Law of Water Content Change in Subgrade Soil Under Action of Dry-Wet Cycle

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(Received 14 May 2021; revised 28 June 2021; accepted 10 July 2021)

Abstract: Due to the influence of the groundwater level, the internal humidity of the subgrade changes and the stability of the subgrade is affected. The main purpose of this paper is to obtain a reliable model of subgrade soil water content variation under the action of dry-wet cycle through sensor readings. Thus, an indoor soil column model test system is designed, and the readings of the sensors are used to determine the changing law of moisture field in the subgrade soil. The sensor readings indicate that the water content gradually decreases along the height of the soil column, and the water in the upper part of the soil column continuously loses, while the water in the lower part migrates upward to supplement. With the increase of dry-wet cycle index, the water holding capacity of soil decreases, and the soil surface gradually cracks and tends to rupture.

Key words: subgrade soil; dry-wet cycle; water content change; soil column; indoor test

CLC number: U416.1 **Document code:** A **Article ID:** 1005-1120(2021)S-0069-07

0 Introduction

According to the field core drilling sampling results of some expressway subgrades and the monitoring data of the humidity sensor embedded in the subgrades, the changes of the groundwater level obviously have an impact on the dry and wet conditions of the subgrades, and the internal moisture content of the subgrade changes and generally increases by about 5% from the optimum moisture content[1]. From the existing research results in soil science, the maximum influence ranges of groundwater level on clay, sandy clay and sandy soil are different and the water content rises fastest in the initial stage of water supply, and then the rising speed declines with time[2]. In some areas, the groundwater level is relatively high. In order to avoid the greater impact of the groundwater level on the subgrade, designers often set a certain thickness of water barrier at the bottom of the subgrade[3], but after excavating the subgrade for several years of service, it is found that the water-proof layer has been completely submerged in water, the function of water-proof has been lost, and it has provided sufficient water source for the increase of humidity in the roadbed[4].

At present, a lot of research progress has been made in the field of water migration. Many scholars mainly use experimental monitoring and numerical simulation to study the water migration in subgrade soil. Hall et al.[5] suggested that the basic properties of soil (liquid-plastic limit, permeability coefficient, and gradation of soil) determined the stable water content of subgrade, and the main sources of subgrade water variation were rainfall and groundwater. Yamabe et al.[6] conducted a water replenishment test at the bottom of a small indoor sample to simulate the rising process of groundwater in the roadbed and established a one-dimensional numerical equation for unsaturated soil water migration to simulate the change of soil moisture content in the test. Johannes et al.[7] used automatic control theory and sensor technology to design a set of water movement test system in road structure to realize artificial

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How to cite this article: ZHANG Qingsong, JI Tianjian, XIAO Lei. Law of water content change in subgrade soil under action of dry-wet cycle[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2021, 38(S): 69-75.

http://dx.doi.org/10.16356/j.1005-1120.2021.S.009

simulation of rainfall, road groundwater control and collection, roadbed soil moisture collection, blind ditch flow collection and other functions. Chen et al. [8] used a method combining discrete element method (DEM) with smooth particle hydrodynamics (SPH) to study the water transfer of unsaturated granular materials under the action of oscillation. Wen et al. [9] conducted a water migration test on loess with different initial dry density and water content in a dry and wet environment, and found that the number of dry and wet times increased and the soil water holding capacity reduced significantly. Morgenstern et al. [10-11] studied water migration in glacial frozen soil and found that the amount of water migration is related to the temperature gradient, and there is a positive correlation between them. Overduin et al. [12] found that water migrated from the high temperature side to the low temperature side in the sealed soil column. Through further research on the water migration and dry-wet cycle effects of subgrade soil, people had realized that water migration caused changes in subgrade soil moisture content and induced uneven settlement, wave deformation and cracks and other diseases[13]. Repeated dry and wet cycles led to the development of internal cracks in the soil and the attenuation of strength to varying degrees[14-15]. Therefore, water migration and dry-wet cycle effects are important factors that affect the stability of the roadbed.

