



# Physical model test of seepage and deformation characteristics of shallow expansive soil slope

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Received: 11 November 2019 / Accepted: 17 April 2020 / Published online: 6 May 2020  
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## Abstract

Large-scale physical model test on expansive soil slope at a shallow depth is conducted with the aim of monitoring moisture content and swelling deformation. In this paper, a wedge-shaped model box with a bevel at the bottom was developed to reflect the actual channel slope in the South-to-North Water Transfer Project. The results provide an improved understanding of the physical behavior and failure mode of a saturated-unsaturated expansive soil slope subjected to moisture content variation. Showing that, after rainfall, the surface soil quickly became saturated, with the deeper soil moisture remaining unchanged. Infiltration depth, speed, and saturation region reduced with the increasing height along the slope. Surface displacement increased from slope foot to slope shoulder, and significantly attenuated towards the depth. Horizontal displacement was about 1/3–1/2 of the vertical displacement. The larger the increment of the soil moisture, the greater the surface deformation. Soil showed dehydration shrinkage with fissures first appearing in the soil surface and expands downward with continuing evaporation. The junction of saturated-unsaturated zone and the wet-dry interface were the areas of stress concentration. Swelling effect led to stress field redistribution in the expansive soil slope, and it was the most important factor causing expansive soil shallow slope failure.

**Keywords** Expansive soil · Shallow depth · Slope · Physical model test · Swelling deformation

## Introduction

Expansive soil slope instability and landslide are seasonal, and environmental factor is one of the main effects (Dhowian 1981; Ruwaih 1984; Houston et al. 2011; Dafalla and Shamrani 2012). Slope instability, embankment slump, and channel landslides caused by climate change are widespread (Liao 1984; Ai-Homoud et al. 1996; Liu 1997; Shi et al. 2002; Meisina 2004; Xeidakis et al. 2004).

The mid-route of the South-to-North Water Transfer Project has a total length of over 1472 km, among which expansive soil area will cover about 340 km (Fig. 1).

Expansive soils are mainly Middle Pleistocene alluvial and flood sedimentary clay, Lower Pleistocene flood sedimentary clay, and Neogene hard clay. Strong expansive soil is mainly distributed in the Xingtai-Handan area and Nanyang Basin.

