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Research paper

Study on the dynamic development law of fissure in expansive soil under different soil thickness

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Abstract: Fissures are an important factor to induce slope instability of expansive soil channel, which destroys the integrity of soil mass and deteriorates soil mass. Currently, the research is limited to the fissures in the plane direction, and it is very important to reveal the development mechanism of fissures in expansive soils along the depth direction by studying the development law of fissures in expansive soils with different thicknesses. In this study, taking expansive soil on channel slope of the Middle Route Project of South-to-North Water Transfer as an example, crack expansion tests with thickness of 10 mm, 20 mm, 30 mm and 40 mm are carried out based on self-designed crack expansion test device. An innovative test method for volumetric fracturing rate is proposed and the following conclusions are drawn: (1) the later the cracking time of soil body is, the lower the water content of cracking and the higher the water content after stabilization when the soil body is thicker; (2) When the fissures develop in soils of different thicknesses, their plane fissure rate changes with time in accordance with the logistic law; (3) Volumetric fracturing increases significantly with thickness; (4) The development of fissures is the form of stress release of soil mass, and the release along depth direction is the main form for soil mass with large thickness. (5) It is of great significance to study the law of fracture development in depth direction for further exploring the mechanism of fracture propagation.

Keywords: crack development, dynamic law, expansive soil, soil thickness, volume crack rate

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1. Introduction

The total trunk channel of the Middle Route Project of South-to-North Water Transfer in China is 1432 km [1]. It is dedicated to providing water for production, living and industrial and agricultural use in more than ten large and medium-sized cities along the route. The geological conditions along the channel are complicated, and the total length of the channel crossing the expansive soil is 340 km. Due to the special engineering characteristics of expansion soil such as wet expansion, dry shrinkage and crack development [2, 3], it is easy to cause channel slope instability, concrete lining uplift and crack, which has a negative impact on the safe operation of the project. Cracks are important factors to induce destabilization damage of expansive soil channel slope [4, 5]. There are a lot of cracks of different sizes in expansive soil channel slope [6–8]. These cracks divide the soil mass, destroy the integrity of the soil mass and deteriorate the soil quality, which often leads to destabilization and deformation damage of expansive soil channel slope. Therefore, it is very important to study the law of crack development of expansive soil and to reveal the destabilization mechanism of expansive soil channel slope [9, 10].

Scholars have achieved important results in the development of plane cracks in expansive soil under different thicknesses and conditions.

For different thicknesses, Tang et al. [11, 12] carried out 5 mm thick clayey soil crack development tests under different climatic conditions. The test results showed that the crack morphology is single and wide at higher ambient temperature, while the crack development is complex and slender at lower temperature. At the same time, the more dry-wet cycles occur, the more obvious the crack development is and the more secondary cracks expand. The conclusion that climatic environmental changes have an important influence on soil cracking is drawn. Zhang et al. [13] carried out experimental research on evolution law of cracks in Nanyang expansive soil of thick 20 mm under repeated dry-wet cycles. Tollernaar et al. [14] systematically compared the effects of different initial water content and different boundary materials on the development of thin soil fissures. The research shows that different initial parameters of soil result in different fissure indexes. At the same time, it is concluded that boundary materials are important factors in the fissure expansion test. Nahlawi et al. [15] carried out shrinkage cracking tests of same thickness under natural conditions with mud samples and precompression clay as research materials. During the tests, indexes such as shrinkage correlation coefficient, crack water content, total area of cracks and depth of crack propagation were systematically extracted. The results indicated that the crack development of mud samples was obvious.

For different test conditions, Velde et al. [16] observed the surface crack characteristics of different mud samples and found that the laws of crack development differed significantly with water content. Yesiller et al. [17] studied the influence of different fine-grained content on surface fissure rate. Three groups of clay drying tests with different fine-grained content concluded that the surface fissure rate was higher when the fine-grained content was high, while it was smaller when the fine-grained content was low. Lakshmikantham et al. [18] carried out fissure development tests on soil samples of different sizes, focusing on the degree of influence on the fissure morphology. Through analysis, it was found that when the size of soil samples is large, the soil is not easy to crack, because it needs more stress, while when the size of soil samples is small, the fissures develop more abundantly. Susanga et al. [19] test shows that when there are obvious defects and pores in the soil, the probability of crack expansion is higher. When the soil is more uniform, the shrinkage will be the main factor.

