Study on Influence Factors of Water Content of Expansive Soil in Canal Slope Based on Grey Correlation Model

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Abstract. The change of water content of expansive soil in canal slope is very unfavorable to the stability of the slope. In order to analyze the influencing factors and laws of water cut, the relationship between water content and voltage of expansive soil, the relationship between initial water content and expansion force, initial water content and disintegration of expansive soil were tested relationship. The gray correlation model was analyzed based on the vertical displacement, water content, suction, rainfall, soil temperature and temperature data collected on the site. It is preliminarily believed that the main influencing factors of the change of water content of expansive soil in the test section are temperature, rainfall, evaporation and suction. The mechanism analysis of the grey relational model is also obtained: due to the lag of the rainfall infiltration process, the atmospheric rainfall can only penetrate into the 1.6m deep strong expansive soil after 3d, and the influence depth is less than 6.1m. The research on the influencing factors of the change of water content of expansive soil provides the basis for the development of prevention and control measures for canal slope soil in the middle route of South-to-North Moisture Diversion Project and the safe management of channel operation.

1. Introduction

The South-to-North Water Diversion Project is the largest Water diversion project in the world thus far, with a total length of about 1,432 km, about 387 km in the main canal crossing the expansive soil area. Due to its special engineering characteristics, expansive soil has the characteristics of water absorption expansion, water loss shrinkage and repeated expansion and contraction deformation, which is easy to cause instability of the canal slope and has a great impact on the safe operation of the project. The change of water content of expansive soil is an important index reflecting the expansion and contraction deformation of expansive soil. Therefore, long-term monitoring of the change of water content of expansive soil in canal slope is of great significance for studying the expansion and contraction deformation of canal slope and the safe operation of the channel.

As a typical special soil, expansive soil has the characteristics of expansion and contraction, fissure and over-consolidation. These characteristics interact and restrict each other under certain external environment, especially under the alternating action of dry and wet cycles, the swelling and water
shrinkage of the expansive soil will lead to the occurrence of cracks in the soil and the decrease of strength, which will bring serious damage and influence to the expansive soil channel buildings[1]. At present, there are many studies on the relationship between the water content and the mechanical characteristics of expansive soils[1-4], and most of the research results are derived from laboratory test and are used to guide actual engineering. In recent years, the on-site monitoring of the water content of expansive soil has been carried out[5-9], most of which use manual measurement as the main means. The literature [8-9] realized the automatic collection and data transmission of the water content of expansive soil, which laid the foundation for studying the variation law of the water content of expansive soil on site.

Xichuan's expansive soil slope section has established an on-site automated observation station[9], which can obtain the canal slope perception information data in real time, such as the expansive soil water content, soil suction, soil temperature, atmospheric rainfall, atmospheric temperature and evaporation, etc. It combines the experimental data of indoor water content characteristics, uses the grey correlation model to study the variation characteristics of the water content of the expansive soil in the canal, reveals the key influencing factors causing the change of the water content of the canal slope. It provides a basis for formulating the prevention and control measures for the expansive soil in the South-to-North Water Transfer Middle Line Project, and the safe operation of the channel.

2. Experiment on water content characteristics of expansive soil

2.1. Analysis of expansive soil structure

- Microstructure: Quaternary Lower Pleistocene Diluvium (plQ1) clay in the Xichuan section: The soil is mainly composed of flaky clay minerals and a small amount of feldspar, quartz particles, etc., some samples contain hair-like palygorskite. The clay minerals are arranged irregularly; a small amount of sample shows linear scratches; the micropores and micro-cracks in the sample develop from development to extreme development.

- Macrostructure: The expansive soil in the Xichuan section exists zonation in terms of color, fissure and groundwater distribution. The upper part of the layer is brownish red with a thickness of 0.5m to 1.5m; the middle part is brownish red with grayish green, 1.5m~2.0m thick, partially containing calcium tuberculosis and iron-manganese infiltration; the lower part is brownish red. The micro-cracks in the upper part are developed, mostly steep dip cracks, and the soil is fragmented; the small cracks in the middle are extremely developed, filled with gray-green clay, forming a fissure dense zone, in which the small fracture density is 32~36 strips/m; the small cracks develop in the lower part, and the long and large fissures are not developed, and the large fissures are locally developed. Among them, the water content of the 152.5~153.5m elevation soil is higher, which is the upper stagnant water layer.

2.2. Relationship between water content and voltage of expansive soil

The indoor test of the relationship between the water content and the voltage of the expansive soil is mainly to establish a calibration model of the soil moisture sensor on site to obtain a more realistic moisture change of the expansive soil. The calculation formula of volumetric water content of strong expansive soil on site is obtained by polynomial regression calculation:

\[
\omega = 7.1293V^3 + 5.4846V^2 - 4.5763V + 2.1774 \quad (R^2=0.9895)
\]  

(1)

In the above formula, \( \omega \) is the volumetric water content; \( V \) is the voltage; and \( R \) is the multiple correlation coefficient.

