Experimental Study on the Swelling Behavior of Expansive Soil at Different Depths under Unidirectional Seepage

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Abstract: The swelling properties of expansive soil at different depths were investigated by the laboratory model test. It was experimentally found that the swelling deformation of different expansive soil layers was obviously different under unidirectional seepage. Pore solution collection boxes were designed to collect the pore solution of different soil layer interfaces during the saturation process. Cation concentration tests were then used to analyze the migration regulation of cations in these soil layers. Results showed that the divalent cations in the surface soil layer migrated downward along with water molecules and aggregated around clay particles to form the electrical environment in expansive soil. Additionally, swelling tests were performed to compare with their initial values to research the variation of swelling behavior of expansive soil at different depths after completion of the model test. It was observed that the swelling potential of the surface expansive soil layer at a depth of 0–30 mm was released while that of the middle and bottom ones at depths of 90–120 mm and 180–210 mm was inhibited. An analysis on the above results was used to clarify the mechanism controlling the swelling difference of different expansive soil layers. This swelling difference may be explained by the joint effect of two factors that can be treated as an electric charge effect, namely (i) the modification effect, (ii) the electrical environment.

Keywords: expansive soil; swelling behavior; soil depth; unidirectional seepage; electric charge effect

1. Introduction

Expansive soil is one typical special soil that is very sensitive to the change in moisture content, which is widely distributed around the world [1]. Such soil swells and shows the considerable volumetric deformation in response to changes in moisture content [2]. Consequently, expansive soil causes serious damage and distortion to structures, particularly for light buildings and pavements [3,4]. As a result, the swelling behavior of expansive soil is closely related to the safety and stability of engineering structures [5,6]. Free swelling ratio, swelling pressure, and swelling percent are usually identified as three important swelling characteristics which are required for the assessment of safe and economical designs of engineering structures resting on expansive soils. However, in the process of engineering design and construction, it is conventionally considered that expansive soil is a homogeneous material that the swelling behavior is the inherent property and consistent along the depth of the soil layer. In fact, the parameters such as moisture content, void ratio and swelling indexes of different soil layers in the active zone are not the same under actual field conditions. Hence, their swelling behavior is different even under saturated state. In this respect, the results of numerous
laboratory and field tests on black cotton soil from MRBC 76 reported by Katti and Katti [7] are noteworthy. It was found that the lower black cotton soil layer will not produce excessive swelling deformation though the swelling pressure (224 KPa) is far greater than the weight stress of the upper soil layer under saturated conditions. In particular, when the thickness of the upper black cotton soil layer reaches 1.2 m, the swelling of the lower black cotton soil can be completely inhibited, and its moisture content, void ratio, dry density and shear strength remain unchanged. This finding indicates that the black cotton soil at different depths has an obvious swelling difference during the saturated process [7,8].

Previous studies revealed that the types and concentrations of cations in soil solution have significant influence on the potential of soil surface and its electrochemical properties [9,10]. In the soil–water–electrolyte system, as a kind of particular clay soil that contains a certain amount of montmorillonite and carries negative charges, the surface of clay particles is absorbed by the cations, so that a very high ion concentration is induced surrounding it [11]. Consequently, it can be speculated that the swelling difference of expansive soil at different depths is closely related to its electrochemical properties and may depend largely on the type and concentration of electrolyte in pore solution. Several scholars have pointed out that different kinds and concentrations of electrolyte can cause the expansion of swelling clays to varying degrees [12–15]. It was demonstrated that different pore solutions have a significant effect on the swelling characteristics of bentonite [16–21]. Lee et al. [17] demonstrated that the swelling pressure of Ca-bentonite is distinct from that of Na-bentonite, and this difference depends on the concentration of electrolyte, which can be ascribed to changes to the thickness of diffuse double-layer (DDL) or cation exchange [22]. According to DDL theory, the DDL thickness decreases as the concentration of solutions increases, resulting in a decrease in the swelling pressure. Additionally, one cation with lower valence can be replaced by another with higher valence. So, when Na–bentonite is infiltrated with calcium solutions, sodium will be replaced by calcium [23,24], resulting in a reduction in the swelling potential. Therefore, when the cation concentration of bulk liquid in expansive soil changes, the electrochemical properties of expansive soil will also change, which finally affects its macroscopic swelling characteristics. Apparently, the difference of moisture content in the upper and lower soil layers will affect the magnitude of concentration of electrolyte in pore solution, resulting in the different swelling deformation.

