
Dry density ρ_d /(g/cm^3)	1.87
Specific gravity G_s	2.73
Void ratio e_0	0.611
Liquid limit W_l / %	26
Plastic limit W_p / %	17
Plasticity index I_p / %	10

204 FEI Quanta FEG 600 scanning electron microscope was used to study the microstructure characteristics of the soil samples. The electron microscope test needs to go through: sampling, soil sample drying, gold spraying, testing, software data processing and other procedures. Ensure that the soil samples are not disturbed in the subsequent test process, so that the obtained microscopic images can truly reflect the special structure of collapsible loess. After 3 months of hardening, the soil samples were cut, ground and polished to make the surface smooth, clean and free of suspended particles, and then made into samples.

When the salinity of seepage liquid decreases, the effective porosity will decrease because the pore space is occupied by bound water, and the viscosity of bound water is higher than that of free water. For expansive soil with high montmorillonite content, when the concentration of electrolyte increases, the swelling pressure of clay particles will decrease, and the size of flow channels will increase, so the inherent permeability coefficient will increase, which will lead to the increase of permeability coefficient [20]. The permeability of unsaturated soil is related to the bending factor of soil pores, and the bending factor is directly related to stress state, soil suction and soil structure.

Literature [21] puts forward that the total void ratio e_0 can be divided into micro void ratio e_0 and macro void ratio e_M, so there is $e_0 = e_m + e_M$. The water in micropores is considered to be immobile. Therefore, the inherent permeability coefficient k is a function of macropores, which can be calculated as follows:

$$k = k(e_M) = k[e_M(S)] \quad (1)$$

When the void ratio e changes, the permeability coefficient changes greatly. However, the permeability of high-pressure compacted bentonite, a special clay, is closely related to the change of microstructure. Dry density, compressive stress, hydration, salinity and temperature will affect the microstructure of bentonite. When the microstructure of bentonite changes, the effective cross section of bentonite will change, so the permeability coefficient of bentonite will change.

In order to study the infiltration characteristics of loess under different irrigation durations, the infiltration durations of 0 d, 5 d, 10 d, 15 d and 20 d were set in this experiment. Calculate the final permeability coefficient of loess after different infiltration periods. The test results are shown in Figure 1. In Figure 1, D indicates undisturbed loess samples, and "D-1~D-4" indicates that the infiltration duration of loess samples is 5 d, 10 d, 15 d and 20 d.

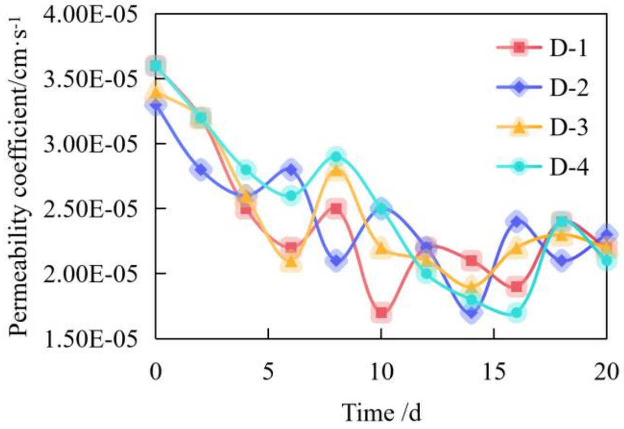

Figure 1Relationship of loess permeability coefficient with time

From Figure 1, it can be found that with the increase of infiltration time, the permeability coefficient of saturated loess has been decreasing, and after the further increase of infiltration time, the decreasing range of permeability coefficient begins to decrease and finally tends to be stable.

The pore distribution of soil satisfies the fractal model statistically, so the pore distribution function of soil conforms to formula (1). Considering pores as spheres, the total volume of pores in soil can be expressed as:

$$V_v = \int_0^{d_{\max}/2} N \cdot 4\pi r^2 dr \quad (2)$$

$d_{\max}$ is the maximum pore size of pores.

In unsaturated soil, the water content is unevenly distributed due to the influence of matrix suction. The small pores with larger matrix suction have higher water content and are often filled with water, while the large pores have lower water content, which is usually unsaturated or even contains no water. The pore structure characteristics of unsaturated soil determine that water in soil is mainly distributed in pores, and pores with small pore sizes are saturated by water first [10].

