Prediction of Soil-Water Characteristic Curve of Compacted Loess With Different Dry Densities Based on Nuclear Magnetic Resonance

kangze yuan

Chang'an University

Wan kui Ni (✉ niwankui@chd.edu.cn)

Chang'an University <https://orcid.org/0000-0001-5296-4045>

Xiang-Fei LV

Chang'an University

Xiang-ning Li

Chang'an University

Hai-man Wang

Chang'an University

Lan Li

Chang'an University

Yong-peng Nie

Chang'an University

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Prediction of Soil-water Characteristic Curve of compacted loess with different dry densities based on Nuclear Magnetic Resonance

Kang-ze Yuan^a, Wan-kui Ni^{a*}, Xiang-fei Lü^{a, b, c*}, Xiang-ning Li^a, Hai-man Wang^a, Lan Li^a, Yong-peng Nie^a

^a*Department of Geological Engineering, College of Geological Engineering and Surveying and Mapping, Chang'an University, No.126 Yanta Road, Xi'an, Shaanxi 710054, P.R. China*

^b*School of Water and Environment, Chang'an University, No. 126 Yanta Road, Xi'an, Shaanxi 710054, P. R. China*

^c*CCCC First Highway Consultants Co., LTD, No. 205 Science and Technology Road, Xi'an, Shaanxi 710075, P. R. China*

**Corresponding author. Email addresses: nwvkk@126.com; Sophie_Lv@126.com*

tel: +0086 29 82339952, fax: +0086 29 82334137

Abstract

Accurate determination of soil-water characteristic (SWCC) is of great importance for understanding the mechanical properties of unsaturated loess. In this study, the compacted loess columns with different dry densities were prepared. Moisture sensor, water potential sensor and nuclear magnetic resonance (NMR) were used to investigate the SWCC and NMR signals intensity of compacted loess under different dry densities. It has been found that with increasing dry density, the saturated water content and the residual water content gradually decreases, but the decrease in residual water content is smaller, and both can establish a linear relationship with dry density. The NMR results showed that the compacted loess pore volume gradually decreased with increasing dry density. When the dry density increased from 1.45 g/cm³ to 1.55 g/cm³, the pore volume of compacted loess decreased by 14.7%, while when the dry density increased from 1.55 g/cm³ to 1.65 g/cm³, the pore volume of compacted loess decreased by 13.2%. The Van Genuchten (VG) model was used to fit the NMR results and SWCC, and a good corresponding relationship was found between the parameters. Therefore, according to the cumulative NMR intensity parameters, SWCC was predicted under different dry densities and the effect was found very well.

Keywords: Soil-water characteristic curve, Nuclear magnetic resonance, VG model, Prediction

1.Introduction

Loess is a special type of sediment formed in arid and semi-arid climatic conditions during the Quaternary Period (Rost et al. 2001; Pye et al. 1995; Smalley et al. 1996; Yu et al. 2019). Loess deposits cover 10% of the continents, including Asia, Africa, Central and Southern Europe, the American Midwest, and northern France (Derbyshire et al. 1988). Loess is extremely important and covers 630,000 km² in northwestern China, mainly in the regions of Shanxi, Shaanxi, Gansu, and Ningxia (Tan 1988). Loess mainly exists in unsaturated form, and the soil-water characteristic curve (SWCC) is one of the most important factors reflecting the internal mechanisms of unsaturated loess (Zhang et al., 2020; Han et al., 2016; Vanapalli et al., 1996). The SWCC plays an important role in understanding and simulating the characteristics of shear strength, permeability and volume change of unsaturated loess (Gu et al., 2019; Li et al., 2020). Therefore, it is very necessary to study the SWCC, which provides theoretical support for scholars to predict the impact of rainfall on the potential stability of loess landslides and the irregular settlement of foundations.