Based on the above analyses, this paper studied the variation regularity of swelling behavior of expansive soil at different depths by laboratory model test under saturated condition of water (de-ionized water) injection from top to bottom. Given the variation of cation concentration in pore solution at different soil layer interfaces in the saturated process, before and after the model test, as well as the variation of swelling characteristics of expansive soil, it is expedient to clarify the mechanism of swelling difference of expansive soil at different depths.

2. Materials and Methods

2.1. Materials

The basic physical and chemical properties of expansive soil selected for this study are listed in Table 1.

An X-ray diffraction (XRD) test was conducted with D8 Advance X-ray diffractometer at the tube voltage of 40 KV and current of 40 mA, using a focused and monochromatized Cu Kα source. In the 20 °C and 60% relative humidity conditions, a homogeneous powder with a particle size of <20 µm was ground with an agate mortar.

According to the method in Test Methods of Soils for Highway Engineering (JTG E40-2007) [25], the soil samples were dried to a constant weight and then were ground until they all passed through a 1 mm standard sieve, the above cation concentration could be obtained by a HACH DR1900 portable spectrophotometer and a HACH HQD portable analyzer to measure the solution through
centrifugation from the soil samples added with de-ionized water. The measured method is based on the Water Analysis Handbook published by the Hach Company.

| Table 1. Basic physical and chemical parameters of materials used in experimental work. |
|----------------------------------------------|
| Property                                      | Expansive Soil |
| Grain size distribution                      |                |
| Sand (%)                                      | 3.90           |
| Silt (%)                                      | 31.70          |
| Clay (%)                                      | 64.40          |
| Specific gravity                              | 2.70           |
| Atterberg limits (%)                          |                |
| Liquid limit                                  | 63.00          |
| Plastic limit                                 | 24.94          |
| Unified soil classification                   | CH             |
| Compaction properties (standard Proctor)      |                |
| Optimum moisture content (%)                  | 16.20          |
| Maximum dry density (g/cm³)                   | 1.80           |
| Swell properties                              |                |
| Free swelling ratio (%)                       | 65.50          |
| Swelling pressure (KPa)                       | 182.72         |
| Swelling percent (%)                          | 19.00          |
| Main minerals                                 |                |
| Montmorillonite (%)                           | 23.17          |
| Kaolinite (%)                                 | 5.93           |
| Quartz (%)                                    | 59.65          |
| Calcite (%)                                   | 11.25          |
| Main cations of pore solution (mg/L)          |                |
| Na⁺                                          | 12.50          |
| K⁺                                           | 10.00          |
| Mg²⁺                                         | 35.00          |
| Ca²⁺                                         | 405.50         |

2.2. Test Apparatus

The experimental setup for the laboratory model test is shown in Figure 1. It is composed of three parts: pore solution collection box, polymethyl methacrylate (PMMA) strip, and PMMA box.

As cation concentration in soil bulk solution cannot be accurately and conveniently measured, but it can be reflected by the change of that in soil pore solution according to the Boltzmann distribution equation. Therefore, pore solution collection boxes were designed to collect the pore solution of different expansive soil layers in the saturation process for analyzing the migration regulation of cations. It contains a rectangle case, a water outlet pipe, and an intake pipe. These two pipes are respectively connected to both sides of the collection box, the former bottom being connected to the pump water device and the latter being used for air admission. The pump water device with the maximum negative pressure of 100 KPa can ensure that the pore solution in soil layer is extracted into separate container. The size of collection box is 5 cm × 5 cm × 2 cm, its upper cover has multiple holes of 1 mm diameter, and the whole box body is wrapped with a layer of geotextile.

The size of PMMA box is 30 cm × 30 cm × 30 cm, its outer wall is marked with a scale on four sides, and the minimum scale is 1 mm. Four PMMA strips with dimensions 10 cm × 2 cm × 0.5 cm are placed at the four sides of different soil layers every 30 mm. When expansive soil produces swelling deformation, the PMMA strip will move along with it. This value can be observed by the scale in outer wall of the PMMA box, which is the swelling deformation of expansive soil.
As shown in Figure 1, the depth of expansive soil is 210 mm, and the thickness of each soil layer is 30 mm. The surface expansive soil refers to the soil layer at a depth of 0–30 mm, the middle and bottom expansive soil are the soil layers at depths of 90–120 mm and 180–210 mm, respectively.

