Study on the Influence of Dry-wet Cycle on the Pore Size of Dam Soil

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Abstract: In view of the influence of dry-wet cycle on soil structure, the suction variation of different parts of the model dam slope was obtained, and the soil-water characteristic curve was drawn accordingly. According to the soil-water characteristic curve, the pore size of soil was analyzed. Based on the assumption that the pore size of soil was a sphere, the change of pore radius in the process of drought was analyzed, and the change of pore volume in the whole process of drought was studied. The results showed that the pore volume of soil without cracks would increase in the process of drought, and the greater the influence of dry-wet cycle condition was, the more obvious the change was. The increase of pore volume would reduce the compactness of soil and threaten the safety of filling engineering.

1. Introduction

The change and variability of the global climate have increased the frequency and intensity of extreme hydrological events. Influenced by that, the climate change in China has increased dramatically in recent years. According to statistics, from 2009 to 2010, south-western region suffered severe drought since the meteorological record. In the summer of 2013, there was a rare history of high temperature and less rain in most areas of the south of the Yangtze River. In 2014, Henan suffered the worst drought in 63 years. The northern and the mid-western areas suffered a severe drought, resulting in that the water level of multiple reservoirs was close to the dead water level or below the dead water level. The extreme low water level and drying of the reservoir caused the dam to produce a large range of cracks which destroyed the continuity and integrity of the impervious body, and it would endanger the seepage safety of the dam [1-2]. At present, many scholars have studied the cracking of soils under the dry-wet cycle and achieved fruitful results. Zhang [3] applied the catastrophe theory in modern nonlinear analysis to study the mechanism of sudden instability and progressive instability in mountain slope under the influence of rainfall infiltration. Li [4] analyzed the opening and closing regularity of fracture mesh by quantitative analysis. Miller and Yesiller [5-6] studied the development and strength change of cracks by dry-wet cycling test. Ye [7] analyzed the location of cracks in dam slope and the effect of cracks on seepage in the process of rapid turning of drought and flood through model test. Huang [8] established the discrete fractured model, based on the concept of discrete fracture. She elaborated the basic principle of discrete fracture model and its two-phase flow mathematical model, and established the finite element numerical calculation scheme of the model based on Galerkin weighted residual method. A permeability coefficient tensor correction method was proposed by Gao [9] under the framework of equivalent continuous medium model. Based on the flow equivalent principle, the permeability coefficient tensor matrix of the
correction element was derived. The finite element analysis software was applied to calculate the seepage field and the results were consistent with the numerical analysis results of the cracks.

The above researches are based on the generation and expansion of cracks. Generally, cracks occur on dam slopes only when there is a long duration of drought. If the time of drought is short, cracks are not easy to appear. Whether the soil properties are affected by drought is not clear at this time. Therefore, it is necessary to study the effect of dry-wet cycle on the soil pore.

2. Pore analysis of soil

2.1 Calculated variables

The influence of dry-wet cycle on soil pore volume can be studied from the analysis of pore volume change. According to the Kelvin equation, the matrix suction is related to the pore size. The Kelvin equation is expressed as follows:

\[
\mu_i - \mu_o = -RT \ln \left( \frac{u_i}{u_o} \right) = \frac{2T_s \nu_s \cos \alpha}{r}
\]

Where \( \mu_i - \mu_o \) is the change of chemical potential energy of water vapor (J/mol) produced by the bending of gas-water interface in capillary tube, \( R \) is the general gas constant (J/(mol·K)), \( T \) is the thermodynamic temperature (K), \( u_o \) is the saturated vapor pressure at equilibrium with free water at temperature \( T \), \( u_i \) is the current vapor pressure in the capillary, \( T_s \) is the surface tension (J/m²), and \( \nu_s \) is the partial molar volume of water vapor (m³/mol).

The total pressure variation \( (u_i-u_o) \) on the surface of water-soil interface in soil pore can be expressed by the following formula:

\[
u_i - u_o = \frac{2T_s \cos \alpha}{r}
\]

Where \( u_i, u_o \) are air pressure and water pressure (kPa), respectively, \( \alpha \) is contact angle between soil particles and pore, and \( r \) is the pore radius.

By introducing Formula (1) into Formula (2), we can get:

\[
u_i - u_o = \frac{RT}{\nu_s} \ln \left( \frac{u_i}{u_o} \right) = \frac{2T_s \cos \alpha}{r}
\]

Where \( RH \) is relative humidity (%).