Current research methods of SWCC mainly include the filter paper method, the pressure plate technique, tensiometers and the sensor test method (Ye et al., 2019; Hoyos et al., 2006; Hedayati et al., 2020). However, during the specific test process, external conditions easily affect the filter paper method, resulting in a large deviation from the actual characteristics. The pressure plate is more expensive, while the test range of tensiometers to matrix suction is small. Although the results of the sensor test method are more accurate, it is generally combined with the large-scale field or model tests, which requires a longer test period and higher test costs. Therefore, it is noticed that majority of the testing methods for SWCC have certain limitations and shortcomings (Kong and Tan 2000). Some studies have begun to predict SWCC through certain loess parameters. Tao et al. (2019) proposed the prediction method of SWCC based on the mercury intrusion porosimeter (MIP) and data on the fractal dimension and air-entry value. Li et al. (2020) proposed a MIP method that uses a soil-water interface bonding angle as a fitting coefficient to predict SWCC. It was found that when the soil-water interface bonding angle was 70° and 50° for the wetting and drying process, respectively, predicted SWCCs by the pore diameter distribution curve agree well with measured SWCCs. The abovementioned literature indicates that the prediction of SWCC is mainly from the perspective of the distribution of pores, with MIP as the test method of pore distribution. However, MIP can damage the sample and the measured amount of micropores is small because it is difficult for mercury to enter the micropores. In addition, as a product of weathering of rocks, loess is fragile and has complex internal structure. Therefore, the mercury intrusion method will greatly damage the loess structure (Tian et al., 2014), which will affect the structure of the internal pores of loess, leading to inaccurate test results. Therefore, it is increasingly important to find a test method that can perform non-destructive testing of the internal pores of loess.

The Nuclear magnetic resonance (NMR) relaxation method is a very effective method for the analysis of pores in loess. Therefore, it is possible to overcome the abovementioned limitations by applying the NMR relaxation method. The

amplitude of the proton NMR signal is proportional to the fluid content, and the pore distribution curve of loess can be obtained through the relaxation time. In recent years, NMR has been gradually applied in the field of geotechnical engineering due to its non-destructive, high-efficient and other advantages (Kleinberg 1994; Strange et al. 1993). It can be used to detect the local structure of the rock matrix (Gallegos et al., 1988) and to identify the formation and decomposition of clathrate hydrate (Gao et al., 2009), and to test the pore distribution in the loess structure.

Based on the above considerations, this study tested SWCC and NMR results of compacted loess under different dry densities, and established a relationship between SWCC and NMR results. The prediction equation of SWCC of compacted loess under different dry densities is obtained through the results of NMR. This is a convenient and effective method to be used in future studies of SWCC, and also it provides a certain guiding idea for the future analysis of the relationship between moisture content and mechanical properties of loess.

2. Materials and methods

2.1 Loess samples

The investigated samples are from the foundation pit of the Loess Plateau in the Yan'an City, China (Fig 1). The sample depth is from 7.0 m to 7.5 m below the surface, and it can be classified as the Malan loess (Liu et al. 2016). The physical properties of the samples were determined according to the standard ASTM test methods (ASTM 2006). According to the XRD pattern of the original loess (Fig 2), the quantitative mineralogical composition was calculated. The physical parameters and mineralogical composition of the loess samples are listed in Table 1.

Table 1. Physical properties of the loess used in this study

Fig 1. The major occurrence of the Loess Plateau in China and the sampling location (latitude 35°42' 46.09" N, longitude 109°26'0.10" E).

Fig 2. XRD pattern of the original loess sample

2.2 Preparation of loess column

The test sample was prepared with an independently developed device for the large-scale soil column preparation (Figure 3). The experimental sample is a loess column with a moisture content of 10%, dry density of 1.45 g/cm³, 1.55 g/cm³ and 1.65 g/cm³, respectively, height of 6 cm and diameter of 30 cm. The preparation process of sample is as follows:

(1) Firstly, the original loess was crushed with a wooden hammer until all aggregates are destroyed. These samples were then passed through a 2 mm sieve and then oven-dried at 105°C for eight hours and cooled to room temperature. Thereafter, the amount of deionized water, calculated from Equation 1, was gradually added to the samples using a spray

bottle until the moisture content reached the natural water content ($w = 13\%$). They were tightly sealed with plastic film and placed in a humidor for about 48 hours at room temperature. Part of the processed loess was subjected to a retest of moisture content. If the difference between the average moisture content error after retesting and the target moisture content is within $\pm 0.2\%$, the sample preparation process can begin. During the processing, the amount of added deionized water was calculated by the Equation 1:

$$m_w = \frac{0.01 \times (w - w_0)}{1 + 0.01 w_0} \times m_0 \quad (1)$$

where m_w is the mass of deionized water added, m_0 the quality of the soil sample after drying, w is the target moisture content, and w_0 is the initial moisture content.