2.3. Test Procedures

2.3.1. Sample Preparation

In this study, a 210 mm thick expansive soil was used for the laboratory model test. According to the method of soil sample preparation in Test Methods of Soils for Highway Engineering (JTG E40-2007) [25], the naturally dried soil samples were ground to through a 2 mm standard sieve, and then be added to the appropriate amount of water and mixed thoroughly to prepare the soil samples with the optimal moisture content.

2.3.2. Model Elaboration

The layer-by-layer fill construction method was used to control the uniform density of the soil samples. The degree of compaction and initial moisture content of each soil layer was controlled at 90 % and optimal moisture content of 16.2 %, respectively. The initial stress ($\sigma_i$) of each soil layer is equivalent to the self-weight stress of the overlying soil layer, can be expressed as:

$$\sigma_i = 0.9\rho gh_i(1 + 0.01w)$$

(1)

where, $\rho$ is the maximum dry density, $g$ represents gravity acceleration, $h_i$ denotes the thickness of the overlying soil layer, and $w$ is the optimum moisture content.

Silicon grease was applied on the inner side of PMMA box to reduce the side friction. Moreover, three pore solution collection boxes were respectively buried in the surface, middle and bottom expansive soil layers to collect the pore solution in these three interfaces, while four PMMA strips were placed at the four sides of different soil layers every 30 mm to observe the swelling deformation of expansive soil. After the model was filled completely, a layer of geotextile was placed over the model surface to avoid the impact of water injection on the soil surface. In this study, all the tests were carried out indoors at a constant temperature of 20 °C, and the effect of temperature was not taken into account.
2.3.3. Cation Concentration Tests

The cation concentration was measured by HACH DR1900 portable spectrophotometer and HACH HQD portable analyzer. The initial cation concentration of pore solution in expansive soil is shown in Table 1. After completion of model test, the cation concentration of soil samples taken from the surface, middle and bottom expansive soil layers was obtained by the same method. On the second day after de-ionized water had been injected into the model, the pore solution accumulated by the collection boxes buried in soil layer was extracted to measure its ion concentration. The collection frequency was every 3–4 days until the model test was completed.

2.3.4. Swelling Tests

In compliance with Test Methods of Soils for Highway Engineering (JTG E40-2007) [25], the dried sample ground to through a 0.5 mm standard sieve was prepared for free swelling ratio test. Free swelling ratio is defined as the ratio of the difference in volumes of soil sample in water and air, to the volume of soil in air. Moreover, the cylindrical specimens with 61.8 mm diameter and 20 mm height were compacted at a target dry density of 1.62 g/cm$^3$ and an initial moisture content of 16.2%, then were inserted into a traditional oedometer along with the stainless steel ring for the swelling pressure, swelling percent and loaded expansion ratio tests. Swelling pressure is determined as the vertical pressure required to keep the original height upon the imbibition of water. The swelling percent and loaded expansion ratio are defined as the ratio of the increase in the height to the original thickness of the specimen. Specimens for swell percent test were allowed to swell freely, but those for loaded expansion ratio test were performed under a certain pressure until swelling was complete. Additionally, the initial values of above each test were obtained by the four parallel experiments. Then, these parameters of expansive soil were measured again by the same method after completion of model test.

3. Results and Discussions

3.1. Swelling Deformation of Expansive Soil Layer at Different Depths

In this study, the approach of unidirectional water injection from top to bottom was adopted to make the expansive soil saturated. The water height was controlled at 1 cm in the total testing process. When the swelling deformation was stable for 48 h, the model test was considered to be completed. After completion of model test, four cylindrical samples with 61.8 mm diameter and 20 mm height were respectively taken from the three soil layers at depths of 0–30 mm, 90–120 mm and 180–210 mm by stainless steel rings. Then, these soil samples were put into separate containers for moisture content determination by oven drying method. At the same time, the dry density could also be obtained. After that, the void ratio was determined according to the specific gravity of 2.7, then based on this to calculate the saturation. The test results obtained are presented in Figure 2.

The moisture content, dry density, void ratio and saturation are the average of the measured values of the four samples taken from each soil layer. As shown in Figure 2, the values of saturation of the soil samples show that all soil layers achieved a saturated state during the unidirectional seepage. Unfortunately, because there is no humidity sensor embedded in the soil, the moisture content of each soil layer in the saturated process is unknown and uncontrollable.