In soils with different water contents, the maximum radius of pores filled with water is different. If the maximum pore size of water-filled pores is d, the total volume of water in the soil can be expressed as:

$$V_w = \int_0^{d/2} br^{-D} 4\pi r^2 dr = \frac{4\pi b}{3-D}\left(\frac{d}{2}\right)^{3-D} \quad (3)$$

With the increase of depth, the soil gradually becomes dense from loose, the pores in the soil gradually decrease, the soil particles gradually gather into clumps from loose grains, the arrangement among the soil particles gradually changes from micro-cemented structure to cemented structure, and the stability gradually improves. It shows that there are abundant overhead pores and strong compaction deformation between microstructure particles, and the soil particles are mainly powder particles. With the increase of the depth of soil sample, the soil is plastically deformed, and the cement filled between soil particles is flattened into sheets.

3.2. Prediction of permeability coefficient of unsaturated loess in dry-wet cycle based on thermodynamics

The permeability coefficient of unsaturated soil often varies widely numerically and is not easy to measure. Therefore, the acquisition of unsaturated soil permeability parameters has always been a difficult point in unsaturated soil research. In practice, it is often necessary to use simple and effective indirect methods to obtain permeability parameters.

In recent years, many scholars have established the soil mechanics of continuous porous media by combining the mechanics of porous media with the classical mechanics of continuous media. Soil mechanics of continuous porous media is mainly based on macroscopic method of continuous media mechanics, which studies the mechanics of porous media from macroscopic angle and establishes a complete theory of multiphase porous media. Describing the behavior characteristics of various soils by the theory of multiphase porous media is the main purpose of soil mechanics with continuous porous media.

One of the biggest characteristics of soil-water characteristic curves is the lag effect. The curves obtained during the dry-wet cycle do not coincide, and the scanning lines obtained under different hydraulic history conditions do not coincide. In order to describe this hysteresis effect, researchers have done a lot of experimental research on different types of soils and put forward a lot of theoretical models [22]. In order to more accurately describe the mechanical behavior of soil in the non-equilibrium process, it is necessary to establish the soil-water characteristic curve model under dynamic conditions. At present, there are two main types of models [23]: first, the pore-scale grid model, which needs to consider the microscopic interface and be calculated by means of statistical theory, electron microscope scanning and other experimental means, is rather complicated; The second is a macro-scale dynamic model, which is mainly based on experimental phenomena and empirical equations, and is convenient for application. This paper will mainly build a hysteresis model based on macro-models.

Thermodynamics is a universal theory and method. Starting from thermodynamics, it is a new research method with strict scientific theoretical basis to study and describe the strength, deformation, soil-water characteristic curve and expression of unsaturated soil.

Without considering the influence of temperature and mass exchange, ignoring the compressibility of solid particles and fluid, the basic expression of deformation work of unsaturated soil per unit volume is derived. On this basis, further considering the influence of interface, the inequality of entropy increase of unsaturated soil fluid is given in reference [20]:

$$\left[n\left(p_g - p_w\right) + \lambda^{wg}\frac{\partial a^{wg}}{\partial S_r}\right]dS_r - d\varphi_w \geq 0 \tag{4}$$

In which n is porosity; p_g, p_w is pore air pressure and pore water pressure respectively; S_r is saturation; λ^{wg} is the surface tension; a^{wg} is the area of gas-liquid interface; φ_w is the free energy of water. The first term is the pressure difference of pore fluid, and the second term is the macroscopic capillary force, which is expressed by p_c.

Equation (5) derived from thermodynamic theory can be used to calculate the dynamic soil-water characteristic curve. Because the boundary line of the soil-water characteristic curve under equilibrium condition can be given by

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empirical equation (such as VG model, etc.), equation (5) can directly calculate the dynamic boundary line, and the calculation of scanning line needs the help of boundary surface model.

$$p_c^d = p_c - \tau \dot{S}_r \quad (5)$$

Where $\tau = \tau^{'} / n$, $p_c^d = p_g - p_w$ represents the dynamic capillary force, which is equal to the pressure difference of fluid, and p_c is the capillary force at equilibrium, which can be calculated by the traditional equation of soil-water characteristic curve. The existence of the second term on the right side of the equation shows that the dynamic capillary force at this time is related to the change history of saturation, and some experiments have proved that this hydraulic history will affect the deformation and strength of soil.