The expression of relative humidity can be obtained by transformation (3):

\[
RH = \exp \left( -\frac{(u_i-u_o) \nu_s}{RT} \right)
\]

The capillary radius \( r \) (Kelvin radius) can be expressed as a function of surface tension \( T_s \), contact angle \( \alpha \) and relative humidity \( RH \) [10]:

\[
r = \frac{2T_s \nu_s \cos \alpha}{RT \ln(RH)} = \frac{2T_s \cos \alpha}{u_i - u_o}
\]

Conceptualization of pore geometry of soils based on possible capillary pressure measurements requires a variety of variables, including pore volume, average pore radius, thickness of water film adsorbed by solid particles in soils, and ratio of pore volume to surface area of soil particles [11]. The small increment of each variable can be determined by analyzing the soil-water characteristic curve.

Pore volume change \( \Delta V_p^i \) can be defined as:

\[
\Delta V_p^i = \frac{\Delta w^i}{\rho_v}
\]

Where \( w^i \) is mass water content, it can be obtained directly from soil-water characteristic curve. The actual pore radius \( r_p^i \) is the sum of Kelvin radius and water film thickness. The Kelvin radius
is shown in formula (5). The water film thickness can be expressed as:

$$t^i = \frac{\tau}{\ln(RH)}$$  \hspace{1cm} (7)

Where $\tau$ is the effective diameter of adsorbate molecule.

$$\tau = \frac{V_r}{AN_{A_d}} = \frac{18 \times 10^{-6} \text{m}^3/\text{mol}}{(10.8 \times 10^{-20} \text{m}^3) \times (6.02 \times 10^{23} / \text{mol})} = 2.77 \times 10^{-10} \text{m}$$

The actual pore radius can be expressed as:

$$r_{p^i} = r_{k^i} + t^i$$  \hspace{1cm} (8)

When the pore geometry is got, the ratio of pore volume to pore area can be used to determine the change of specific surface area corresponding to suction increment in step $i$. In this paper, the pore is defined as a sphere, and the increment of specific surface area $\Delta S^i$ can be expressed as follows:

$$\Delta S^i = \frac{3\Delta V_{p^i}}{r_{p^i}}$$  \hspace{1cm} (9)

2.2 Computation process

(1) Converting matric suction in the soil-water characteristic curve into relative humidity.

(2) Converting the mass water content into the volume of pore filled with water in solid per unit mass.

(3) Calculating Kelvin radius by formula (5).

(4) Calculating the thickness of water film by formula (7).

(5) Calculating pore radius by formula (8).

(6) Calculate the reduction of pore volume per unit mass of solid under a given relative humidity change (e.g. considering the decrease along the dehumidification curve).

(7) Calculating the average Kelvin radius in the process of pore volume reduction.

(8) Calculating the average pore radius in the process of reducing pore volume.

(9) Calculating the increment of surface area by formula (9), under the condition of Jiading pore geometry.

(10) Calculating the cumulative pore volume per unit mass by adding the aforementioned increments of pore volume.

3. Measurement of soil-water characteristic curve

3.1 Testing system

The test system was shown in Figure 1 and Figure 2. In the test, a self-developed environment box was used, in which a long arc xenon lamp and a fan were installed to simulate drought, and the rain frame could be adjusted to simulate rainfall weather.

FTC-100 Fredlund heat-conduction sensors were used for measuring the matric suction in this test. The sensors measure the temperature of the soil directly and then calculate the suction based on the thermal conductivity of the ceramic block. For accurate measurement of the suction value, an
environmental temperature correction coefficient is built into the software of the sensor, and used to correct for the influence of the environment temperature on the sensor. The sensor range is 0–1500 kPa and the precision is better than 5%. The suction sensor probes and data acquisition instrument are shown in Figure 3. During the test, the water content at a specific site was measured by a rapid soil moisture measurement instrument.

![Figure 3 Suction sensor and data acquisition instrument](image)

### 3.2 Test model
According to ASTM standard (2013), tests for determining the basic parameters of soil were conducted. The soil was consisted of clay (23%) and silt (46.8%), with some sand (18.5%) and gravel fractions (11.7%). The particle distribution curve was shown in Figure 4. The liquid limit and plasticity index of the soil were 30.8% and 17.1%, respectively. The plastic index (PI) was 13.7% (>5). According to Unified Soil Classification System, the soil used in this test can be seemed as clay of low plasticity (CL). The optimum water content and maximum dry density were 19.2% and 1.4 g/cm³, respectively. The coefficient of uniformity of the soil was 17.5 (>5) and curvature coefficient was 0.914 (close to 1). The whole model was 25 cm in height, 130 cm long and 40 cm wide, and the upstream and downstream slope gradients of the model were 1:3 and 1:2, respectively. To ensure good-quality model filling, layered filling was used to fill the mode, with 5-cm-thick layers. Three sensors used to measure suction were embedded. The No. 1 sensor was buried at the dam foot of the model, the No. 2 sensor was buried near the surface in the middle of the upstream dam slope, and the No. 3 sensor was embedded in the lower part of the dam top (in the interior of the model, less affected by the external dry-wet cycle) (as shown in Figure 5). The data collection during the test was automated, with researchers monitoring the collected data.