1 Test System and Experimental Steps

1.1 Test system

Indoor model test is an effective method to study the law of soil water migration under the action of dry-wet cycle. Based on the previous research on the test system and the existing test equipment around it, this paper improves the test system to meet the dry and wet cycle conditions, ensuring that the system can have a superior performance. The entire test system consists of three subsystems, a test tube for storing soil samples, a dry and wet cycle simulation device, and a temperature and humidity reading device. The test tube is the core of the entire system. All the test processes are conducted in the tube, and the test conditions simulating natural conditions are obtained through the dry and wet environment simulation device, including the heating & drying system and the water supplement & humidification system. The temperature and humidity reading device, including temperature sensors and capacitive soil humidity sensors, is mainly working for data recording, reading, and collection during the test.

The test system is shown in Fig.1. During the test, the soil sample is loaded into the test tube, and the bottom of the test tube is pre-paved with three layers of gauze to prevent the soil sample from directly contacting and clogging the replenishment hole. The upper part of the test tube is equipped with a heating lamp and a fan to simulate the temperature conditions of the subgrade.

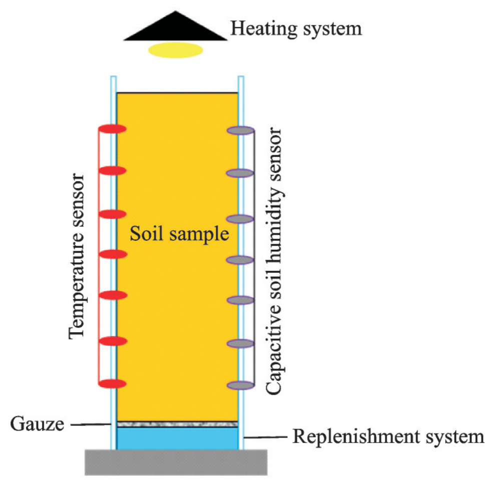


Fig.1 Design drawing of test system

1.2 Experimental scheme and steps

The experimental steps are as follows:

Step 1 According to the volume of the plexiglass test tube and the density of the wet soil, the mass of the required soil is calculated. The test soil sample is weighed according to 1.2 times the calculation result and passes through a 5 mm sieve to remove larger impurities. In order to ensure the isotropy of the soil sample as much as possible, the sieved soil sample is packed into a plastic box for 48 h. After completion, three soil samples are randomly prepared and the moisture content is measured by the drying method. The moisture content are all around 10%±1%.

Step 2 Fill the soil sample prepared in Step 1 into the plexiglass tube in 8 layers. Smoothing and compaction are carried out after each layer is filled completely. Scrape the surface of the soil sample in the plexiglass tube with a geotechnical knife and fill it with about 5 cm at a time until the filling height reaches 40 cm. Insert the temperature and humidity sensor into the corresponding side hole, connect it to the control panel through the signal line, and then complete the assembly of the main test system. The assembled test system is shown in Fig.2.