It can be seen that current scholars mainly focus on the influence of plane size, climatic conditions, mineral composition on the development of fissures, while ignoring the key factor of soil thickness. Expansive soil fissures develop not only in plane, but also downward along depth [20, 21]. At present, the thickness factor is seldom considered in the research, and the volume fracturing rate is seldom studied. The research on the law of fracture development under different thickness is very important to reveal the mechanism of fracture development.

In view of the problems existing in the current law of crack development, a test device for crack expansion of expansive soil which can control ambient temperature and humidity is designed in this paper, and a new method for measuring crack volume of expansive soil by grouting method and drainage method is proposed. Fracture expansion tests of expansive soils under evaporation of water under different soil sample thicknesses were carried out with this test device. The evaporation process of water and the dynamic development process of apparent fissures with time are measured systematically. After evaporation is stable, the key indexes such as total length of fissures, average width of fissures, area fissures and volume fissures in each group are counted. The law of expansion of fissures in expansive soil under different soil sample thicknesses is obtained, and the dynamic development mechanism of fissures in expansive soil under thickness factor is obtained.

2. Crack propagation test method

2.1. Test materials

Expansive soil test samples are taken from the channel slope of Nanyang section of the Middle Route Project of South-to-North Water Transfer with a depth of 5 m. The schematic diagram of the Middle Route Project of the South-to-North Water Transfer Project is shown in Figure 1. The field photograph of the excavation and particle size distribution of expansive soil is shown in Figure 2.

The basic physical index of expansive soil is shown in Table 1.

Table 1. Expansive soil foundation index

Natural moisture content (%)	Natural density (g/cm^3)	Free expansion rate (%)	Liquid limit (%)	Plastic limit (%)	Shrinkage limit (%)
19.65	1.94	58	47.6	17.9	8.4

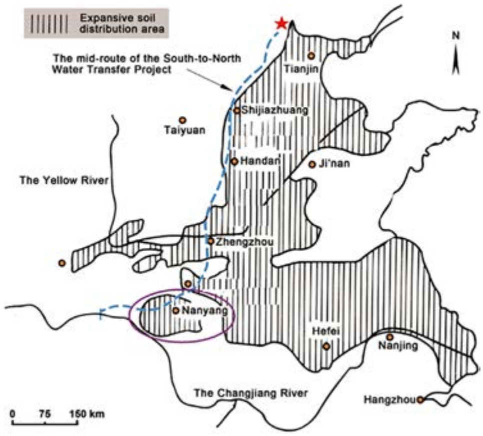

Fig. 1. The Middle Route Project of China's South to North Water Diversion Project