In practice, due to the influence of climate and environment, the soil experienced dry-wet cycles, resulting in its water-holding characteristic curve often lying on the scanning line. Generally, it is easier to determine the equation of boundary line through indoor tests, but the scanning line is closely related to hydraulic history and difficult to determine. According to the boundary surface plasticity theory, the plastic reaction on the loading surface depends on the distance between the stress point on the loading surface and its mapping point on the boundary surface.

According to equation (5), the dynamic boundary curve is no longer the same as the boundary curve under static conditions, which are:

Boundary humidification curve:

$$p_c^d = \kappa_w(S_r) - \tau_w \dot{S}_{rw} \quad (6)$$

Boundary drying curve:

$$p_c^d = \kappa_D(S_r) - \tau_D \dot{S}_{rD} \quad (7)$$

When the scanning line is predicted, the boundary line with the same speed is generally used. When the saturation is the same, the difference r^d of suction between the two boundary lines can be expressed as:

$$r^d = \kappa_D(S_r) - \kappa_w(S_r) - \left(\tau_D \dot{S}_{rD} - \tau_w \dot{S}_{rw}\right) \quad (8)$$

Combine with that initial conditions given by equation (7), use:

$$\dot{p}_c^d = -K_\alpha^d \dot{S}_r \quad (9)$$

Through the above steps, the model of dynamic scanning line is established. When calculating, the equation of boundary curve should be given first, and then the parameter c and fine damping coefficient of scanning line can be calibrated, so that the dynamic scanning line can be predicted.

The general hysteretic model established in the previous section is concretized below, and a simplified hysteretic model of soil-water characteristic surface is given. There are many formulas for soil-water characteristic surface considering the influence of deformation, and different formulas can be selected according to specific situations. For the convenience of calculation, the boundary surface equation is selected as the model proposed by Tarantino [17]:

$$(S_r)_{d,w} = \left\{1 + \left[\left(\frac{e}{a_{d,w}}\right)^{1/b_{d,w}} s\right]^{n_{d,w}}\right\}^{-b_{d,w}/n_{d,w}} \quad (10)$$

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Where: subscript d,w represents drying process and wetting process respectively; a,b,n is the parameter; a_d is related to air intake value, a_w is related to air closure value, and b_d,b_w is related to soil pore size distribution. a,b can be determined by interpolating straight lines from test data in the $\ln(s)-\ln(e_w)(e_w = eS_r)$ plane, where a is determined by the slope of the inner difference straight line and b is determined by the intercept of the straight line. After a,b is determined, the value of n is determined by the least square method.

In addition, when the test data is sufficient, the McQuart method can be used for direct fitting.

Based on the above test data and the fitting parameters obtained by fitting the soil-water curve with van Genuchten model, the unsaturated permeability coefficient of loess can be predicted by van Genuchten seepage model. The basic form of van Genuchten seepage model is as follows:

$$K_r = \nabla^{0.5}\left[1-\left(1-\nabla^{1/m}\right)^m\right]^2 \quad (11)$$

$$\nabla = \frac{\theta - \theta_x}{\theta_s - \theta_r} \quad (12)$$

Where m is the fitting parameter, s,r is the saturated volumetric water content and residual volumetric water content, θ is the volumetric water content, and K_r is the relative permeability coefficient when the matrix suction is φ, that is, the ratio of unsaturated permeability coefficient to saturated permeability coefficient.

4. Result analysis

4.1. Unsaturated porosity and collapsibility

Through the microstructure analysis of the sample, it is found that the soil particles in the test area have the following characteristics: the skeleton particles of the soil are mainly crumb particles and aggregates composed of fine particles. Most of the large particles in soil particles are aggregate particles cemented by micro-debris particles and clay particles. The angular particles with poor roundness are mainly in point-to-surface contact or edge-to-surface contact with other particles. The contact area is small and the adhesion is weak. When there is water immersion, the particles are prone to slide, and the structural mode gradually changes from bracket contact to inlay contact, which causes the soil to collapse.

The relationship between the porosity $n(d>d_0)$ of 18 samples in unsaturated state under natural water content and the collapsibility at p=200 kPa was plotted as a scatter plot, and the fitting curve was obtained, as shown in Figure 2.

