Study on salt expansion characteristics and influencing factors of saline soil foundation of transmission lines

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Abstract. Due to the high salt content, strong expansibility, and low bearing capacity of saline soil, the safety and stability of transmission line towers crossing salt lake areas are seriously threatened. In this study, the deformation of tower structure in salt lake areas was investigated using satellite remote sensing and on-site field survey methods. Indoor model tests were conducted to systematically analyze the factors affecting salt expansion deformation, including salt content, moisture content, and temperature. The grey relational analysis method was introduced to calculate the sensitivity of influencing factors. The conclusions are as follows: tower deformation and damage mainly occur in the salt lake areas; salt is the fundamental cause of salt expansion; salt expansion deformation is the most obvious in the optimum moisture content state of saline soil; the factor with the greatest impact on salt expansion characteristics of saline soil is salt content, followed by moisture content, while temperature has a relatively minor impact.

Keywords: transmission line; tower structure; saline soil; salt expansion; optimum moisture content; grey relational analysis method; sensitivity

1 Introduction

With the advancement of the “carbon neutrality and carbon peaking” goals, the western region of China uses the advantaged and abundant “wind and solar” resources to vigorously promote the development of clean energy. The “Green Power Transmission” major channel project has also started comprehensive construction. The transmission line route inevitably crosses salt lake areas. The salt lake environment in China is characterized by high salt content, high permeability, high expansibility, and low bearing capacity. The phenomenon of endangering the foundation of power transmission and transformation facilities is increasing, with uneven settlement of

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transmission tower foundations and excessive inclination of towers, which seriously threaten the safe and stable operation of the power grid.

Since the 1940s, experts and scholars have conducted extensive research on the engineering characteristics of saline soil through a large number of indoor tests and practical engineering applications. Chai [1] et al. conducted experiments on the dry density, saturation, porosity ratio, and other indicators of coastal lacustrine facies saline soil, and explored the influence of salt content on the activity index and plasticity index of the soil. Feng et al. [2] estimated the salt expansion sensitive depth of highway subgrade with sulfate saline soil based on temperature field and soil salt expansion characteristics. Lai et al. [3] pointed out that the salt expansion of sodium sulfate saline soil is affected by temperature and cooling rate. Wan et al. [4] explored the influence of different temperatures on the salt expansion of sodium sulfate saline soil, and found that the salt expansion worsens and tends to stabilize with the decrease of temperature. Xiao [5] pointed out that the salt frost heave of sulfate saline soil is controlled by salt content and moisture content. Zhang et al. [6] found that the sensitive factors affecting the salt expansion of sulfate saline soil include salt content, moisture content, and temperature, etc. Zhang et al. [7] used numerical simulation to study the multi-field mathematical coupled water-thermal-salt-mechanical model of saline soil. Wu [8]et al. proposed a water-thermal-salt-mechanical coupling model for saturated saline frozen soil, focusing on the coupling effects between fluid flow, heat transfer, crystallization, and deformation in saline soil porous media. Cheng[9] took the typical coarse-grained saline soil in Xinjiang as the research object, and carried out experimental research on backfilling, rolling, soaking and collapsibility. However foundation subsidence disease has always been a thorny problem faced by infrastructure construction in salt lake areas. Saline soil is a collection of multiple factors and scales, with complex and diverse characteristics. It is easily affected by drastic changes in the external environment. When the environment (temperature, humidity, salt content, etc.) deteriorates, the structural strength and bearing capacity of the saline soil foundation rapidly decrease, which easily leads to varying degrees of settlement deformation of the foundation and damage to transmission tower structure. Understanding and revealing these characteristics are essential for the safety, reliability, applicability, and durability of engineering. Conducting research on the salt expansion characteristics and influencing factors of transmission tower foundations in salt lake areas is of certain significance for improving the reliability and durability of power grid engineering in salt lake areas, as well as for the long-term stable operation and essential safety enhancement of the power grid.