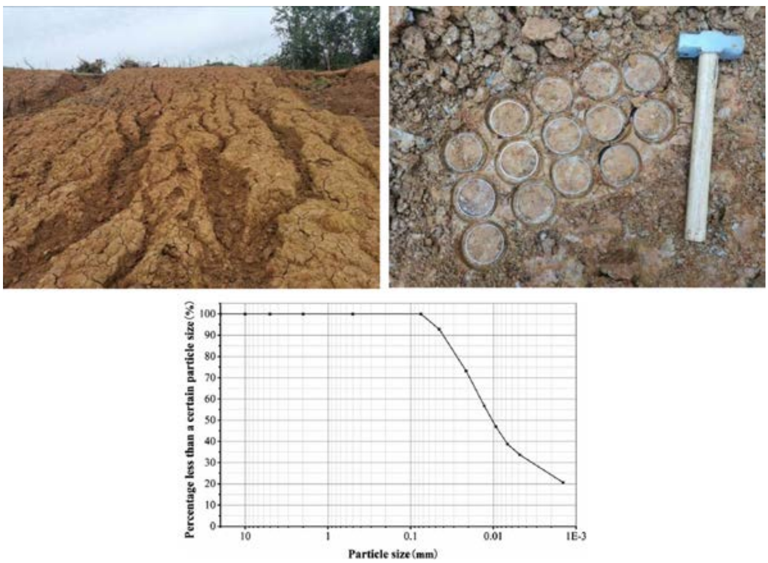

Fig. 2. Site sampling photos of channel slopes in the middle route of the South to North Water Diversion Project

2.2. Fracture expansion test method

As shown in Figure 3, the test device controls the ambient temperature through the air-conditioning system in a closed room and the ambient humidity by various kinds of saturated salt solutions placed in a closed test box. Electronic weighing is used to test the change in the overall mass of the sample and to obtain the change in the overall water content of the sample. Calipers around the sample are used to observe changes in the height direction of the sample during the test. The light source uses a fixed lighting system. A high-precision area array camera is used to test the variation of apparent cracks during tests.

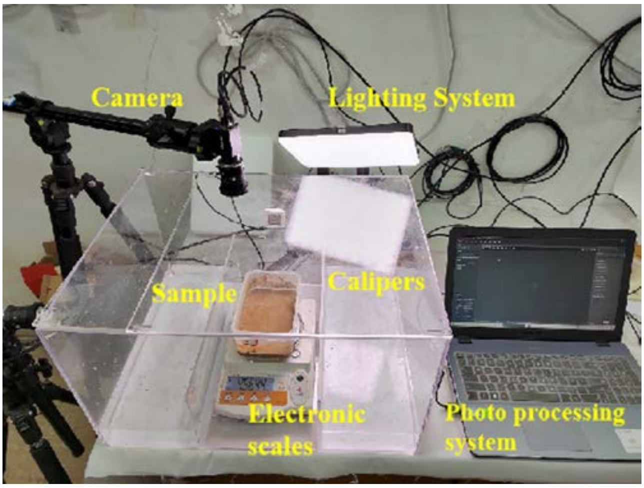

Fig. 3. Observation device for expansive soil fissures

The recovered expansive soil samples are crushed and air-dried, screened by 2 mm, and fully stirred to form mud samples. The air bubbles in the mud are expelled by means of a vibration device and the initial water content of the mud sample is 55%. Figure 4 shows sample preparation and saturation methods for fissure expansion tests on expansive soils.

Fig. 4. Sample preparation method and saturation method for expansive soil fissure growth test

In order to study the crack propagation law of expansive soil with different thicknesses under natural conditions, put the mud sample into the test box, which is 10 cm long and 15 cm wide. Expansive soil fissure expansion tests with 10 mm, 20 mm, 30 mm and 40 mm thickness were carried out under the ambient temperature of 25°C and relative humidity of 31%.

2.3. Crack indicators

The main fracture parameters studied in this paper include total length, area fissure rate, average width and volume fissure rate. The total length of the fissure is the result of the superposition of the length of the fissure framework at different locations on the surface of the soil sample. Area fissure rate is used to characterize the degree of surface fissure development of soil samples. It refers to the percentage of the area of fissure expansion on the surface of soil samples to the initial total area, in which the area of fissure expansion does not include the area of shrinkage of soil samples. Volumetric fissure rate is the percentage of the calculated fissure volume to the initial volume in the soil, where the fissure volume does not include the shrinkage volume of the soil sample.

2.4. Volumetric fracture rate test method

During evaporation, cracks in expansive soil extend along the horizontal and depth directions of soil samples respectively. Volumetric fissure rate is the proportion of fissure volume to the total volume of soil samples. It shows the distribution of fissures in space more comprehensively and is a key index in fissure parameters.