(2) Sample preparation was compacted in three layers with each layer being 2 cm high. According to the moisture content, the target dry density and the bottom area of the sample, the required loess quality is calculated for the 2 cm high sample, the surface is smoothed evenly and the horizontal ruler is used to adjust the reaction frame beam;

(3) Switching on the air pump and adjusting the pressure control knob to pressurize the loess in stages, with a load of 25 kPa per stage. After the end of the first stage of pressure, the pressure plate is removed, and the height of the soil mass is measured and recorded. When the height of the soil mass after pressure is about 0.5 cm different from the target height (2 cm), the loess mass is slowly pressurized to ensure that the height of the soil mass is accurately maintained at 2 cm;

(4) Before the next layer of soil is compacted, the soil surface is completely leveled. Since water potential and moisture sensors need to be placed on the second layer, the 1 cm high soil sample was firstly weighted, and then added to the test device and smoothed. After that, the MPS-6 water potential sensor (Fig 4a) and the EC-5 moisture sensor (Fig 4b) were added on the previously prepared soil (Fig 4d). After placing the sensors, another 1 cm high soil sample was added and smoothed. The pressure method is the same as in the step (3);

(5) The third compaction process is the same as the first compaction process. After leveling the soil surface, steps (2) and (3) are repeated;

(6) After the sample is prepared, it is sealed with a cling film to prevent moisture evaporation. The data collector EM50 (Fig 4c) is used to store the water potential and moisture data.

Fig 3. An independently developed device for the large-scale soil column preparation

Fig 4. Experimental equipment (a. MPS-6 water potential sensor; b. EC-5 moisture sensor; c. EM50 data collector; d.

Sensor placement)

2.3 Theoretical background of NMR

Geophysical NMR methods were used to analyze the pore size distribution in loess samples using MacroMR12-150H-1. According to the previous studies (Costabel et al. 2013; James et al. 1992), the amplitude of the ^1H protons NMR signal

in water molecules of a loess sample is proportional to water content, while relaxation time (T_2) provides information on pore size distribution when the sample is placed into a magnetic field and then excited by a short pulse of radio frequency (RF) energy. The relaxation time (T_2) is the transverse relaxation time of the pore water between loess particles measured by the Carr-Purcell-Meiboom-Gill (CPMG) sequence. From the above description, it can be concluded that the pore water between the loess particles is a necessary condition for this measurement. Thus, compacted loess samples from the cutting ring were saturated under vacuum conditions and fixed in a specially made quartz tube ($\varnothing$ 23 mm, height 20 mm). Then, the quartz tube containing the loess sample was placed in the testing tube to obtain a T_2 curve. This process is shown in Figure 5.

For water-saturated loess samples, T_2 can be obtained from Equation 2 based on the NMR relaxation mechanisms:

$$\frac{1}{T_2} = \frac{1}{T_{2B}} + \frac{1}{T_{2S}} + \frac{1}{T_{2D}} \quad (2)$$

where, T_{2B} is the bulk water relaxation time, T_{2S} is the surface-enhanced relaxation time on the pore walls, and T_{2D} is the diffusion relaxation time that accounts for the transverse relaxation in an inhomogeneous magnetic field. For water, T_{2B} is much larger than T_{2S} and T_{2D} , so the effect of T_{2B} on T_2 can be neglected. In fact, for pore water in porous loess, the T_2 of the pore water in the soil is directly related to the internal structure of the loess pores:

$$\frac{1}{T_2} = \frac{1}{T_{2S}} = \rho \frac{S}{V} = \rho \frac{\alpha}{r} \quad (3)$$

where, ρ ($\mu\text{m/s}$) is the surface relaxivity coefficient characterizing the magnetic interactions at the water-loess particles interface, and S/V (m^{-1}) is the ratio of the pore surface area (S) to the pore water volume (V). The S/V ratio is proportional to the reciprocal pore radius (r), expressed as $\frac{\alpha}{r}$. In Equation 3, the geometry factor (α) depends on the pore shape ($\alpha=1$ for planar, $\alpha=2$ for cylindrical, $\alpha=3$ for spherical shape). In this study, we assume that the pores in loess samples are cylindrical. Therefore, for cylindrical pores, Equation 3 can be written as follows:

$$\frac{1}{T_2} = \rho \frac{\alpha}{r} = \rho \frac{2}{r} \quad (4)$$

and it can be simplified to Equation 5:

$$T_2 = \frac{1}{2\rho} r \quad (5)$$

From Equation 5, the relaxation time (T_2) shows a linear relationship with the pore radius (r). Thus, if we know the value of the surface relaxivity coefficient (ρ), the pore size distribution in loess samples can be obtained by measuring the T_2 distribution.