2 Analysis on settlement of typical transmission tower foundations in salt lake areas

2.1 Overview of research area

The typical route in the research area is the Chaiyu Double Lines, which completely traverses the entire Qarhan Salt Lake area from north to south. It is set up in parallel with two single-loop circuits. The total length of Line I is approximately 104.73km, and Line II is approximately 104.86km. The middle part of the route passes through the Qarhan Salt Lake area, where the terrain is extremely flat in the salt pool area. The entire lake area has a height difference of less than 5m, with an altitude of 2,675m-2,700m. The region has long, cold winters, dry climate, rapid warming in spring, short and mild summer, gradually cooling temperatures in autumn, low annual precipitation, short frost-free period, abundant sunshine, intense solar radiation, large temperature difference between day and night, and hot and dry weather in the same season. The saline soil in the Qarhan Salt Lake area is mainly chloride-chlorite saline soil, with a salt content ranging from 8% to 80%, classified as strong to extremely saline soil, as shown in Figure 1.

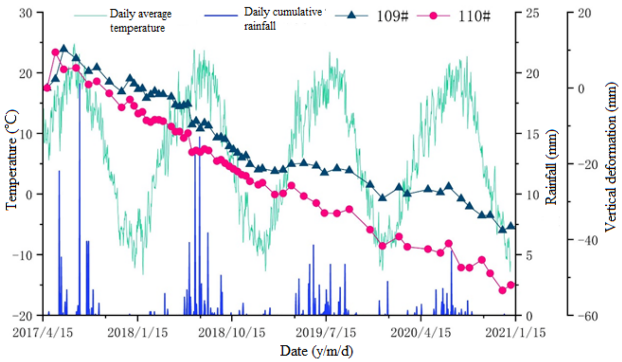


Fig. 1. The annual distribution of temperature and rainfall in the study area

2.2 Statistics on transmission line and foundation deformation in salt lake areas

Through satellite remote sensing analysis and on-site field investigation, a survey and analysis on the stability of towers is conducted from three aspects: foundation, base, and tower body, in order to obtain the current settlement status of typical transmission line tower foundations. For the deformation survey of tower foundations, the analysis mainly focuses on the deformation of the soil layers near the foundation and the water seepage and deformation of the foundation. In the investigation on foundation deformation status of the towers, the analysis mainly focuses on the deformation of the tower foundation protection devices and the height difference between the foundations of each tower. As for the investigation on the tower body, the analysis is based on the deformation of the main beams and components of the tower, as well as the displacement of the insulator strings.

The investigation results, as shown in Figure 2, indicate that the total number of towers with a settlement greater than 30mm on the Chaiyu Line I is 33, while in the salt lake area, the number of towers with a settlement exceeding 30mm reaches 28, accounting for 84.8%. The total number of towers with a settlement greater than 30mm on the Chaiyu Line II is 22, while in the salt lake area, the number of towers with a settlement exceeding 30mm reaches 22, accounting for 100%. The deformation and damage of transmission line towers mainly occur within the salt lake area, with the most obvious deformation and damage to towers near the operating salt ponds. In the environments such as deserts, grasslands, abandoned salt ponds, mountains, and deserts that the transmission lines pass through, although some tower protection materials are damaged, the main structure of the towers remains in a relatively stable state. Through on-site measurements and observations, no significant deformation or damage is observed.