The volume fracturing rate test method proposed in this paper is realized by grouting method and drainage method. Mix the epoxy resin A adhesive with the epoxy resin B adhesive at 1:1 and mix well. After the crack reaches a stable state, the epoxy resin AB adhesive is injected into the expanded stable crack. After the colloid solidifies, the colloidal part of the filled epoxy resin is separated from the soil sample. The colloidal volume is calculated by drainage method and the colloidal volume is the total volume of cracks. The volume fissure rate of the soil can be obtained by the ratio of the fissure volume to the original volume of the soil sample. Figure 5 shows the gelling test process.

Fig. 5. Test method for volume fissure ratio of expansive soil

3. Fracture growth law under different thickness

At present, there is little research on the law of crack propagation under different soil sample thicknesses. In this section, based on the basic test conditions of 25°C ambient temperature and 31% ambient relative humidity, the crack expansion tests of expansive soils with 10 mm, 20 mm, 30 mm and 40 mm soil sample thickness were carried out respectively.

The fissure laws corresponding to different soil sample thicknesses are different, mainly reflected in the process of water content change and fissure expansion. Starting from the process of water content change and crack propagation, this section focuses on the crack law after expansion and stabilization, trying to analyze the influence of thickness factor on the crack propagation law.

3.1. Change process of water content

Figure 6a shows a time-dependent curve of water content in soil samples with different thicknesses. According to the illustration, at the beginning of evaporation, the water content decreases continuously, and the water loss of soil samples with larger thickness is slower during the same period. The reason is that when the soil sample is thicker, the greater its mass, the more water will need to evaporate when the water content drops to the same gradient. When evaporated to a certain extent, the water content in soil samples is stable. With the increase of soil sample thickness, the stable water content gradually increases, the stable water content is 8.1% at 10 mm of soil sample thickness and 11.5% at 40 mm of soil sample thickness. Smaller soil samples have a more stable water content close to the shrinkage limit of the soil.

Figure 6b shows the variation of evaporation rate with time under different soil sample thicknesses. The evaporation rate of soil samples with different thicknesses fluctuates slightly at the initial stage and all of them are in the stable evaporation stage. The soil samples with larger thicknesses go through this stage for a longer time. As water continues to evaporate, evaporation rate gradually decreases and is in the deceleration stage. When water content changes slowly, soil samples gradually enter the difficult evaporation stage. With the increase of soil sample thickness, the higher the water content entering the difficult evaporation stage, and the longer it takes to enter this stage. For soil samples with different thicknesses, the change process of water evaporation rate can still be divided into stable stage, deceleration stage and residual stage.

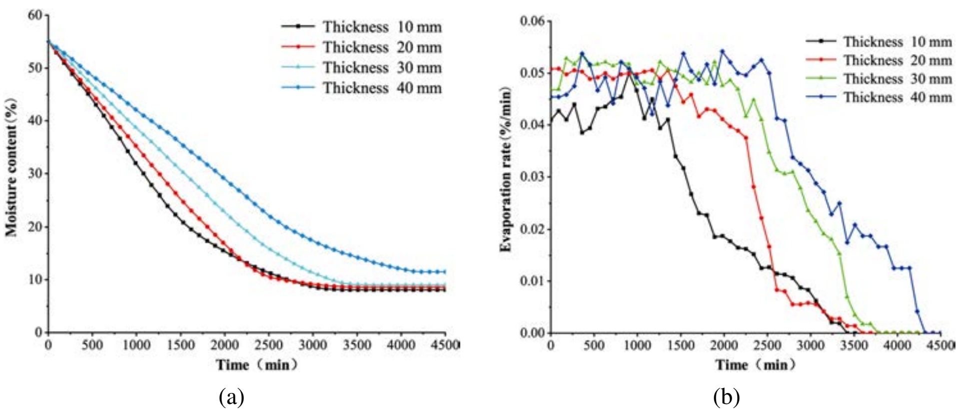

Fig. 6. Curves of soil moisture content with time under different thicknesses: a) moisture content change process, b) evaporation rate change process

Water evaporation starts from the surface of soil sample. When free water evaporates in the surface layer, the evaporation rate of soil sample remains constant and is in the stable stage of evaporation. However, the stabilization stage of soil samples with larger thickness lasts longer because deep water of soil samples supplements free water evaporated from surface layer during evaporation.