To determine ρ , the widely accepted NMR-permeability equation, known as the Schlumberger-Doll Research (SDR) equation developed by [Kenyon et al. \(1996\)](#), is used to obtain ρ :

$$k_s = C \phi^4 T_{2LM}^2 \quad (6)$$

According to [Kleinberg et al. \(2003\)](#), the constant (C) of the SDR equation is expected to be proportional to the square of ρ . Therefore, the equation is as follows:

$$k_s = \rho^2 \phi^4 T_{2LM}^2 \quad (7)$$

and it can be also written as:

$$\rho = \sqrt{\frac{k_s}{\phi^4 T_{2LM}^2}} \quad (8)$$

where, k_s is the saturated soil permeability, ϕ is the saturated porosity of the NMR samples, and T_{2LM} is the geometric mean of the T_2 distribution.

Among them, a dry density sample of 1.45 g/cm^3 was taken as an example. The saturated permeability of loess (k_s) is $1.18 \times 10^{-13} \text{ m}^2$, the saturated porosity of the soil (ϕ) is 0.49, the mean geometric value of the T_2 distribution is 0.52989 ms. Inserting it in Equation 8, the value ρ_2 of 2.69 $\mu\text{m/ms}$ is obtained. In the same way, ρ_2 values of dry density of 1.55 kg/m^3 and 1.65 kg/m^3 can be calculated as 2.51 $\mu\text{m/ms}$ and 2.25 $\mu\text{m/ms}$, respectively.

Figure 5. Preparation and test process for NMR sample

3. Results

3.1 SWCC under different dry densities

The SWCCs of compacted loess under different densities are shown in Fig 6a. It can be noticed that the saturated water content is high in the low-density loess sample, while the rate of water loss is faster. The high-density loess samples show a strong water holding capacity due to small pores and poor connectivity, so the SWCC is more gentle. The SWCC crosses the curve of the high-density soil sample as the matrix suction increases. As the matrix suction continues to increase, the SWCCs of low-density and high-density soils gradually approach each other.

Fig 6. a) SWCCs under different dry density; and b) VG model fitting curve

Currently, there are many fitting models of SWCCs in academic circles, and the VG model (Aschonitis et al., 2013; Yang et al., 2013) is the most commonly used in the study of unsaturated loess. This paper uses the VG model to fit the experimental data. The expression of the VG model is as follows:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{(1 + (a\psi)^n)^m} \quad (9)$$

where, S_e is the effective saturation and θ is the soil volume saturation; θ_r is the residual volumetric water content, and θ_s is the saturated volumetric water content; a , m , and n are the fitting parameters and ψ is the matrix suction (kPa); a is a function of the air intake value, and usually $m = 1 - \frac{1}{n}$. The fitting curve and parameters are shown in Fig 6b and Table 2.

Table 2. Parameters of the VG model fitting curve

It can be noticed from the semi-logarithmic coordinates that the VG model fits well with the measured data of the SWCC of the compacted loess under different dry densities, all of which are above 0.99. For a low-density loess sample, the saturated water content corresponding to the curve of the low suction section is higher, indicating that as the dry density increases, the pore volume within the compacted loess gradually increases. However, the residual moisture content

gradually decreases with increasing dry density, but the range of changes is small and basically remains stable. This is because the residual water content is mainly affected by micropores and small pores, and compacted loess with different dry densities has a small difference in the volume of micropores and small pores. The residual water content and the saturated volumetric water content are linearly fitted, and the results are shown in Fig 7. The fitting equations are respectively as follows:

$$\theta_s = -40.53\rho_d + 105.04 \quad (10)$$

$$\theta_r = -3.77\rho_d + 22.81 \quad (11)$$

It was noticed that the residual moisture content and the saturated moisture content of compacted loess show a linear decreasing trend with the increase of dry density. The saturated water content can be calculated according to the basic physical parameters of loess. The saturated water content in compacted loess with different dry densities is calculated to be 46.5%, 42.8%, and 39.1%, which is in accordance with the fitting results. Therefore, the reliability of the fitted data has been proven.