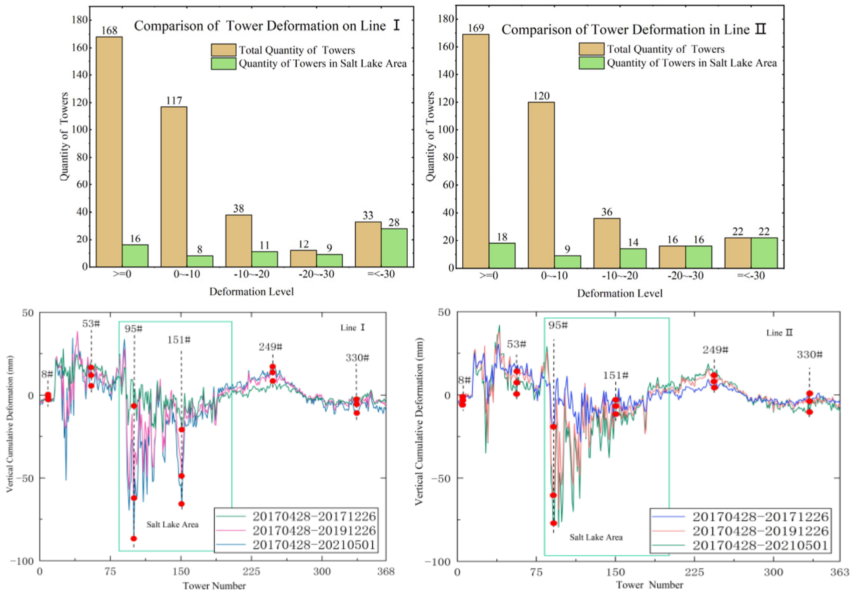


Fig. 2. Statistics of Tower Deformation in Salt Lake Area

3 Indoor salt expansion test of saline soil

In order to further understand the salt expansion characteristics of saline soil in salt lake area, this paper explores the evolution law of salt expansion of saline soil in salt lake area under different temperature, moisture content, and salt content states based on the salt expansion mechanism through indoor salt expansion tests, and analyzes the most important influencing factors of the evolution law of salt expansion. The experimental materials in this paper used indoor artificially prepared saline soils. The basic physical properties of the original soil samples for test are shown in Table 1. The original soil sample of the test is determined to be plain soil (salt content less than 0.1 %) by the soluble salt content. According to the relevant regulations in the technical code for the design of foundation of overhead transmission line, the content of NaCl and Na_2SO_4 is taken as the limit salt content, and the quality method is used to evenly mix with the coarse-grained soil with good gradation to obtain the coarse-grained saline soil with the specified salt content.

Table 1. Basic Physical Properties of Original Soil Samples

Source of soil samples	d<2mm (%)	d<20mm (%)	ρ_{dmax} (g·cm^{-3})	ω_{opt} (%)	Nonuniform coefficient Cu	Curvature coefficient Cc	Gradation status
Golmud	25.65	100	1.7	9.6	18.11	1.42	Good gradation

3.1 Test conditions

In order to study the evolution law of salt expansion deformation of saline soil in salt lake area under different moisture content, salt content, and temperature, the uniform degree of compaction was controlled at 96% in the test, and the specimens under different salt content and moisture content states were prepared. The specific test conditions are shown in Table 2.

Table 2. Test Conditions

Condition Number	Degree of compaction	Salt content	Moisture content	Temperature (℃)
1	96%	10%	5%	-10
2				0
3				10
4			10%	-10
5				0
6				10
7			15%	-10
8				0
9				10
10		20%	5%	-10
11				0
12				10
13			10%	-10
14				0
15				10
16			15%	-10
17				0
18				10
19		30%	5%	-10
20				0
21				10
22			10%	-10
23				0
24				10
25			15%	-10
26				0
27				10

3.2 Test procedure

(1) Specimen preparation

The test specimens for indoor salt expansion test are obtained from the heavy compaction test, the compaction cylinder is placed on a hard ground, and the prepared soil sample is poured into the cylinder five times. Each layer needs about 1000 grams of flat surface of the sample, and slightly pressed, and then hammered 27 times to compact the first layer of soil. The real-time hammer should fall freely and vertically, and the hammer trace must be evenly distributed on the soil sample surface. After the first layer is compacted, the sample layer is ' roughened ', and then loaded into the sleeve, and the above method is repeated to compact the remaining layers of soil. After compaction, the specimen should not be 6 mm above the top of the barrel. In this study, specimens with a diameter of 152mm and a height of 170mm were prepared using a compaction mold (see Figure 3). The soil samples for test were prepared under the optimum moisture content conditions, and the target degree of compaction is controlled by mass/volume. In order to analyze the effect of moisture content on the salt expansion characteristics of coarse-grained saline soil, a comparative test group with a moisture content of $\omega opt \pm 5\%$ is also set up.