![Figure 4. Particle size distribution](image)
3.3 Drawing Curves
The test process was divided into three parts to simulate the dry-wet cycle:

(1) The first wet–dry cycle
   The initial rainfall intensity was 80mm/h, and after an hour of rainfall, the water level in the upper reach rose to the middle of the model dam. At this time, the rainfall stopped and water gradually infiltrated into the interior of the model dam. Finally, with the long-arc xenon lamp and the fan turned on, drought conditions were simulated to gradually lower the water content of the model over 10 days at temperatures of 30±2°C.

(2) The second wet–dry cycle
   After 19 days of continuous drying, the second cycle began with the same rainfall intensity as in the first cycle. When the water level in the upper reach rose to the middle part of the model dam slope, the rainfall stopped. The drying process was then carried out with the same drying environment as in the first cycle.

(3) The third wet–dry cycle
   After 27 days of continuous drying, the third cycle began with the same rainfall intensity as in the previous two processes at the 46th day. When the water level in the upper reach rose to the middle of the model dam slope, the rainfall stopped and the drying process was carried out in the same conditions as in the previous two processes.

   Because the test cycle was too long and the inner space of the environmental chamber was limited, only a set of experimental simulation was carried out.

   The cycle schedule was presented in Figure 6.

   Cracks occurred at the foot of the dam during the dry-wet cycle, and the cracks penetrated around the sensor, so the change of matrix suction was not considered here. The matrix suction changes in the remaining two locations were shown in Figure 7.

   Soil moisture content was measured every two hours during the drying stage, and the soil-water characteristic curve was drawn according to the matrix suction at the corresponding time, as shown in Figure 8.
3.4 Analysis results

According to the calculation steps in Section 2.2, the calculation process was shown in Table 1 and Table 2.

Table 1. Calculating table of pore size distribution (middle of dam slope)

| w/g | RH | \( V_p \) | \( T \) | \( r_p \) | \( ΔV_p \) | \( <T> \) avg | \( <r_p> \) avg | \( Δν \) | \( Σ(V_p) \) |
|-----|-----|---------|------|------|--------|------|--------|-------|--------|
| 0.580 | 1.0 | 0.580 | 42603.6 | 2.847 | 42606.4 | 33.8 | 2.847 | 42606.4 | 33.8 |
| 0.354 | 1.0 | 0.354 | 45141.1 | 2.847 | 45143.9 | 31.9 | 2.847 | 45143.9 | 31.9 |
| 0.256 | 1.0 | 0.256 | 35555.6 | 2.847 | 35558.4 | 40.5 | 2.847 | 35558.4 | 40.5 |
| 0.147 | 1.0 | 0.147 | 21524.7 | 2.847 | 21527.5 | 66.9 | 2.847 | 21527.5 | 66.9 |
| 0.126 | 1.0 | 0.126 | 16308.0 | 2.847 | 16310.9 | 88.3 | 2.847 | 16310.9 | 88.3 |
| 0.116 | 1.0 | 0.116 | 13483.1 | 2.847 | 13486.0 | 106.8 | 2.847 | 13486.0 | 106.8 |
| 0.098 | 1.0 | 0.098 | 8607.3 | 2.847 | 8610.1 | 167.3 | 2.847 | 8610.1 | 167.3 |
| 0.085 | 1.0 | 0.085 | 4524.0 | 2.847 | 4526.9 | 318.3 | 2.847 | 4526.9 | 318.3 |
| 0.076 | 1.0 | 0.076 | 4319.1 | 2.847 | 4322.0 | 333.4 | 2.847 | 4322.0 | 333.4 |
| 0.067 | 1.0 | 0.067 | 3547.7 | 2.847 | 3550.5 | 405.9 | 2.847 | 3550.5 | 405.9 |
| 0.063 | 1.0 | 0.063 | 3127.0 | 2.847 | 3129.9 | 460.5 | 2.847 | 3129.9 | 460.5 |
| 0.060 | 1.0 | 0.060 | 3076.9 | 2.847 | 3079.8 | 468.0 | 2.847 | 3079.8 | 468.0 |
| 0.055 | 1.0 | 0.055 | 2646.1 | 2.847 | 2648.9 | 544.2 | 2.847 | 2648.9 | 544.2 |
| 0.053 | 1.0 | 0.053 | 2218.8 | 2.847 | 2221.6 | 649.0 | 2.847 | 2221.6 | 649.0 |
| 0.048 | 1.0 | 0.048 | 2117.6 | 2.847 | 2120.5 | 680.0 | 2.847 | 2120.5 | 680.0 |
| 0.043 | 1.0 | 0.043 | 2099.1 | 2.847 | 2102.0 | 686.0 | 2.847 | 2102.0 | 686.0 |
| 0.042 | 1.0 | 0.042 | 2057.1 | 2.847 | 2060.0 | 700.0 | 2.847 | 2060.0 | 700.0 |
| 0.036 | 1.0 | 0.036 | 2051.3 | 2.847 | 2054.1 | 702.0 | 2.847 | 2054.1 | 702.0 |
| 0.035 | 1.0 | 0.035 | 2033.9 | 2.847 | 2036.7 | 708.0 | 2.847 | 2036.7 | 708.0 |