Fig 7. Fitting curves of saturated moisture content and residual moisture content

3.2 NMR results for different dry densities of loess

The relaxation time distribution is normalized to the sum of all amplitudes. Then, each amplitude represents the proportion of water corresponding to the relaxation time of the water (decay of the NMR signal). The transverse relaxation times (T_2) distribution curves of different dry densities in the NMR experiment are shown in Fig 8a, which indicates the trimodal relaxation distribution. The results show that the trimodal relaxation distribution of all samples mainly consisted of T_2 relaxation time range from 0.015 ms to 310.78 ms. With increasing dry density, the maximum values of Peak 1 are at 0.060 ms, 0.053 ms, and 0.046 ms for dry density of 1.45 g/cm³, 1.55 g/cm³, and 1.65 g/cm³, respectively. The maximum values of Peak 2 are at 2.248 ms, 1.047 ms, and 0.912 ms for dry densities of 1.45 g/cm³, 1.55 g/cm³, and 1.65 g/cm³, respectively. However, at Peak 3, the peaks of the three dry densities are about 51.11 ms. Due to the linear relationship between T_2 relaxation time and pore diameter. This proves that as the dry density increases, the predominant micropores and mesopores gradually decrease in the compacted loess, but the impact on super-large pores is small. Fig 8b shows the cumulative NMR signal intensity. Compared with the distribution curve of NMR T_2 results, it can be noticed that as the dry density increases, the proportion of NMR signal gradually decreases. It can be seen that the dry density increased from 1.45 g/cm³ to 1.55 g/cm³, while the total peak area decreased from 87934.5 ms to 75034.9 ms, which is a 14.7% decrease. When the dry density increased from 1.55 g/cm³ to 1.65 g/cm³, the total peak area decreased from 75034.9 ms to 65162.5 ms, which is a decrease of 13.2%. This is because the signal amplitude of the T_2 distribution curve represents the number of water molecules or the water content in the pores. Therefore, as the dry density increased from 1.45 g/cm³ to 1.55 g/cm³, the pore volume of compacted loess decreased by 14.7%. When the dry density increased from 1.55 g/cm³

to 1.65 g/cm³, the pore volume of compacted loess decreased by 13.2%.

Fig 8. T₂ distribution curve of different dry densities (a. NMR signal intensity; b. Cumulative NMR signal intensity)

According to the Young-Laplace equation (DasGupta et al., 1993; Chen et al., 2006), the pore diameter (D) has the following relationship with the equivalent matrix suction (φ):

$$\varphi = \frac{4\sigma_s \cos\alpha}{D} \quad (12)$$

where, φ_d is the matrix suction, and σ_s is the surface tension on the air-water meniscus; α is the contact angle between moving water and loess particles, which is taken with a value of zero at the interface of the loess particles and water; D is the diameter of the loess particles.

According to Equation 5 and the Young-Laplace equation, the abscissa coordinate in Fig 6b and Fig 8b is converted into a pore diameter, respectively. Since the accumulated NMR signal intensity is a long straight line, this study considers only the change in pore size in the range from 0.1 μm to 1000 μm . It can be noticed from Fig 9 that SWCC and cumulative NMR signal intensities, corresponding to different pore distributions, have a very close relationship. These two curves can be divided into three sections. The first section is characterized with a slower growth rate and both curves are in a stable state. In the second section, the growth rate of the two curves gradually increases with increasing pore size and a stage of steep increase occurs. The third section is characterized with a further increase of pore size in the compacted loess. The growth rate of the two curves gradually decreases, and then enters into a stable stage. By comparing the two curves, two intersection points can be noticed for different dry densities, regardless of the cumulative NMR intensity curve or the SWCC, and they are $X_1=0.57 \mu\text{m}$ and $X_2=15.77 \mu\text{m}$. Therefore, when the pore size is less than 0.57 μm , the SWCC corresponds to a steady state, while when the pore size is between 0.57 μm and 15.77 μm , it corresponds to the steep increase stage of the SWCC. When the pore diameter is greater than 15.77 μm , the SWCC corresponds to a steady state. The growth rate of the water characteristic curve gradually decreases and enters into a stable stage. Therefore, it shows that the SWCC of compacted loess under different dry densities is a process in which the pores are gradually filled with water, which is closely related to the cumulative NMR signal pore size distribution curve.