(2) Specimen installation

Tighten the pull rods on both sides of the compaction mold with a wrench, and install the dial gauge on the bracket. After checking for no errors, place the specimen, dial gauge, and porous plate into the temperature control box, as shown in Figure 4.

(3) Salt expansion monitoring

1) Adjust the temperature of the low-temperature control box to 10°C and keep it constant for 24 hours.

2) The next day, read the initial reading of the dial gauge and record it.

3) Lower the temperature of the low-temperature control box from +10°C to -10°C, decreasing by 10°C at each level. After maintaining the temperature for 24 hours, record the final reading of the dial gauge under this temperature condition and record the salt expansion value in this temperature range.

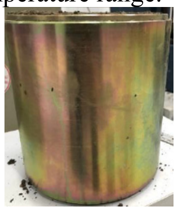


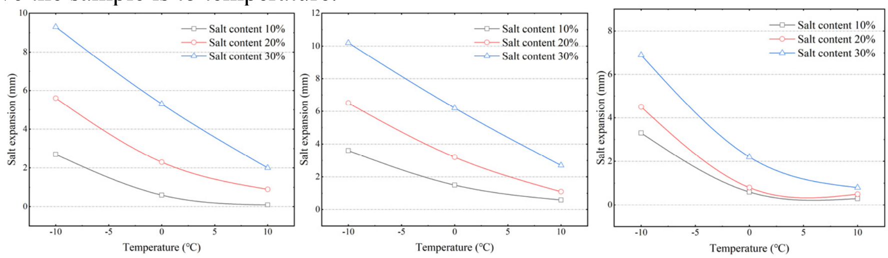
Fig. 3. Test Sample

Fig. 4. Sample Installation and Measurement

3.3 Test results and analysis

(1) Influence of temperature on salt expansion deformation of saline soil

The relationship between the salt expansion and temperature under different salt contents of saline soil at different moisture contents with a degree of compaction of 96%, as shown in Figure 5. The temperature gradually decreases, the saline soil begins to expand. However, due to the certain pores between the particles of saline soil, some salt crystals are absorbed by the large pore structure, resulting in a relatively slow initial expansion of the soil during cooling, and even a phenomenon of slight contraction of the body; as the temperature continues to decrease, the amount of salt water absorption and crystallization in the saline soil gradually increases, showing a gradual increase in volume. When the temperature is below 0°C, the volume expansion accelerates, mainly due to the freezing expansion deformation of water. Comparing the three figures, it can be found that the higher the salt content, the more sensitive the sample is to temperature.

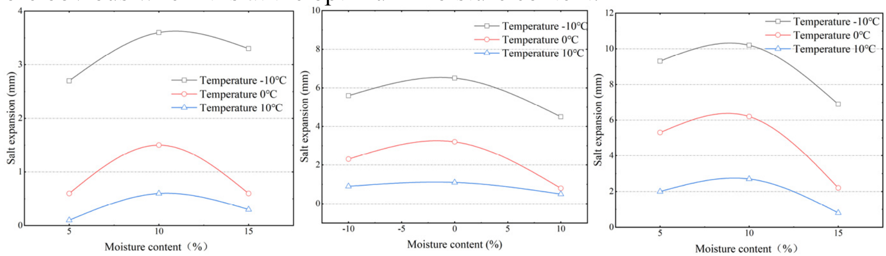


(a)Moisture content 5% (b) Moisture content 10% (c) Moisture content 15%

Fig. 5. Relationship curve between salt content and temperature under different moisture content conditions of saline soil with different salt content