The test results show that the voltage curve changes gently when the water content of the expansive soil is below 20%, and the slope of the voltage curve becomes larger after the water content is greater than 20% (see Figure 1).
2.3. Relationship between initial water content and expansion force

The expansion force of expansive soil has a tendency to decrease with the increase of initial water content. This is because the expansion force is generated after the soil absorbs water. When the initial water content of the soil is high, the amount of water absorbed by the soil is smaller when saturation is reached, the smaller the expansion force generated. The relationship between the expansive soil expansion force and the initial water content is shown in Figure 2.

![Figure 1. Indoor test of water content and voltage curve of expansive soil.](image1)

![Figure 2. Relationship between initial water content and expansion force of expansive soil.](image2)

2.4. Relationship between initial water content and disintegration characteristics of expansive soil

The disintegration curve of the expansive soil in Nanyang area within 0.5h under different initial water content (Figure 3), when the soil water content is less than 14%, it completely disintegrates in less than 5 minutes, indicating that even weakly expansive soil, when the initial water content is less than a certain value, it can also completely disintegrate in a short time.

![Figure 3. Disintegration curve of expansive soil within 0.5h under different water content conditions.](image3)

Based on a large number of experimental results, it can be concluded that the initial water content is the most critical among the factors affecting the disintegration characteristics of the expansive soil. When the initial water content is greater than the normal natural water content, other factors (such as swelling, crack development, etc.) gradually increase, and the soil also exhibits many different disintegration characteristics. Generally, the lower the water content, the more the crack develops, and the stronger the swelling, then the faster the disintegration rate and the larger the disintegration amount. Therefore, when performing the disintegration test, it should be selected as far as possible under the natural water content, and the water loss or water absorption will change its disintegration property.

3. Grey correlation model theory method

The basic idea of the grey relational degree theory is to judge whether the connection is close according to the degree of similarity of the sequence curve geometry. The closer the curves are, the greater the degree of association between the corresponding sequences, and vice versa. In correlation analysis, a measure of the degree of association between two factors in two systems or systems over
time is called the degree of association. It quantitatively describes the relative changes between factors in the development of the system.

According to the basic idea of Professor Deng Julong's theory of grey relational degree\cite{10-11}, Liu Sifeng et al.\cite{12} proposed a more realistic ash comprehensive correlation calculation model. The basic method is to first calculate the gray absolute correlation degree and the gray relative correlation degree between the series, and then calculate their linear combination to obtain the gray comprehensive correlation degree.

Assume that the water content observation sequence $X_0$ is the same length as the series of cause quantities $X_i$ ($i = 1, 2, ..., n$ is the number of causes), and the initial values are not equal to 0. $\varepsilon_{0i}$ and $r_{0i}$ are respectively the gray absolute correlation degree and the gray relative correlation degree, the calculation method is shown in the literature \cite{8}, and the weighted average is taken as the gray comprehensive correlation degree, that is,

$$\rho_{0i} = \theta \varepsilon_{0i} + (1 - \theta)r_{0i} \quad (2)$$

In the above formula, $\theta \in [0,1]$ is the comprehensive weight coefficient. The gray comprehensive correlation degree not only reflects the similarity between the $X_0$ and $X_i$, but also reflects the closeness of the $X_0$ and $X_i$ relative to the change rate of the starting point. It is a comprehensive indicator of whether the relationship between the sequences is tight. If you prefer absolute correlation, you can take $\theta > 0.5$, if you value the relative rate of change relationship, take $\theta < 0.5$.

Since the gray correlation analysis is based on the same correlation degree model, the degree of association between the parent sequence and each subsequence is calculated. Then, sort by the degree of association to find the subsequence that is most relevant to the parent sequence. Therefore, the core of gray correlation analysis is to focus on the association sequence, not the size of the correlation value. A gray relational sequence is a set of sequences arranged in descending order of relevance of several subsequences to the same parent sequence. It visually reflects the degree of association of each subsequence with respect to the same parent sequence.

4. Analysis of water content and influencing factors of expansive soil in canal slope

4.1. Qualitative analysis of water content

According to the obtained effective monitoring data, the measured results of the water content of the strong expansive soil in the Xichuan section are shown in Fig. 4. According to the analysis in Figure 4, the water content of the three measuring points CW01, CW02 and CW03 located in the strong expansive soil is obviously related to atmospheric rainfall. In the annual rainy season, the water content has a significant increase, which is delayed by the rainfall infiltration process. In addition, the change of water content in the strong expansive soil is positively correlated with the soil temperature, that is, the period with high water content, the soil temperature and temperature are also high generally; but the measuring point CW04 is buried in the medium expansion rock, its water content changes smoothly, independent of atmospheric rainfall and temperature.
Figure 4. Process line of water content and soil temperature and rainfall of expansive soil.

4.2. **Correlation analysis between water content and suction, etc. influence factors**

Using the above method, we calculated the water content (monthly average), rainfall (monthly accumulation), evaporation (monthly accumulation), atmospheric temperature (monthly average), soil temperature (monthly average) and suction (monthly average) of Xichuan strong expansive soil. Their gray comprehensive correlation matrix between them is shown in Table 1.