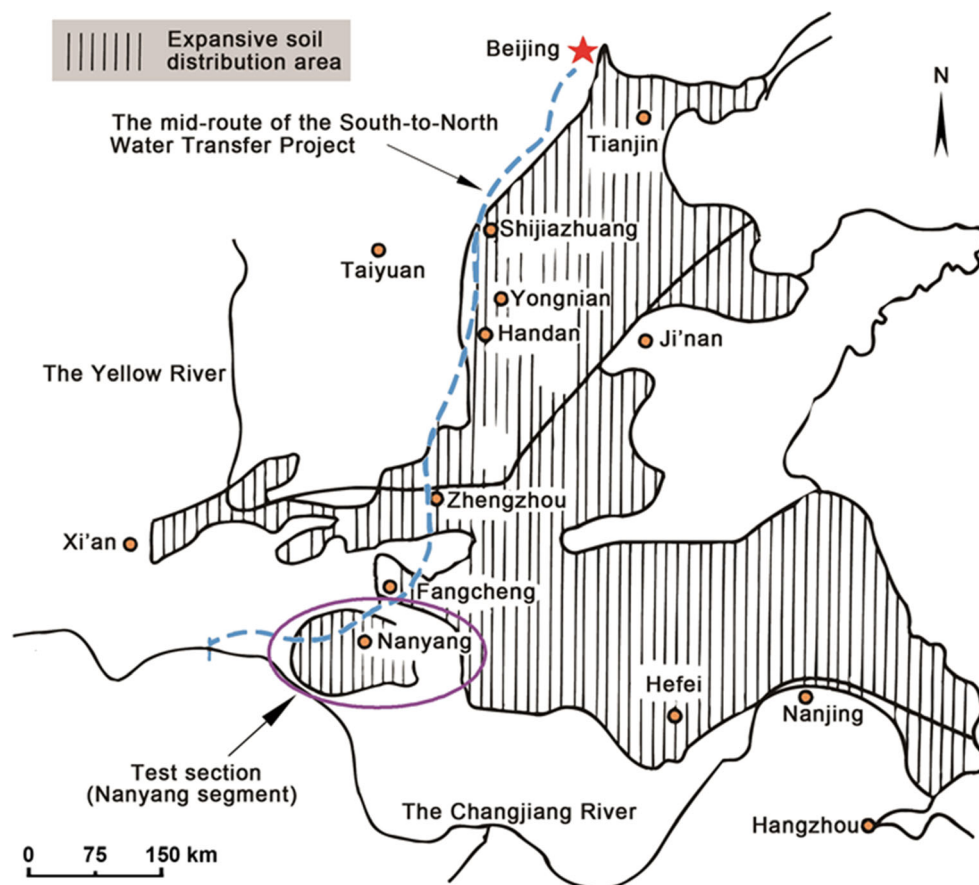
Nanyang area is in the transition zone from subtropical to warm temperate zone. It is a typical monsoon humid climate with four distinct seasons, plenty of sunshine, and abundant rainfall. The Nanyang Basin is a fault-type inland basin formed since the Mesozoic and Cenozoic. The strong expansive soils in the area are mainly Middle and Lower Pleistocene flood sedimentary clays and Neogene lacustrine sedimentary clays, including brown clay and gray-green clay. The thickness of brown clay is generally 10 to 25 m, which is often sandwiched with gravel layers, coarse sand layers, fine sand and silt layers, or lens bodies. It is rich in black spherical manganese nodules with particle size of 2 to 4 mm. Gray-green clay is the main body of the strong expansive soil in the Nanyang Basin. It is formed in a deep-water reduction environment. Its lithology is relatively uniform and its thickness is large, which can reach hundreds of meters. This kind of clay is mainly gray-green or light green, and it is gray-white after drying.

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**Fig. 1** Expansive soil distribution in the mid-route of the South-to-North Water Transfer Project



According to available statistics, it has been more than 40 slides of all kinds in the mid-route of the South-to-North Water Transfer Project since 2011. Because of the working condition of the channel and the soil's sensitiveness to water, the stability of expansive slope is important to the safety and functionality of the channel.

In general, the continuous or repeated rainfall is the main cause of landslides (He et al. 2018). Under rainfall conditions, with the water infiltration, expansive soils, which are rich in hydrophilic minerals such as montmorillonite and illite (Dhowian 1981; Sridharan et al. 1990; Abduljawad et al. 1992; Mutaz et al. 2011; Mutaz and Dafalla 2014), absorb a large amount of water (Sivapullaiah et al. 1987; Gadre and Chandrasekaran 1994; Basma et al. 1996), on the one hand, there is a great expansion (Dakshanamurthy 1979; Tisot and Aboushook 1983; Al-Shamrani and Al-Mhaidib 1999; Al-Shamrani and Dhowian 2003; Chen and Ng 2005), on the other hand, the shear strength of expansive soil continues to decrease with the growth of the saturation, eventually accumulating excessive deformation, and landslides occur (Bao 2004; Huang and Wu 2007). It has some significance for landslide prediction, prevention, and treatment to study the deformation of expansive soil slope under rainfall conditions.

Due to the particularity of deformation and instability of expansive soil slope, the swelling deformation after absorbing

water becomes one of the main research contents (Basma 1991; Zhan et al. 2007; Yilmaz and Kaynar 2011; Cheng et al. 2014). A lot of researches were conducted by the means of long-term monitoring, centrifuge model tests, and indoor model tests (Ng et al. 2003; Zhan et al. 2007). However, the existing expansive soil slope deformation test models were often modified on the basis of the clay soil slope test models, basically using the methods of clay soil slope deformation test, when the slope deform to a certain degree, it reaches ultimate state, the sliding surface is often considered as the arc-shaped, which is difficult to reflect the low permeability, shallow depth of large deformation, deformation and failure obviously controlled by fissures and many other features (Liu et al. 2008; Yin et al. 2010; Yin and Xu 2011; Zhou et al. 2013; Kong et al. 2017). In addition, some slopes with slow slopes and high safety factors still have landslides, which is difficult to explain in general soil mechanics theory. Therefore, in order to solve the defects, improvements are needed for the existing test devices and methods, and also deformation and failure mode and mechanism of expansive soil are still needed for further study.