Fig.2 Test system completed by filling

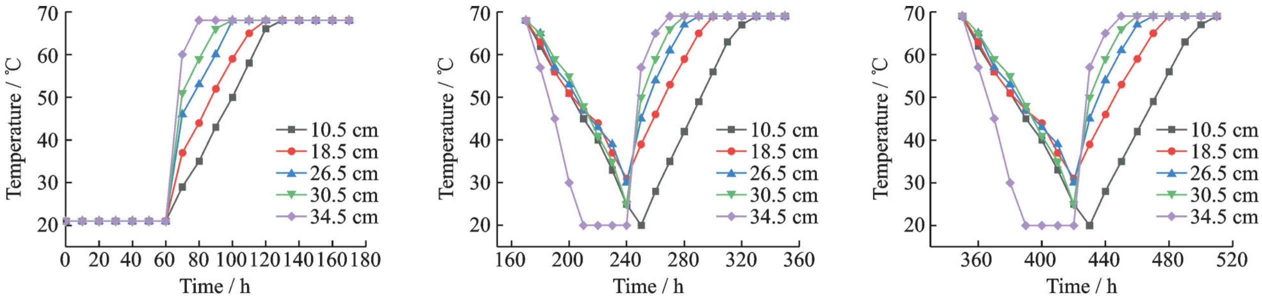
Step 3 In order to avoid the influence of room temperature on the test results, an air conditioner is used to control the room temperature at around 21 ℃. Connect the filled plexiglass tube to the water source, after checking whether all devices are correct. Turn on the power, and set to collect data every 10 min, confirming that all sensors have data returned, opening the lower water inlet valve, and starting the humidification process. Through the outer wall of the plexiglass, it can be clearly observed that the wet front gradually rises with time, and when it reaches the upper surface of the soil column, the valve is immediately closed to stop water supply. The next step is heating and drying. Install the heating lamp above the soil column as a heating device, and turn on the heating lamp until the measured moisture content reaches or approaches the initial moisture content of the soil column, which is regarded as the end of the drying process. A humidification and a drying process constitute a dry-wet cycle. In this paper, a total of three dry-wet cycles are performed.

2 Test Results and Analysis

Groundwater is one of the primary sources of moisture in subgrade soil. Due to temperature and capillary action during the dry-wet cycle, liquid water migrates from the bottom of the subgrade to the top of the subgrade. To study water migration law of subgrade soil under the condition of the dry-wet cycle is to analyze the variation law of moisture field and temperature field with time and space during the dry-wet cycle, and then analyze the development of soil fissure through multiple dry-wet cycles.

2.1 Effects of multiple dry-wet cycles on water migration

Fig.3 is the temperature changes of each measuring point at different heights (10.5, 18.5, 26.5, 30.5, and 34.5 cm) of the soil column in three dry-wet cycles with time. For the first wet-dry cycle, 0—60 h is the stage of humidification by water supply, without heating, and the temperature basically remains unchanged. When entering the heating-drying stage, the temperature of the upper measuring point rises rapidly, while that of the lower measuring point rises slowly. Finally, the temperature of each measuring point tends to be stable. During the second wet and dry cycle, the temperature of each measuring point begins to drop due to the loss of heat source for heating. The upper measuring point is close to the external environment, the temperature drops greatly and reaches room temperature very quickly. The middle measuring points cannot transmit heat quick enough, and the temperature drops slowly and starts to re-heat again at 420 h, but the bottom measuring point is not affected by re-heating at first because it is far away from the heat source. After re-heating, the temperature of each measuring point rises again and gradually stabilizes. In the third dry-wet cycle, the temperature change trend of the whole process is basically the same as that in the second cycle, which is shown as humidification and cooling, heating and temperature rising,



(a) The first dry-wet cycle (b) The second dry-wet cycle (c) The third dry-wet cycle

Fig.3 Temperature changes with time of three dry-wet cycles

and finally tends to be stable.

In general, the closer the soil is to the heat source, the faster the temperature rises. With the increase of the distance from the heat source, the rate of temperature slows down obviously and eventually remains within a certain range. The test results indicate that: ① The subgrade soil has the function of heat absorption and conduction, and the temperature rises fastest at the initial stage of high temperature field. ② The value of the final steady-state temperature at each height is inversely proportional to the distance from the heat source, that is, the farther the distance of the heat source, the smaller the final steady-state temperature, which is due to the loss of soil and the delay in performing heat radiation transfer.

Fig.4 shows the changes of water content of each measuring point at different heights (10.5, 18.5, 26.5, 30.5, and 34.5 cm) of the soil column in three dry-wet cycles with time. The moisture content curves of each measuring point after three cycles of drying and wetting have the same change