Additionally, it can be observed that the dry density of surface expansive soil layer is the minimal while the moisture content and void ratio are the maximal. As the depth of soil layer increases, the dry density increases while the moisture content and void ratio are dropping down. Furthermore, these three parameters of the lower soil layer change slightly, while those of the upper soil layer vary greatly. This phenomenon indicates that the swelling deformation of expansive soil is nonlinear with the depth of soil layer and has the apparent difference between the upper and lower soil layers.
It is further known from Figure 3 that the swelling deformation of expansive soil non-linearly increases with the depth of soil layer. The swelling deformation of upper soil layer is higher than that of lower soil layer, which is consistent with the conclusion of some previous studies. However, it can be observed that the measured swelling deformation of expansive soil is sharply reduced with the depth of soil layer. Furthermore, these three parameters of expansive soil layers are non-linear with the depth of soil layer and have the apparent difference between the upper and lower soil layers.

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Figure 2. The variation of saturation, moisture content, dry density, void ratio of expansive soil layer with depth.

During the saturated process of unidirectional water injection, the swelling deformation of each soil layer is the average value of the four-side expansion. The results obtained are depicted in Figure 3.

Figure 3. The swelling deformation of expansive soil with depth of soil layer.
of lower soil layer, which is consistent with the conclusion of Figure 2. It is illustrated that there is the inhibition effect on the swelling of lower soil layer under saturated process.

Figure 4 shows the relationship of the measured swelling deformation of different soil layers and those calculated via a loaded expansion ratio. In this section, the saturated density of each soil layer could be calculated by its average void ratio (Figure 2) and specific gravity (Table 1), so that its saturated self-weight was determined. The applied load of loaded expansion ratio is considered equivalent to the saturated self-weight of overlying soil layer. It is indicated that the loaded expansion ratio of different soil layers is different and controlled by the overburden load. Therefore, if the error of the estimation method is neglected, the calculated swelling deformation of expansive soil at different depths can be determined by the product of the corresponding loaded expansion ratio and the thickness of soil layer. Based on this, the inhibition effect of self-weight of overlying soil layer on expansive soil can also be evaluated.

Figure 4. The relationship of the measured and calculated swelling deformation of expansive soil at different depths.

According to the Figs. 2 and 3, there is the inhibition effect on the swelling of expansive soil due to the self-weight of overlying soil layer. However, from Figure 4, the calculated swelling deformation of expansive soil at different depths just decreases slowly with the self-weight of overlying soil layer. Even though the thickness of overlying soil layer reaches 180 mm, the swelling deformation is reduced only 0.62 mm. This means that the self-weight of overlying soil layer only has a weak effect on the swelling of expansive soil. However, it can be observed that the measured swelling deformation of expansive soil is sharply reduced with the increase of soil depth. The swelling deformation of the surface expansive soil layer is 7 mm, and that of the bottom one is only 2 mm. This difference illustrates that these alterations are brought about not only by the self-weight but are mainly attributed to other factors. Previous attempts indicated that this effect is most likely to be the electrical charge effect which caused by the aggregated cations under the saturation process [7,8].

3.2. Cation Concentration of Pore Solution

In the soil–water–electrolyze system, it is difficult to accurately measure the cation concentration of soil bulk solution. According to the Boltzmann distribution equation, the cation concentration of soil pore solution can reflect the change of that in soil bulk solution. Therefore, in this section, the cation concentration of pore solution in expansive soil at different depths was measured to analyze the migration regulation of cations.
3.2.1. In the Saturated Process

To research whether the overlying soil layer can induce the cations to migrate downward and aggregate, and then form the electrical environment, on the second day after injecting de-ionized water into the model, the pore solution was extracted to measure its ion concentration.

In so far as cations in expansive soils in China are mainly Ca$^{2+}$, Mg$^{2+}$ and Na$^+$, while K$^+$ accounts for only about 2–3% of the total cations [26]. Moreover, the expansive soil selected in this study mostly contained Ca$^{2+}$ and Mg$^{2+}$ (Table 1). Therefore, only Ca$^{2+}$ and Mg$^{2+}$ concentrations were analyzed and the results are presented in Figure 5.

![Figure 5](https://via.placeholder.com/150)

**Figure 5.** The cation concentration of pore solution at three soil layer interfaces under the saturation process: (a) Mg$^{2+}$; (b) Ca$^{2+}$.