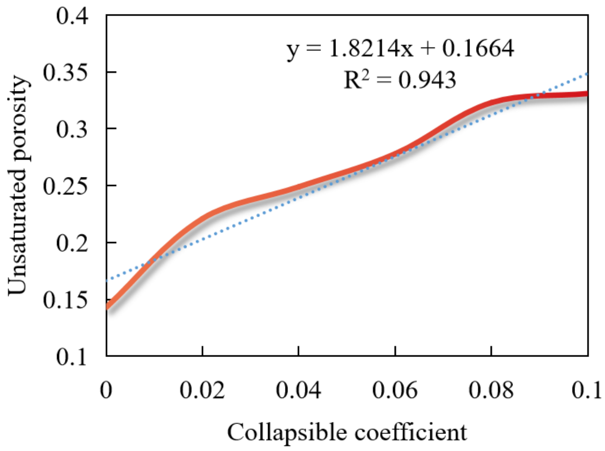

Figure 2 Relationship curve

It can be seen from Figure 5 that the collapsibility coefficient of the sample and the collapsibility of the soil increase with the increase of the saturated porosity. In loess with low natural humidity, the pores with smaller pore sizes are saturated, and the soil is unlikely to be damaged when immersed by water. However, most of the large pores in unsaturated state are overhead pores, which are unstable in structure and have good water permeability, and are easily damaged and collapse when immersed by water. Therefore, natural macropores are one of the main reasons for loess collapsibility.

4.2. soil-water characteristic curve

In unsaturated soil mechanics, many parameters of hydraulic characteristics of unsaturated loess can be predicted by studying soil-water characteristic curve. Soil water characteristic curve not only reflects the relationship between matrix suction and volumetric water content of soil, but also reflects the pore state of soil. Studies have shown that both the initial dry density and the number of dry-wet cycles have great influence on the soil-water characteristic curve, and they influence the changing trend of the soil-water characteristic curve by influencing the pore structure of the soil. See fig. 3 for the fitting parameters of van Genuchten model of loess samples in each test scheme.

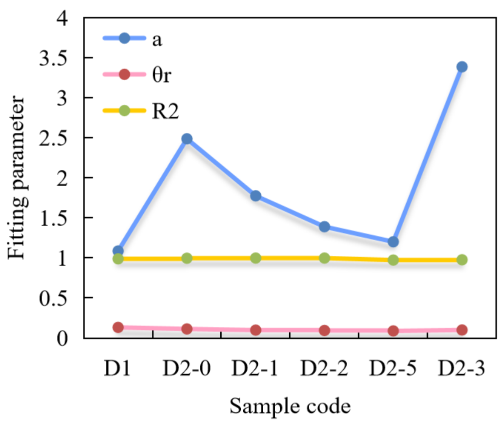

Figure 3 Fitting parameters of water characteristic curve

It can be seen from Figure 3 that the determination coefficient R^2 of each fitting curve is higher than 0. 97, which shows that this model can be used to fit the loess in this area.

When the matric suction is the same, the internal structure of the soil is affected by the moisture removal and absorption process of the soil sample, so the volumetric water content of the two processes of the sample is not exactly the same. With the process of soil moisture removal, the moisture in the soil is gradually discharged to the outside of the soil, which makes the pore size between soil particles change. In the process of moisture absorption, the cement inside the soil is dissolved due to the increase of moisture, and the relative position of soil particles changes, which changes the original state of the soil.

The process of drying and wetting cycles leads to the continuous change of the internal structure of soil, and finally the original properties of soil samples change, which makes the soil-water characteristic curves with different drying and wetting cycles show different changing trends. However, the above effects will weaken with the increase of the number of dry-wet cycles. After five dry-wet cycles, the change trend of soil-water characteristic curve tends to be consistent.

4.3. Prediction of unsaturated permeability coefficient

First, the model is used to predict the scanning line under dry conditions, as shown in the test point in Figure 4. The static boundary line test points can be used to calibrate the parameter b, d of soil-water characteristic curve, and then the static scanning line test points can be used to calibrate the parameter c.