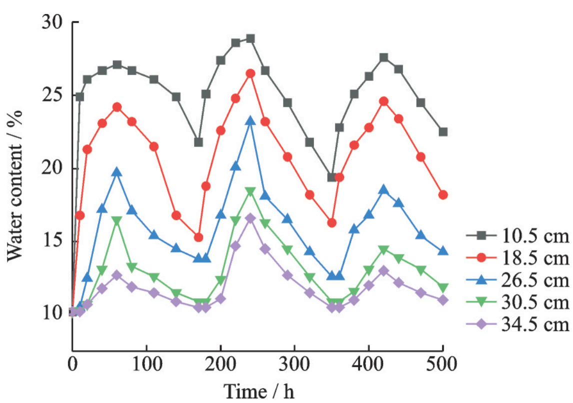


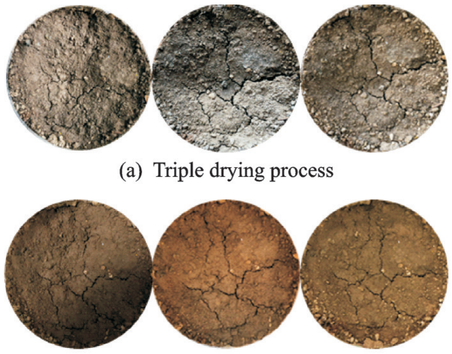
Fig.4 Water content changes with time of three dry-wet cycles

trend with time. The water supplement and humidification stage shows an upward trend and the heating and drying stage shows a downward trend. After entering the heating and drying stage, the rate of decreasing rate of water content increased with the increase of the number of dry-wet cycles, indicating that the water holding capacity of the soil gradually weakens with the increase of the number of dry-wet cycles.

2.2 Development characteristics of soil cracks under the action of multiple dry-wet cycles

There are a lot of clay minerals in clay soil. Clay minerals have strong hydrophilicity. Therefore, when clay soil encounters water, the volume of the soil will swell. Conversely, the volume shrinks when dehumidifying. When the shrinkage reaches a certain value, the cohesive force between the soil particles can no longer maintain the integrity of the soil surface, resulting in a gradual cracking of the soil surface and an increasing trend. The number of dry and wet cycles often determines the development of cracks on the soil surface to a large extent. The surface of the soil column model body is photographed under different dry-wet cycles to obtain the development of surface cracks, as shown in Fig.5.

It can be seen from Fig.5 that after the first dry-wet cycle, the soil column has several small strip-shaped cracks on its upper surface, and the measured maximum crack width is less than 1 mm. After the second dry-wet cycle is completed, the cracks on the surface of the soil sample become significantly larger. After measurement, the maximum crack width reaches 1 mm, and no new cracks have



(a) Triple drying process

(b) Triple humidification process

Fig.5 Development of cracks on the surface of the soil column at different dry-wet cycles

been found on the upper surface of the soil column. By the end of the third dry-wet cycle, not only the original widths of several cracks have been further expanded, with the largest reaching 1.5 mm, and the adjacent cracks have penetrated, but also many branches are observed at the ends of the original cracks. The surface soil is easily broken. Micro cracks are formed after the first dry-wet cycle, and the development position of the main crack is determined, but the future development trend of the crack is not clear. After experiencing a dry-wet cycle, the location of existing cracks no longer change. The location of the cracks generated in the first dry-wet cycle is random, and a weak structural surface is formed at the crack. At this time, the integrity of the soil structure has been destroyed. In each subsequent dry-wet cycle, in the humidification stage, the cracks are narrowed due to the expansion and closure of the soil. While the narrowed cracks will open again in the drying stage due to the loss of water in the soil. Ren et al.[16] obtained the microstructure of the soil under the dry-wet cycles through the scanning electron microscope. He pointed out that with the increase of dry-wet cycles, the soil particles "grid" repeatedly expanded and contracted, and gradually produced micro-cracks. The hole and the "grid" were damaged, and there was a stress concentration effect. The distance between the soil particles was significantly increased, and the particle arrangement was intricate.

In this paper, due to the limited test time, only three dry and wet cycles are carried out. Cai[17] conducted ten dry-wet cycles on the test soil column. According to his conclusion, when the number of cycles reached 10, the cracks on the surface of the soil column were shown in Fig.6. The width of the main crack and the width of other through cracks were further increased, and the maximum crack width was more than 2 mm. But the bifurcations that had occurred before is gone, that is, the phenomenon of "healing".