It is seen in Figure 5 that the cation concentration of pore solution in the surface expansive soil layer is the minimal while that of middle and bottom ones is the maximal. Moreover, the concentration in the surface expansive soil layer decreases whereas those of middle and bottom ones increase when the soil gradually reaches the saturated state, which indicates the Ca$^{2+}$ and Mg$^{2+}$ will migrate downward along with water molecules and aggregate around clay particles to form the electrical environment.

3.2.2. After Completion of Model Test

The next goal of this study was to verify whether the divalent cations of surface expansive soil layer migrate downward and aggregate around the clay particles. Therefore, after completion of model test, the soil samples taken from the surface, middle and bottom expansive soil layers (soil layers at depths of 0–30 mm, 90–120 mm and 180–210 mm, respectively) were dried to a constant weight and then were ground through a 1 mm standard sieve. Then, the cation concentration in pore solution of the above soil samples was measured. The results obtained are plotted in Figure 6.

As seen in Figure 6, the concentration of Ca$^{2+}$, Mg$^{2+}$ of pore solution, in contrast to the initial values (Table 1), drops down in the surface expansive soil layer while increases in the middle and bottom ones. Therefore, this phenomenon proves that the Ca$^{2+}$ and Mg$^{2+}$ cations in the surface soil layer migrate downward along with water molecules and aggregate around clay particles in the saturated process, and eventually form the electrical environment.
applied and assess the modification effect produced by the latter exchange on
expansive soil layer are slightly higher than its initial values. This phenomenon indicates that the swelling of lower expansive
soil layers are lower than their initial values, while these parameters of surface expansive soil layer are

3.3. Swelling Behavior of Expansive Soil at Different Depths

Since the above analyses confirmed the assumption on the migration and aggregation of Ca\(^{2+}\) and Mg\(^{2+}\), the next step was to check whether these aggregated cations participate in the ionic exchange with expansive soil and assess the modification effect produced by the latter exchange on expansive soil. After completion of the model test, the surface, middle and bottom expansive soil layers (soil layers at depths of 0–30 mm, 90–120 mm and 180–210 mm, respectively) was removed from the test apparatus and was put into separate containers, then was naturally dried and ground to prepare the powder and cylindrical samples for the free swelling ratio, swelling pressure, and swelling percent tests by the same method in Section 2.3.4. Noteworthy is that the each swelling parameter was determined by the four parallel experiments. The test results obtained are presented in Figure 7.

![Figure 6](image1.png)

**Figure 6.** The cation concentration of pore solution at three soil layer interfaces after completion of the model test: (a) Mg\(^{2+}\); (b) Ca\(^{2+}\).

![Figure 7](image2.png)

**Figure 7.** The variation of swelling properties of expansive soil after completion of the model test: (a) Free swelling ratio; (b) swelling pressure and swelling percent.

It can be observed from Figure 7 that all swelling parameters of the middle and bottom expansive soil layers are lower than their initial values, while these parameters of surface expansive soil layer are slightly higher than its initial values. This phenomenon indicates that the swelling of lower expansive soil layer is inhibited in the saturated process. The most reasonable explanation is that the lower expansive soil layer has been modified due to the cation exchange with the migrating and aggregating cations where the divalent cations (Ca\(^{2+}\), Mg\(^{2+}\)) enter into the diffuse double layer (DDL) of clay particles and interlayer of montmorillonite crystals, but the swelling potential of the surface expansive
soil layer is released because of the downward migration of bivalent cations. However, the swelling pressure of the middle and bottom expansive soil layers is over 120 KPa that is still higher than the self-weight of overlying soil layer. This implies that the inhibition effect produced by cation exchange cannot completely balance the swelling pressure. A tentative explanation is that the impact of electrical environment formed by the migrating and aggregating cations counteracts this part of the swelling pressure (described in the next section). But due to the above soil samples soaked in de-ionized water, the electrical environment was destroyed so that the swelling potential of expansive soil cannot be completely inhibited.