As the water evaporates, the soil sample will continue to shrink and the soil particles will be arranged closely after the shrinkage. However, the surface of soil sample lost more water and contracted more, and the narrowing of particle spacing hindered the passage for further upward evaporation of deep water. Therefore, for soil samples with large thickness, when the surface water evaporates completely, the moisture content in the deep layer is still high, then the stable water content will be higher than that of soil samples with small thickness. For soil samples with large thickness, the evaporation degree of water is different at different depths. The evaporation rate of water in surface layer of soil sample is fast and that of water in deep layer of soil sample is slow. Different water loss rates at different depths result in different shrinkage. The greater the thickness of the soil sample, the more obvious the difference in shrinkage is and the more likely it is to cause cracking of the soil sample. Table 2 shows the distribution of cracked water content and stable water content in soils with different sample thicknesses.

Table 2. Typical water content distribution of expansive soil under different soil thicknesses

Soil sample thickness (mm)	Cracking moisture content (%)	Stable moisture content (%)
10	39.99	8.1
20	38.78	8.6
30	38.87	9.0
40	40.97	11.5

3.2. Fracture dynamic development process

Figure 7 shows a typical diagram of the development process of fissure morphology in expansive soils with different soil sample thicknesses. For soil samples of different thicknesses, the development process has undergone the stages of fissure initiation-fissure development-fissure stability, which is similar to the previous study. Fractures begin to develop at weak points along the boundary of the soil. As the length of micro-fractures increases, secondary fractures begin to develop perpendicular to the initial ones. Different initial and secondary fissures jointly form a soil sample fissure network.

When water evaporates to a certain extent, the crack length does not increase any more, and the crack width expands continuously until it is stable. Frame cracks vary due to thickness effects. The thicker the soil sample is, the fewer the frame fissures and the fewer the fragmented areas formed by the fissure partition, the larger the fragmented areas are. The smaller the thickness of soil sample, the more frame cracks, the more fragmented areas formed by fracturing, and the smaller the fragmented area.

(a)

(b)

(c)

(d)

Fig. 7. Dynamic development process of fissures with different thicknesses. Crack development process at a thickness of: a) 10 mm, b) 20 mm, c) 30 mm, d) 40 mm

In the final form of fissures of soil samples with different thicknesses, the thicker the soil samples, the more single and few fissures are developed, while the smaller the thickness, the more and more complex the fissures are developed.

Figure 8 shows a time-dependent curve of the total length of the fissure under different soil sample thicknesses. Over time, the total length of the fissures shows a trend of beginning growth – rapid growth – gradually stable. Soil samples with a thickness of 10 mm cracked first, and the fissures developed the longest, and the total length of the fissures was the longest when they reached steady state. The cracking time of soil samples with 40 mm thickness is the latest, and the total length of cracks is stable in a short time, while the total length of cracks after stabilization is the smallest.

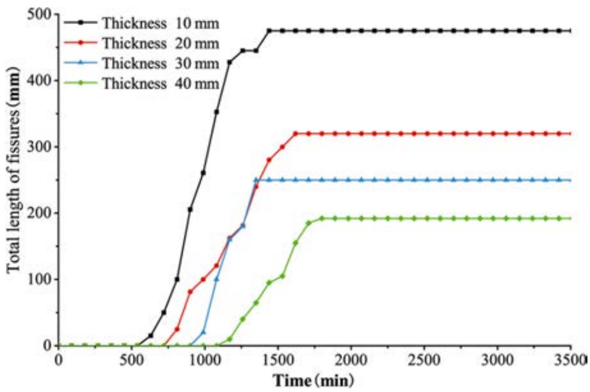

Fig. 8. Variation curve of total length of fissures with time under different thickness

Figure 9 shows the curve of the average crack width over time with different thickness. With the passage of time, the change of average crack width also shows a trend of slow increase-fast increase-gradually stable. When 10 mm thick soil samples reach steady state, the average width of cracks is the smallest. The 40 mm thick soil sample has the largest average crack width after stabilization.