Fig.6 Cracks on the upper surface of the soil column after ten dry-wet cycles[17]

The cracks and "healing" phenomenon on the upper surface of the soil column under the action of the dry-wet cycle are mainly caused by the shrinkage and swelling of the soil. There are a lot of clay minerals in the soil, and this mineral shows extremely strong hydrophilicity. In the humidification stage, the water content in the soil column increases. The combined water film on the surface of the soil particles gradually thickens, the distance between the soil particles becomes longer, and the gravity becomes smaller. As a result, the volume of the soil expands, resulting in a narrowing of the width of the bifurcation, which is the phenomenon of "healing". When the soil column enters the heating and drying state, the water in the soil column is heated and evaporated, and gradually loses. The combined water film on the surface of the soil particles gradually becomes thinner, and the distance between the soil particles becomes closer. At the same time, the gravitational force becomes larger, causing the volume of the soil to shrink and the original crack width to become larger or new cracks to form.

In summary, the width and number of cracks on the upper surface of the soil column are related to the number of dry-wet cycles. In general, there is a positive correlation: the more the number of dry and wet cycles, the wider the cracks on the upper surface of the soil column and the more the number. As the number of wet-dry cycles increases and gradually narrows, "healing" occurrs.

In the future research, the research results can be further deepened in the following two aspects:

(1) In this study, indoor soil column test and later subgrade soil field test are to further study the hydrothermal transfer law of subgrade soil under actual working conditions.

(2) The distribution of the humidity sensors can only measure and monitor the one-dimensional water movement law in the vertical direction. In the later stage, new sensors and distribution methods can be developed to study the three-dimensional flow law of water in the soil column.

3 Conclusions

Based on the basic theory of water movement in unsaturated soil, this paper selects subgrade soil as the research object, and independently designs and manufactures an indoor dry-wet cycle test system of subgrade soil on the basis of previous studies. Combined with the actual situation of the road, the water migration test of the subgrade soil under the action of the dry-wet cycles is carried out, and the distribution changes of the temperature field and the moisture field during the dry-wet cycles are analyzed. The main conclusions are as follows:

(1) The entire dry-wet cycle indoor test system can simulate the actual natural environment of the roadbed as much as possible under controlled conditions to carry out the dry-wet cycle test, realizing real-time collection and recording of the two main parameters of temperature and humidity during the test.

(2) The law of temperature and water content changes under the action of multiple dry-wet cycles: The temperature change curves of multiple dry-wet cycles with time show a "concave" shape, with humidification and cooling, heating and temperature rising, and the temperature of each measuring point of the soil column finally tends to be stable.

(3) The development characteristics of the cracks on the surface of the soil under the action of multiple dry-wet cycles: The more dry-wet cycles are experienced, the wider and the more numerous the cracks appear on the surface of the soil column. It gets bigger and some small cracks "heal" with the increase of dry-wet cycles. Eventually, as the number of dry-wet cycles increases, the crack development on the upper surface of the soil column will gradually stop.

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Author contributions Mr. ZHANG **Qingsong** conducted the experiment and wrote the manuscript. Dr. **JI Tianjian** was responsible for project management and revision of manuscript. Mr. **XIAO Lei** was responsible for auxiliary testing and collecting sensor data. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: XU Chengting)

干湿循环作用下路基土水分迁移规律试验研究

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摘要：受地下水位影响，路基内部湿度变化，影响路基稳定性。为通过传感器读数获得干湿循环作用下路基土壤含水率变化的可靠模型，设计了室内土柱模型试验系统，利用传感器的读数可确定路基土中水分场的变化规律。试验结果表明，土壤含水率沿土柱高度逐渐降低，土柱上部的水分不断流失，下部的水分向上迁移补充。随着干湿循环次数的增加，土壤的持水能力下降，土壤表面逐渐开裂并趋于破裂。

关键词：路基土；干湿循环；含水率变化；土柱；室内试验