(2) Influence of moisture content on salt expansion deformation of saline soil

Figure 6 shows the relationship between salt expansion and moisture content of saline soil at different temperatures under various salinity concentrations when the degree of compaction is 96%. Figure 6 suggests that for saline soil, the salt expansion under different temperature environments first increases and then decreases with the increase of moisture content in the soil. At the optimum moisture content condition, the expansion of saline soil reaches its peak. This is because, as the moisture content in saline soil increases, gases are continuously expelled, causing the soil volume to undergo micro-shrinkage; as the temperature gradually decreases to below 0°C, the moisture in the soil pores gradually freezes and causes frost heave, leading to an increase in soil volume. For the saline soil used in the test, good compaction can only be achieved at the optimum moisture content state. In samples formed on both sides of the optimum moisture content, the soil voids are relatively large. When salt frost heave occurs, it first fills the voids between soil particles, thereby promoting the expansion deformation of the soil. When the moisture content is less than the optimum moisture content, the expansion of the soil is mainly dominated by salt, the moisture content increases, the salt in the soil absorbs water and crystallizes, causing volume expansion; when the moisture content is greater than the optimum moisture content, the salt in the soil is diluted, weakening the salt expansion effect. At the same time, under negative temperature conditions, water solidifies and expands in volume, but the presence of salt weakens the solidification of water, resulting in a phenomenon where higher moisture content leads to less volume expansion. Therefore, the higher the compactness of saline soil, the greater the salt expansion, and the deformation is more obvious when it is at the optimum moisture content.

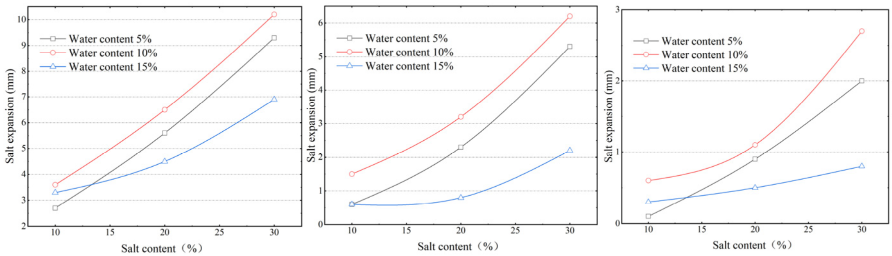


(a)Salt content 10% (b) Salt content 20% (c) Salt content 30%

Fig. 6. Relationship curve between salt content and salt expansion of saline soil under different salt content conditions and different environmental temperatures

(3) Influence of salt content on salt expansion deformation of saline soil

Figure 7 shows the relationship between salt expansion and salt content at different moisture contents of saline soil under different environmental temperature conditions when the degree of compaction is 96%. From the figure, it can be seen that under different environmental temperature conditions, the salt expansion of saline soil at different moisture contents gradually increases with the increase of salt content. This indicates that the salt content is the fundamental reason for salt expansion. The higher the salt content, the more water absorption and crystal generation, and the excess free water freezes and expands below 0°C. Under the combined effects of salt expansion and freeze expansion, the expansion of the soil mass increases dramatically. Under the optimum moisture content conditions, the expansion of saline soil remains at a high value as the salt content changes. Under low salt content and low moisture conditions, the amount of salt absorbing water and crystallizing is small, which cannot fully fill the gaps between soil particles, resulting in a decrease in salt expansion. With the increase in salt content, water molecules in the soil can combine with more salt particles to form bound water, causing volume expansion and an increase in salt expansion. However, under conditions of excessive moisture content, salt will dissolve in the water, leading to loss of bound water and a decrease in salt expansion. This is also the reason for the appearance of the intersection point in the graph.