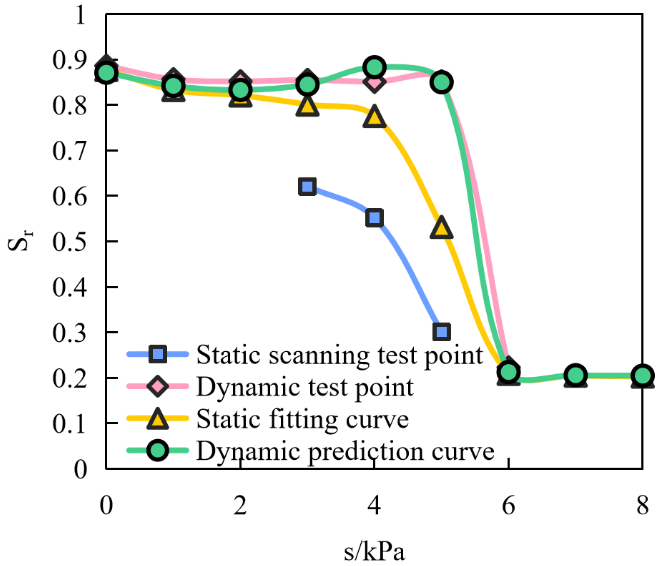

Figure 4 Prediction of dynamic scanning line under drying condition

It can be seen from Figure 4 that the dynamic drying line is located on the right side of the static drying line, which indicates that the suction of the dynamic curve is larger than that of the static curve under the same saturation condition. The greater the flow velocity, the faster the saturation change rate and the greater the dynamic suction. This is of great significance for simulating the deformation of unsaturated soil in the process of foundation precipitation. Rapid precipitation will lead to greater suction in soil, which will lead to greater deformation, indicating that rapid precipitation may increase the settlement of unsaturated soil foundation.

Using the obtained parameters, the dynamic scanning line is predicted, and the result is shown in Figure 5.

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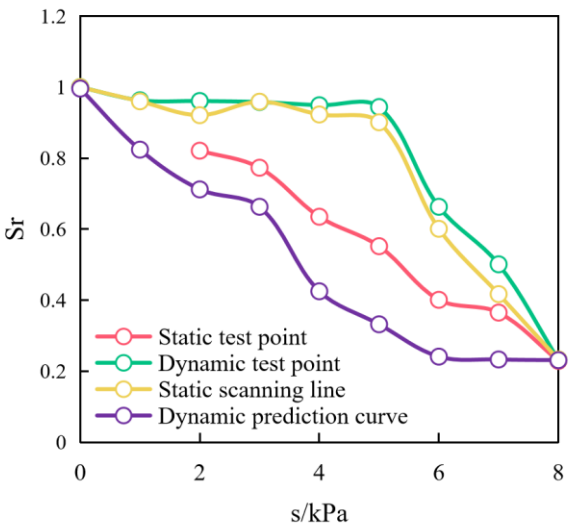

Figure 5 Prediction of dynamic scanning line under humidification condition

It can be seen from Figure 5 that the dynamic humidification curve is located below the static humidification curve. The greater the rainfall intensity, the smaller the suction corresponding to the same saturation. According to the strength theory of unsaturated soil, suction contributes to the strength, and the decrease of suction may reduce the strength of soil, which can explain why landslides are more likely to occur during heavy rainfall.

Enhanced body permeability; With the increase of the number of dry-wet cycles, the small pores in the sample gradually tend to develop into large pores, and the permeability coefficient of the soil increases steadily. Secondly, there are gases in the pores of the sample that can prevent the water exchange and flow. When the volume water content decreases, the gas content in the pores increases, and the water dissipation in the soil becomes slow. At the same time, the external water is not easy to enter the soil. When the drying-wetting cycle reaches a certain number of times, the properties of the soil tend to be stable, and the unsaturated permeability coefficient remains basically unchanged.

5. Conclusion

In this paper, through the soil-water characteristic curve test of unsaturated loess with different initial dry densities and different times of dry-wet cycles, and combining with the model, the permeability coefficient of remolded unsaturated loess is predicted, and the following conclusions are obtained:

(1) The permeability coefficient of unsaturated loess in the study area decreases with the increase of initial dry density, but increases with the increase of dry-wet cycles.

(2) When p=200 kPa, the change trend of the collapsibility coefficient of the sample is basically the same as that of fractal dimension, and the appropriate fractal dimension can be selected to predict the collapsibility of loess, so that it can become a bridge between microstructure analysis and macro performance evaluation.

(3) The numerical prediction results show that under the same saturation, the corresponding suction under dynamic conditions is different from that under static conditions, and the suction during dynamic drying process is larger, while the suction during dynamic wetting process is smaller, which is of great significance to the analysis of practical engineering problems. The next step is to analyze practical problems by using dynamic soil-water characteristic curves.

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