Fig 9. Correspondence between cumulative NMR intensity and SWCC

3.3 NMR results predict SWCC

The obtained cumulative NMR signal intensity curve of samples with different dry density are fitted with the VG model. The mathematical formula is:

$$T_{D_i} = T_r + \frac{T_s - T_r}{[1 + (aD_i)^b]^c} \quad (13)$$

where, T_{D_i} is the cumulative pore volume smaller than pore diameter D_i (μm), T_s is the saturated NMR signal

intensity, T_r is the residual NMR signal intensity, and a, b and c are empirical constants associated with the solid phase characteristics.

Due to the NMR data are very closely related to SWCC data, the cumulative NMR curve is used to predict SWCC. Since the first stage of the cumulative NMR intensity curve has a straight line close to $Y=0$, the residual NMR intensity is 0. The VG model is corrected, and the correction equation is:

$$T_{Di} = \frac{T_s}{[1+(aD_i)^b]^c} \quad (14)$$

Using a modified VG model in terms of cumulative NMR signal intensity, the fitting curves and corresponding fitting parameters of the obtained cumulative NMR signal intensity are shown in Fig 10 and Table 5, respectively.

Fig 10. The modified VG model fits to the cumulative NMR intensity curve

Table 3. Parameters of the modified VG model fitting curve

To predict the SWCC of compacted loess through NMR data, a relationship is established between the SWCC parameters and NMR data. The fitted curve and equations are shown in Fig 11 and Equations 15 and 16, respectively.

Fig 11. Fitting parameters of SWCC and cumulative NMR intensity curve

$$a = -0.019a' + 0.0636 \quad (15)$$

$$n = 0.294n' + 1.953 \quad (16)$$

Combining Equations 10, 11, 15, and 16, and entering them into the VG model in order to obtain the SWCC model predicted by the cumulative NMR intensity curve is as follows:

$$\theta = -5.495\rho_d - \frac{34.655\rho_d - 79.07}{(1 + (-0.019a' + 0.064)x^{(0.294n' + 1.953)})^{\frac{0.294n' + 0.953}{0.294n' + 1.953}}} + 24.19 \quad (17)$$

In order to investigate the accuracy of the SWCC model established in this study, the distribution curve of the cumulative NMR intensity of the compacted loess with dry density of 1.35 g/cm^3 and the VG model fitting curve are used to obtain the fitting parameters a' and n' , which are 0.127 and 4.241, respectively.

Figure 12. The modified VG model fits the cumulative NMR intensity curve with a dry density of 1.35 g/cm^3

By bringing the parameters a' and n' into the SWCC model (Equation 17) it is possible to obtain the predicted SWCC and compare it with the measured data, as shown in Fig 13. The obtained values are relatively close, which proves the accuracy of predicting SWCC of different dry densities through the cumulative NMR intensity curve.

Fig 13. Comparison of the predicted SWCC curve and the actual SWCC curve

4. Discussion

With the increase of dry density, the saturated water content in the SWCC of compacted loess gradually decreases. Meanwhile, the residual moisture content gradually decreases, but the range of changes is small and basically remains stable. This is because the saturated water content is mainly affected by macropores and mesopores. However, residual water content is mainly affected by micropores and small pores, and compacted loess with different dry densities has a small difference in the volume of micropores and small pores (Shao et al., 2018; Li et al., 2019). Therefore, it is proved that the SWCC is actually the process of gradually filling the pores in the compacted loess. It can be seen from Figure 10 that the compacted loess SWCC under different dry densities has a good corresponding relationship with the cumulative NMR intensity curve: There is a good correspondence between the inflection point of SWCC (i.e., the reverse bending point, which has the largest slope $S_{\max}$) and the intersection point of the curve. With the increase of matrix suction, the loess loss the water in the macropores and mesopores, and then the water in the small pores and micropores. When the loess loss the water in the dominant pore range, there will be obvious water loss due to the more pores in this range. The water loss is the most near the peak point of the pore distribution, so the SWCC has a steep drop. Through the VG model to fit SWCC and cumulative NMR intensity curves respectively, it is found that there is a good linear relationship between the fitting parameters. As we know, The amplitude of the proton NMR signal is proportional to the fluid content, and the pore distribution curve of loess can be obtained through the relaxation time. The POSD curve is essentially related to SWCC. Therefore, the linearity of the relationship between the fitted parameters in SWCC and POSD is considered to be attributed to the similarity of the physical meaning of the parameters of the loess. This proves the feasibility of using NMR results to predict SWCC.