(a)Environmental temperature -10°C (b) Environmental temperature 0°C (c) Environmental temperature 10°C

Fig. 7. Relationship curve between salt expansion and moisture content under different salt content conditions and environmental temperatures

4 Sensitivity analysis of factors affecting salt expansion in saline soil

In the previous section, we explored the impact of salt content, moisture content, and temperature on salt expansion in saline soil through indoor test, and found a close relationship between the occurrence of salt expansion in saline soil and these three factors. In this section, we will use sensitivity analysis[10] to compare the impact of these three factors.

4.1 Basic principles and methods of grey relational analysis

In order to analyze the impact of salt content, moisture content, and temperature on salt expansion in saline soil, the grey relational analysis method is introduced to conduct sensitivity analysis of the impact. Grey theory[11] is often applied to the analysis process of systems with incomplete information and difficulty in determining the primary and secondary relationships between factors. By calculating the grey relational degree of limited data sequences in grey systems, the primary and secondary relationships between various influencing factors within the system are analyzed. Thus, the close relationship between each factor and the target variable is determined. The steps of grey relational analysis are as follows:

(1) Determine the matrix of sensitive factor sequences and the matrix of target sequences.

Take the factors affecting salt expansion in saline soil (including salt content, moisture content, and temperature) as comparative column X, denoted as

$$X = [X_1, X_2, \cdots, X_m]^T \tag{1}$$

Take the salt expansion variation in saline soil as reference column Y

$$Y = [Y_1, Y_2, \cdots, Y_m]^T \tag{2}$$

where,

$$X_i = \left[x_i(1), x_i(2), \cdots, x_i(n)\right] \tag{3}$$

$$Y_i = \left[y_i(1), y_i(2), \cdots, y_i(n)\right] \tag{4}$$

(2) Nondimensionalization of matrices

Dimensionalization processing using interval relative values:

$$X_i^{'} = \left[x_i^{'}(1), x_i^{'}(2), \cdots, x_i^{'}(n)\right] \tag{5}$$

Where, $x_i^{'} = \dfrac{x_i(j) - \min x_i(j)}{\max x_i(j) - \min x_i(j)}$, interval relative processing is also performed on the reference column Y .

(3) Determine the gray relational degree difference information space of the matrix.

The difference information is obtained by equation (4.6) to obtain the difference sequence matrix Δ_{ij}, and the maximum value $\Delta_{\max}$ and minimum value $\Delta_{\min}$ are extracted from Δ :

$$\Delta_{ij} = \left|x_i(j) - y_i(j)\right| \tag{6}$$

(4) Calculate the gray relational coefficient matrix and gray relational degree.

Relational degree A_i can be calculated by the following equation:

$$A_i = \frac{1}{n}\sum_{j=1}^{n} \gamma_{ij} \tag{7}$$

Where, γ_{ij} is the relational coefficient, $\gamma_{ij} = \dfrac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta_{ij} + \zeta\Delta_{\max}}$; ζ is the resolution coefficient, usually taken as 0.5. Relational degree A_i is the change in the interval $[0,1]$. The larger the relevance of the influencing factor in the relevance sequence is, the greater the impact of the influencing factor on the salt expansion is.

4.2 Gray relational analysis of influencing factors

By substituting the experimental data into equations (4.1) and (4.2), we can get:

$$\mathrm{x} = \begin{bmatrix} \mathrm{x}_1 \\ \mathrm{x}_2 \\ \mathrm{x}_3 \end{bmatrix} =$$

| 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.2 0.2 0.2 0.2 0.2

0.05	0.05	0.05	0.1	0.1	0.1	0.15	0.15	0.15	0.05	0.05	0.05	0.1	0.1
-10	0	10	-10	0	10	-10	0	10	-10	0	10	-10	0

0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
0.1	0.15	0.15	0.15	0.05	0.05	0.05	0.1	0.1	0.1	0.15	0.15	0.15
10	-10	0	10	-10	0	10	-10	0	10	-10	0	10

$Y = [Y_1] =$

2.7	0.6	0.1	3.6	1.5	0.6	3.3	0.6	0.3	5.6	2.3	0.9	6.5	3.2	1.1

4.5	0.8	0.5	9.3	5.3	2	10.2	6.2	2.7	6.9	2.2	0.8

According to the steps of grey relational analysis, the grey relational degrees for salt content, moisture content, and temperature are 0.68, 0.58, and 0.50, respectively.