Table 2. Calculating table of pore size distribution (lower part of dam crest)

| w/g | RH | \( V_p \) | \( T \) | \( r_p \) | \( ΔV_p \) | \( <T> \) avg | \( <r_p> \) avg | \( Δν \) | \( Σ(V_p) \) |
|-----|-----|---------|------|------|--------|------|--------|-------|--------|
| 0.999 | 0.518 | 0.518 | 20123.0 | 2.847 | 20125.8 | 71.6 | 2.847 | 20125.8 | 71.6 |
| 0.999 | 0.393 | 0.393 | 16042.8 | 2.847 | 16045.6 | 89.8 | 2.847 | 16045.6 | 89.8 |
| 0.999 | 0.284 | 0.284 | 14913.0 | 2.847 | 14915.9 | 96.6 | 2.847 | 14915.9 | 96.6 |
| 0.999 | 0.195 | 0.195 | 9778.6 | 2.847 | 9781.5 | 147.3 | 2.847 | 9781.5 | 147.3 |
| 0.999 | 0.182 | 0.182 | 7482.1 | 2.847 | 7484.9 | 192.5 | 2.847 | 7484.9 | 192.5 |
| 0.999 | 0.174 | 0.174 | 7248.6 | 2.847 | 7251.4 | 198.7 | 2.847 | 7251.4 | 198.7 |
| 0.999 | 0.141 | 0.141 | 6543.7 | 2.847 | 6546.5 | 220.1 | 2.847 | 6546.5 | 220.1 |
| 0.999 | 0.127 | 0.127 | 6126.1 | 2.847 | 6128.9 | 235.1 | 2.847 | 6128.9 | 235.1 |
| 0.999 | 0.115 | 0.115 | 5728.8 | 2.847 | 5731.7 | 251.4 | 2.847 | 5731.7 | 251.4 |
| 0.999 | 0.102 | 0.102 | 5398.1 | 2.847 | 5401.0 | 266.8 | 2.847 | 5401.0 | 266.8 |
| 0.999 | 0.092 | 0.092 | 5188.1 | 2.847 | 5190.9 | 277.6 | 2.847 | 5190.9 | 277.6 |
| 0.999 | 0.087 | 0.087 | 5072.9 | 2.847 | 5075.8 | 283.9 | 2.847 | 5075.8 | 283.9 |
The calculated results in Table 1 and Table 2 showed that the accumulative pore volume per unit mass in the middle of the dam slope was 0.58 cm$^3$/g, and that in the lower part of the dam top was 0.518 cm$^3$/g. When the sensors were buried, the sensors in the middle of the dam slope were close to the slope surface, while the sensors on the top of the dam are relatively located in the interior of the model. During the dry-wet cycle, the dam slope surface was more susceptible to external environmental impacts. Generally speaking, during the drying process, with the decrease of soil saturation, the increase of matrix suction made the soil shrinkage [12-15]. However, the test results showed that the pore volume in the dam slope area which was more affected by the external environment was larger than that in the model after the wet-dry cycle. Under the same initial porosity, the shrinkage of the internal soil was larger than that of the slope surface, which was inconsistent with the existing research. In fact, for dam model, soil shrinkage was not isotropic, and the direction of soil shrinkage was different in different parts. When the shrinkage was large, the visual expression of this inconsistency was cracking. For soils without cracks, there was no macro-fracture in the process of dry-wet cycling, but the connection between soil particles decreased. When the saturation increased again, the shrinkage volume expanded and the overall volume increased. Increasing the number of cycles would lead to a larger volume increasing, and the larger the influence of the dry-wet cycle condition was, the larger the volume increase of the parts would be. As the test results showed, the accumulative pore volume per unit mass in the middle of the dam slope was larger than that in the interior. Therefore, it can be considered that the dry-wet cycle will increase the pore volume of soil, reduce the compactness of soil, and make the quality of soil filling decline.

4. Conclusion
The soil-water characteristic curves of different parts of the model were obtained by model tests, and the pore distribution of the soil was analyzed. The results showed that the pore volume of the soil increased with the increase of the number of cycles, but the degree of the increase was not analyzed in detail in this paper.

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