5. Conclusions

This paper analysed the SWCC and NMR results of compacted loess with different dry densities. The conclusions obtained from this study are summarized as follows:

- (1) The VG model was used to fit the compacted loess with different dry densities. It was found that with the increasing dry density, both saturated moisture content and residual moisture content gradually decrease and show a good linear relationship with dry density;
- (2) As the dry density increases, the total pore volume of compacted loess gradually decreases. When the dry density increases from 1.45 g/cm³ to 1.55 g/cm³, the pore volume of compacted loess decreases by 14.7%. Furthermore, when the dry density increases from 1.55 g/cm³ to 1.65 g/cm³, the pore volume of compacted loess decreases by 13.2%;
- (3) The abscissa of the SWCC and cumulative NMR intensity curve under different dry densities are converted into pore size. It was found that when the pore size is smaller than 0.57 μm , the SWCC corresponds to a steady state. When the pore size is between 0.57 μm and 15.77 μm , this corresponds to the steep increase in SWCC.

Furthermore, when the pore diameter is greater than 15.77 μm , the SWCC corresponds to a steady state. The growth rate of the water characteristic curve gradually decreases and enters into a stable stage;

- (4) The NMR results of compacted loess with different dry densities were related to SWCC, and a prediction model of SWCC based on the NMR result was obtained. The results of NMR with a dry density of 1.35 g/cm^3 and measured SWCC were used for verification, and high accuracy was obtained .

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Author Contributions

Wan-kui Ni and Xiang-fei Lü designed research; Kang-Ze Yuan performed all experiments and analyzed the data; Kang-ze Yuan and Xiang-ning Li did this experiment. Kang-Ze Yuan and Xiang-fei Lü wrote the paper. The map data in Figure 1 was provided by the Data Center for Resources and Environmental Science, Chinese Academy of Science (RESDC) (<http://www.resdc.cn>). All authors read and approved the final manuscript.

Compliance with ethical standards

The authors declare no conflict of interest. This article does not contain any studies with human participants and/or animals. Informed consent was obtained from all individual participants included in the study.

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The Captions of Tables and Figures

Table 1. Physical properties of the loess used in this study

Fig 1. The major occurrence of the Loess Plateau in China and the sampling location (latitude $35^{\circ}42'46.09''$ N, longitude $109^{\circ}26'0.10''$ E).

Fig 2. XRD pattern of the original loess sample

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Table 3. Parameters of the modified VG model fitting curve

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Fig 13. Comparison of the predicted SWCC curve and the actual SWCC curve

Table 1.

Sample measurements	Value
In situ density (g/cm^3)	1.35~1.42

Natural moisture content (%)	13
Specific gravity	2.71
Plastic limit (ω_p %)	16.1
Liquid limit (ω_L %)	28.9
Optimal water content w (%)	14.1
Maximum dry density (g/cm ³)	1.74
Quartz (%)	45.2 %
Feldspar (%)	21.0 %
Calcite (%)	15.5 %
Chlorite (%)	8.0 %
Kaolinite (%)	5.8 %
Illite (%)	4.5%

Figure 1.

Figure 2.

Figure 3.

Figure 4.

a.

b.

c.

d.

Figure 5.

Figure 6.

Table 2.

Dry density (g/cm ³)	Parameter				
	a	n	θ_r	θ_s	R ²
1.45	0.057	2.856	17.349	46.221	0.9923

1.55	0.049	2.576	16.974	42.338	0.9965
1.65	0.036	2.544	16.595	38.116	0.9938

Figure 7.

Figure 8.

Figure 9.

Figure 10.

Table 3.

Dry density (g/cm ³)	Parameter			
	a'	n'	T _s	R ²
1.45	0.293	3.065	87976.1	0.9998
1.55	0.887	2.125	75240.9	0.9995
1.65	1.388	1.998	65299.3	0.9997

Figure 11.

Figure 12.

Figure 13.

Figures

Figure 1

The major occurrence of the Loess Plateau in China and the sampling location (latitude 35°42'46.09" N, longitude 109°26'0.10" E). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

XRD pattern of the original loess sample

Figure 3

An independently developed device for the large-scale soil column preparation

a.

b.

c.

d.

Figure 4

Experimental equipment (a. MPS-6 water potential sensor; b. EC-5 moisture sensor; c. EM50 data collector; d. Sensor placement)

Figure 5

Preparation and test process for NMR sample

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T_2 distribution curve of different dry densities (a. NMR signal intensity; b. Cumulative NMR signal intensity)

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