From the relational degree calculation result, it can be seen that when the three influencing factors act together, the factor that has the greatest impact on the salt expansion of saline soil is the salt content, followed by moisture content, while temperature has a relatively smaller impact compared to the other two factors. Clearly identifying the most significant factors affecting salt expansion in saline soil helps to formulate targeted measures to prevent salt expansion, which is of guiding significance for disaster prevention and reduction of tower foundations in salt lake areas.

5 Study on prevention and control technology of salt expansion deformation of saline soil

Through the indoor salt expansion test results, it is found that the saline soil is more likely to absorb water and crystallize when the temperature decreases, resulting in excessive volume expansion and uplift of the saline soil, resulting in uneven settlement of the tower foundation of the transmission line. At the same time, due to the phenomenon of water and salt migration in the saline soil foundation, as well as the temperature difference between day and night and the seasonal alternation of each year, the salt expansion deformation occurs repeatedly. This repeated expansion deformation of the saline soil foundation will lead to a continuous decline in the mechanical properties of the soil and the overall stability of the tower foundation[12]. In this section, based on the indoor experimental study of salt expansion characteristics and mechanical properties of coarse-grained saline soil and the existing research on salt expansion of saline soil, the treatment methods of coarse-grained saline soil foundation and the prevention and control measures of salt expansion deformation are proposed.

(1) The collapsibility rate and salt expansion rate meet the existing norms and standards of saline soil section. The salt crust, salt frost and growing saline-alkali-resistant vegetation on the surface of the foundation should be cleaned, and the gravel

with good strength and permeability should be filled, and the filling depth should be greater than 0.3 m.

(2) In areas where the salt expansion rate of soil does not meet the specifications and standards, treatment methods such as increasing the depth of foundation replacement and reasonably increasing the height of foundation can be used.

(3) The foundation soil subsidence rate does not meet the specified saline soil section, which can be treated by replacement, foundation replacement, dynamic compaction and soaking pre-dissolution, and the waterproof and drainage facilities of the tower foundation can be designed.

(4) For salinized soft foundation, treatment methods such as replacement, inorganic binder improvement and stability, dynamic compaction replacement, and vibro-replacement gravel pile can be adopted.

6 Conclusions

This paper conducts a study on the salt expansion characteristics of saline soil foundations of transmission lines through methods such as satellite remote sensing, field surveys, and indoor test, and introduces the grey relational analysis method to analyze the sensitivity of factors affecting salt expansion characteristics. The following conclusions are drawn:

(1) Through satellite remote sensing analysis and on-site investigations, it is found that the deformation and damage of transmission line towers in the research area mainly occur within the salt lake area, with the most obvious deformation and damage near the operating salt ponds.

(2) Through indoor salt expansion model test, it is found that: salt content is the fundamental cause of salt expansion; the higher the salt content in saline soil, the more sensitive its salt expansion deformation is to temperature; salt expansion deformation is the most obvious in saline soil at the optimum moisture content state.

(3) The grey relational analysis reveals that the factor that has the greatest impact on the salt expansion characteristics of saline soil is the salt content, followed by the moisture content, with temperature having a relatively small impact.

In all test conditions of salt expansion test in this paper, there is no water and salt supply before and after the test, and the water and salt content in the specimen remains unchanged. However, there is a phenomenon of salt loss with water in the actual environment. In the future, it is necessary to consider the salt expansion and mechanical properties of coarse-grained saline soil under the influence of water and salt migration. At the same time, the fluctuation of the factor value of the indoor test index is small. It is suggested that on the basis of the preliminary research results, it can be verified and corrected by on-site field monitoring.

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