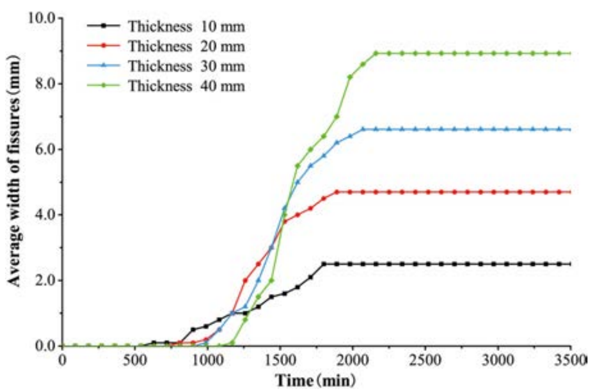

Fig. 9. Curve of average fissure width with time under different thicknesses

Figure 10 shows the time-dependent curves of plane fracturing rates with different thicknesses. Fit the plane fracturing rate with time under different thickness conditions, in which the expression of the relationship between plane fracturing rate and time under different thickness can be expressed by formula (3.1).

$$\xi_H = \gamma_1 + \frac{\gamma_2}{1 + (t/\gamma_3)^{\gamma_4}} \tag{3.1}$$

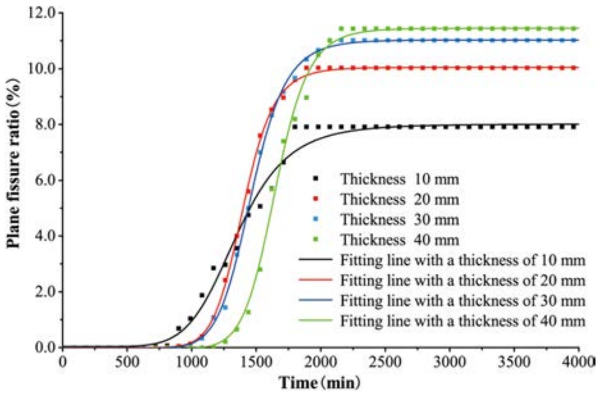

Fig. 10. Variation curve of plane fissure ratio with time under different thickness

In the formula, ξ_H is plane fissure rate of soil samples with different thickness and t is fissure propagation time. γ_1, γ_2, γ_3, γ_4 is the thickness-dependent coefficient. Relevant parameters for different thicknesses shown in Table 3.

Table 3. Distribution of relevant parameters under different soil thicknesses

Soil sample thickness (mm)	γ_1	γ_2	γ_3	γ_4
10	8.01	–7.98	1348.8	6.8
20	10.05	–10.08	1399.7	11.7
30	11.03	–11.05	1463.8	10.9
40	11.45	–11.49	1650.9	12.9

The curves between water content and plane fissure rate under different thicknesses are shown in Figure 11. At the beginning, the plane fracturing rate increases slowly with the decrease of water content and gradually enters the rapid growth stage, then enters the stable state. The smaller the thickness, the higher the water content of the soil entering the rapid growth phase of the fissure, the longer the duration of the rapid growth phase, and the lower the water content corresponding to the stable state of the fissure; The higher the thickness, the lower the water content of soil entering the rapid growth stage of cracks, the shorter the duration of the rapid growth stage, and the higher the water content corresponding to the stable state of cracks.