3.4. Discussions

Based on the above analyses, the mechanism of swelling difference of different expansive soil layers can be explained as follows. As shown in Figure 8, during the saturation process of water (de-ionized water) injection from top to bottom, the divalent cations (Ca\(^{2+}\), Mg\(^{2+}\)) in the surface soil layer migrate downward along with water molecules and aggregate around clay particles, eventually form the electrical environment. In this process, the cation exchange with expansive soil occurs where the bivalent cations (Ca\(^{2+}\), Mg\(^{2+}\)) enter into the DDL of clay particles and interlayer of montmorillonite crystals, resulting in the modification effect to restrain the swelling potential of the lower expansive soil layer. On the other hand, the hydrated exchangeable cations adhere to soil particles and form the adsorbed water film surrounding the aggregates [11], which produces the crystalline swelling and the diffuse double-layer swelling [15,27,28]. Followed by the swelling of aggregates, this induces the collapse and rebuilt of soil skeleton at the expense of porosity which decreases in volume under the confined condition [21,29]. After the cations further migrate downward and aggregate, the aggregates continue to swell and fill the micropores [29]. As high concentration of solution will cause the reduction in the DDL thickness and consequently a decrease of the diffuse double-layer swelling based on the DDL theory [15,30–32]. Thus water molecules tend to adsorb in the interlayer space rather than in the micropores in the case of the confined condition [33]. Moreover, with the increase of concentration of the migrating and aggregating cations, the adsorbed water, particularly the inner water molecules layer surrounding the surface of aggregates, may be in the state of solid water without movement and exchange under the influence of Coulumbian electrical charges [8,34]. Therefore, the water molecules are hard to penetrate the adsorbed water film surrounding the aggregates into the interlayer space, resulting in the inhibition effect on the swelling of the lower expansive soil layer. On the contrary, the swelling potential of surface expansive soil layer is released because of the downward migration of bivalent cations. Consequently, the swelling difference between the upper and lower expansive soil layers can be observed during the saturated process. Such a difference is mainly attributed to the joint effect of two factors that can be treated as an electric charge effect, namely (i) the modification effect, (ii) the electrical environment.

In addition, the concentration of the migrating and aggregating cations increases with the thickness of overlying expansive soil layer, and so the swelling potential of the middle expansive soil layer is higher than that of the bottom expansive soil layer. In the literature reported by Katti and Katti [7,8], the reason why the 1.2 m thick soil layer can completely restrain the swelling of the lower black cotton soil is that the electric charge effect can completely balance its swelling pressure, the water molecules only accumulate in micropores rather than entering into the soil particles and montmorillonite interlayer, and thus it will not lead to swelling deformation.

Based on the above analyses, the electric charge effect on expansive soil provides helpful insights into the swelling behavior of expansive soil under seepage. For the subgrade, foundation and cross-drainage structures on expansive soil areas, the damage to structures caused due to volumetric changes occurring through the active zone of expansive soil has always been of concern to civil engineers [35]. Conservative design of a structure on expansive soil must consider the maximum amount of heave that can occur in the lifetime of the structure [36]. In order to predict the maximum heave of expansive soil, it is necessary to define the largest active zone of expansive soil that can be
wetted and determine the properties of expansive soil in that zone [36]. In this process, traditional methods usually neglect the effect of electric charge on the swelling properties of expansive soil in the active zone. In fact, the electric charge effect produced by the migration and aggregation of cations in the soil can significantly eliminate the swelling potential of expansive soil, which is the reason why the depth of the active zone obtained by dividing the swelling pressure by the self-weight of the overlying soil layer is usually greater than the actual value. Therefore, the results obtained in this study will provide a good basis for the rational design, construction and maintenance of engineering constructions on expansive soils.

Figure 8. The mechanism of electric charge effect on the swelling of expansive soil.

4. Conclusions

In this study, the swelling behavior of expansive soil at different depths was experimentally investigated through laboratory model test under saturated condition of water injection from top to bottom. Two different factors controlling the swelling difference of different expansive soil layers were discussed. The following conclusions can be drawn from the test results:

(1) It could be observed that there was the distinct swelling difference between the expansive soil layers at different depths under the saturation process. The swelling potential of the surface expansive soil layer at a depth of 0–30 mm was released while that of the middle and bottom ones at depths of 90–120 mm and 180–210 mm was inhibited.

(2) It was experimentally proved that the divalent cations (Ca$^{2+}$, Mg$^{2+}$) in the surface soil layer migrated downward along with water molecules and aggregated around clay particles to form the electrical environment under unidirectional seepage. Moreover, the concentration of migrated and aggregated cations was positively correlated with the thickness of the overlying soil layer.

(3) The swelling difference of different expansive soil layers was mainly caused by the electric charge effect including two factors, namely (i) the modification effect, (ii) the electrical environment. Firstly, the cation exchange between the aggregated bivalent cations and the expansive soil could reduce the swelling potential of expansive soil. Additionally, the adsorbed water film surrounding the aggregates obstructed the further adsorption of water molecules into the montmorillonite interlayer, which restrained the swelling of the expansive soil.

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