It is known from Table 1 that the main factors affecting the change of water content of strong expansive soil are atmospheric temperature, rainfall, evaporation and suction. The correlation between soil temperature and atmospheric temperature is 0.909, followed by rainfall and evaporation with a correlation of 0.876. The third is the correlation between rainfall and soil temperature and atmospheric temperature, is 0.797 and 0.790. The last one is the correlation between evaporation and atmospheric temperature and soil temperature, is 0.730 and 0.723. The calculation results are in line with the actual situation.

| Water content (CW01) | Rainfall (RA01) | Evaporation (EV) | Atmospheric temperature (AT01) | Soil temperature (GT01) | Suction (MS01) |
|----------------------|-----------------|------------------|-------------------------------|-------------------------|---------------|
| CW01                 | 1               | 0.721            | 0.677                         | 0.879                   | 0.873         | 0.573         |
| RA01                 | 0.721           | 1                | 0.876                         | 0.790                   | 0.797         | 0.701         |
| EV                   | 0.677           | 0.876            | 1                             | 0.730                   | 0.723         | 0.673         |
| AT01                 | 0.879           | 0.790            | 0.730                         | 1                       | 0.909         | 0.597         |
| GT01                 | 0.873           | 0.797            | 0.723                         | 0.909                   | 1             | 0.624         |
| MS01                 | 0.573           | 0.701            | 0.673                         | 0.597                   | 0.624         | 1             |

4.3. **Analysis of atmospheric rainfall infiltration time and influence depth**

In theory, atmospheric rainfall is an important factor affecting the change of soil water content, but the infiltration process of strong expansive soil has a lag period[4], so it is not reasonable to directly calculate the correlation between them. In order to explore the time when atmospheric rainfall infiltrates into a strong expansive soil or the depth of atmospheric rainfall, it is necessary to quantitatively analyze the relationship between atmospheric rainfall and water content[13-15].

Using the gray correlation model modeling mechanism, we fix the rainfall sequence and sequentially move the water content sequence of 1 unit, then calculate the correlation degree between them, and calculate repeatedly until the calculated correlation degree sequence reach its peak. At this time, the corresponding time is the lag time of rainfall infiltration.
4.3.1. **Strong expansive soil slope.** This paper selects the data of the Xichuan section from August 9, 2012 to April 10, 2013, and the data collected automation automatically is complete. During this period, it experienced a rainy season and a low temperature season, which is representative. Through calculation, the correlation graph between the daily atmospheric rainfall and the daily soil moisture lag days is plotted (Figure 5). The results are analyzed as follows.

- The water content monitoring point CW01 of 1.6m below the ground has an obvious correlation degree peak on 3rd day of lag, indicating that it can penetrate into the expansive soil of 1.6m depth after 3 days of atmospheric rainfall.
- The water content monitoring point CW02 of 2.5m below the ground has a weak correlation degree peak on 10~11rd day of lag, indicating that it can penetrate into the expansive soil of 2.5m depth after 10~11 days of atmospheric rainfall, it also shows that the influence of rainfall is weak.
- The water content monitoring point CW03 of 3.7m below the ground has a weak correlation degree peak on 14rd day of lag, indicating that it can penetrate into the expansive soil of 3.7m depth after 14 days of atmospheric rainfall.
- The water content monitoring point CW04 of 6.1m below the ground has a step-like correlation degree change, which indicates that the water content is little related to atmospheric rainfall, mainly due to changes in groundwater.

![Figure 5. Relationship between the lag days of water content and the correlation degree of atmospheric rainfall expansion soil.](image)

4.3.2. **Impact analysis.** In the Xichuan section, there is no correlation peak between the water content sequence of the monitoring point with a depth of 6.1m and the atmospheric rainfall, indicating that the influence of atmospheric rainfall on the strong expansive soil is <6.1m.

5. **Conclusion**

- During the dry-wet cycle of the expansive soil in the top of the canal, the water content at a certain depth of the expansive soil surface is obviously related to atmospheric rainfall. In the annual rainy season, the water content has increased significantly, and it is delayed by the influence of rainfall infiltration. In addition, the change of water content in the expansive soil is positively correlated with the soil temperature, that is, in the period of high water content, the soil temperature and atmosphere temperature are generally high.
- Analysis of grey correlation model shows that the correlation sequence between monthly water content and influencing factors of the top expansive soil is monthly evaporation > monthly average temperature > monthly rainfall, and the correlation sequence indicates that the monthly evaporation and soil water content change most closely.
- According to the atmospheric rainfall and on-site measured soil water content time series, using the grey correlation model mechanism, this paper quantitatively analyzes the soil water content
and its influencing factors, as well as the atmospheric rainfall infiltration lag time and atmospheric rainfall impact depth.

- Through the monitoring and analysis of the water content of the expansive soil in the South-to-North Water Transfer Middle Line Project, this paper has certain engineering significance for promoting the on-site automatic testing of the expansive soil water content.

Acknowledgments
This study is supported by the National Sci-tech Support Plan, No.2011BAB10B02, and the Changjiang Survey Planning Design And Research Co., Ltd. Research Project, No.CX2018Z26.

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