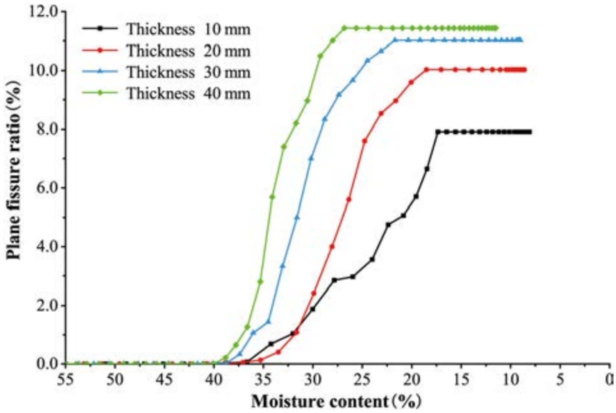

Fig. 11. Variation curves of plane fissure ratio and water content under different thicknesses

3.3. Fracture regularity under different soil sample thicknesses

For soil fissures with different thicknesses, the variation laws of total length, average width, area fissure rate and volume fissure rate after evaporation stabilization are mainly studied.

The plane fissure rate and average width of expanded and stabilized soil samples with different thicknesses are shown in Figure 12. The average width of cracks increases with increasing thickness. The average width of cracks is 2.5 mm when the thickness is 10 mm and 8.9 mm when the thickness is 40 mm. The plane fracturing rate increases with increasing thickness. As the thickness increases, the total length decreases when the crack expands and stabilizes. Figure 13 shows the variation rule of volumetric fissure rate after stabilization of soil samples with different thicknesses, which increases with the increase of soil sample thickness.

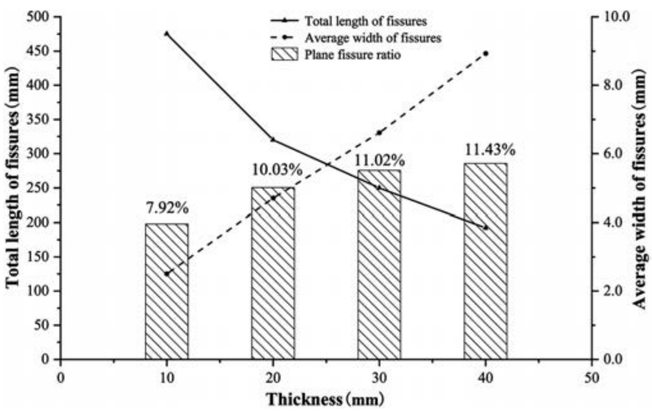

Fig. 12. Variation of parameters of soil plane fissures under different thicknesses

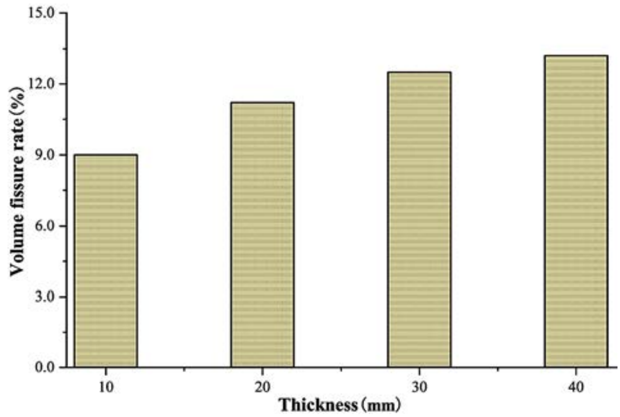

Fig. 13. Distribution of volumetric fissures after stabilization of soils with different thicknesses

4. Discussion on influence of thickness factor on cracking of soil

Thickness effect is an indispensable factor in the process of crack development, and different soil samples with different thicknesses have different crack development patterns and laws. When the soil sample is thicker, its area and volume fissures are larger, and the average width of the fissures is larger but the development is relatively single. When the thickness of soil sample is small, its area and volume fissures are small, the average width of fissures is small and the development is very complex. The crack propagation mechanism of soil samples with different thicknesses is shown in Figure 14.

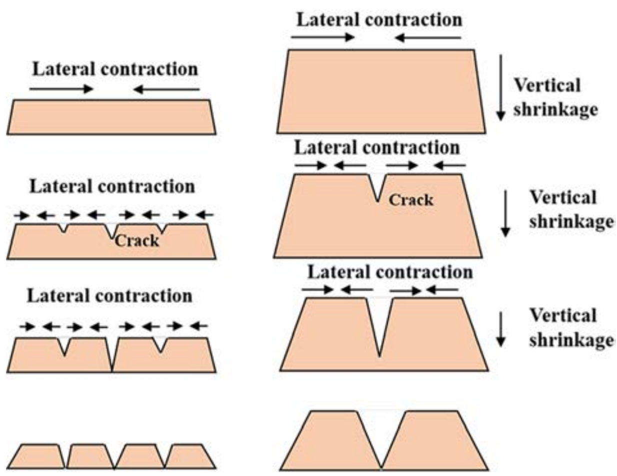

Fig. 14. Diagram of fissure propagation mechanism of soil with different thicknesses

Soil sample evaporates free water on its surface first under saturated state. During evaporation, particles in soil sample shrink continuously and stress is balanced due to the influence of wet expansion and drying shrinkage of expansive soil. For soil samples with large thickness, in addition to contraction in the plane, it will also contraction in the vertical direction. The evaporation surface of soil sample is large and the water loss rate is fast. Deep water evaporation of soil sample needs to pass through the upper soil body, and the evaporation rate is slow. Different evaporation rates of water cause uneven distribution of water in soil samples and different shrinkage amplitudes of soil at different depths. The greater the thickness, the more pronounced the difference and therefore the earlier the fractures occur. The formation of cracks is the result of stress balance and energy release in soil samples. In thicker soil samples, the development of the initial fissures will continue not only in the plane but also in the depth direction. The development of cracks along the depth direction releases large amounts of energy and is the optimum path. According to the minimum energy principle, there will be fewer cracks in the plane, so the cracks in soil samples with larger thickness will expand and deepen along a single crack. For soil samples with small thickness, cracks, as the form of energy release in soil samples, mostly concentrate on the surface, so the surface cracks are rich.

It is found that the volume change rates of soil samples with different thicknesses differ slightly. The volume change rate consists of volume shrinkage rate and volume fracturing rate. The thicker the soil, the smaller the volume shrinkage is due to the different gradients of water content. Volumetric fracturing increases with thickness. Under the same environment, when the soil sample changes from saturated state to solid state, its water content changes from liquid limit to contraction limit, and the water content decreases uniformly, so the volume change rate is not significantly different.

5. Conclusions

In this paper, a test device for crack expansion of expansive soil which can control ambient temperature and humidity is designed independently, and a new method for measuring crack volume of expansive soil by grouting method and drainage method is proposed. Taking expansive soil on channel side slope of the Middle Route of South-to-North Water Transfer Project in China as an example, the crack expansion tests of expansive soil under water evaporation under different soil sample thicknesses were carried out with test equipment, and the law of crack expansion of expansive soil under different soil sample thicknesses was obtained.

1. The evaporation rate in the stable stage gradually increases with the increase of soil sample thickness. The later the cracking time is, the lower the cracking water content and the higher the stable water content are when the soil sample is thicker.
2. The process of plane fissure rate changing with time conforms to logistic law.
3. Expansive soil crack growth test under different soil sample thicknesses shows that when the soil sample thickness is large, the total length of the crack is small, the average width of the crack is large, but the development of the crack is relatively

single. When the soil sample thickness is small, the larger the total length of the fissure, the smaller the average width of the fissure, but the more complex the fissure development is. The plane fissure rate of soil samples increases with thickness, while the volume fissure rate increases significantly with thickness.

4. The reason for this phenomenon is that the development of fissures is the form of stress release of soil mass. Based on the principle of minimum energy, the stress release of soil samples with small thickness is better than that of fissures along the plane direction. For soil samples with large thickness, the optimum path for stress relief is that cracks develop along the depth direction.
5. As a key influence index, soil sample thickness needs further analysis and study. It is of great significance to further explore the mechanism of crack propagation to study the law of crack development in depth direction and the process of local water content change.

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