In this paper, relying on the typical channel section of the middle route of the South-to-North Water Transfer Project, expansive soil slope model was established according to the real proportion. Considering the depth of the atmosphere influence, combining peculiar engineering geological

characteristics such as permeability, swelling, and developing fissures of expansive soil, large-scale physical model test on expansive soil slope swelling at a shallow depth was carried out. In the model test, strong expansive soil was used, because of the low hydraulic conductivity of the soil, a wedge-shaped model box with a bevel at the bottom was designed to simulate the real working conditions and save the filling soils. And also, a low-rate water supply rainfall device with needles was used to carry out small-scale drip-type rainfall. Then, through dynamic monitoring of the moisture content and deformation of the soil during rainfall, the characteristics of moisture infiltration, surface and deep deformation of different parts of the slope, and the relationship between soil deformation and changes of moisture content were analyzed, which was conducted with the aim of studying the failure mode of the shallow expansive soil slope, providing a theoretical basis for the engineering design and construction.

## Large-scale static model test of expansive soil slope

### Overview of static model test system

The expansive soil used in the static model test was sampled from the mid-route of the South-to-North Water Transfer Project Nanyang segment, it was a typical strong expansive soil (brown and gray-green clay). Physical and mechanical properties of material maintained good similarity, and the index of strong expansive soil physical properties are listed in Table 1. The expansive soil is mainly composed of fine particles, the silt particles ( $<0.05$  mm) content is about 90%, the clay particles ( $<0.005$  mm) account for 31%, and the rubber particles ( $<0.002$  mm) content is about 14%. In the expansive soil, clastic minerals such as quartz and feldspar account for 61.23%, clay minerals account for 38.77%, including 21.57% of montmorillonite and 2.70% of illite. The permeability of strong expansive soil is poor and the saturated permeability coefficient is about  $10^{-8}$  to  $10^{-9}$  m/s.

The geometry and dimensions of the model showed similarity with the actual slope morphology. Experimental prototype was Nanyang segment TS95 + 640 ~ TS95 + 850 of the South-to-North Water Transfer Project channel, the slope ratio was 1:2.

Strong expansive soil showed low hydraulic conductivity, water infiltration was difficult on the slope surface, and soil

had a limited depth of water absorption and expansion deformation. The thickness of the filled soil was 0.7 m. The model box was designed as a wedge-shaped box with a bevel at the bottom, which could simulate the real working conditions and save the filling materials. The box size was  $5.4$  m  $\times$   $2.11$  m  $\times$   $1.3$  m, and slope ratio was 1:2 (Fig. 2).

The soil was filled in a stepped layer, and the slope was finally cut at a slope ratio of 1:2. Soil filling process is shown in Fig. 3. The test soil should control the moisture content and dry density. In order to ensure the water penetration and prevent water loss in the form of surface runoff, the original soil moisture content was appropriately reduced to 60%, so the soil moisture content was controlled by about 17 to 20%. The soil should maintain a large density to avoid collapse due to the large porosity of the soil after absorbing water. Therefore, the dry density of the soil should be close to or reach the maximum dry density of the original soil, the dry density of the test soil was about  $1.5$  g/cm<sup>3</sup>. At the time of filling, the method of manual sub-layer compaction was used, and the dry density of the soil was repeatedly checked during the compaction process to meet the requirements.

Due to the limitation of the size of the model box, the expansive soil easily adhered to the box after encountering water, which caused the boundary soil to restrain the internal soil, restricted the development of the expansion force and the sliding force, and caused the distortion of the stress field and the deformation field and restricted the formation and development of landslides. Therefore, the inner sidewalls of the model box should be ground and cleaned, and a layer of Vaseline should be evenly applied to eliminate adverse boundary effects.

### Monitoring components and layout solutions

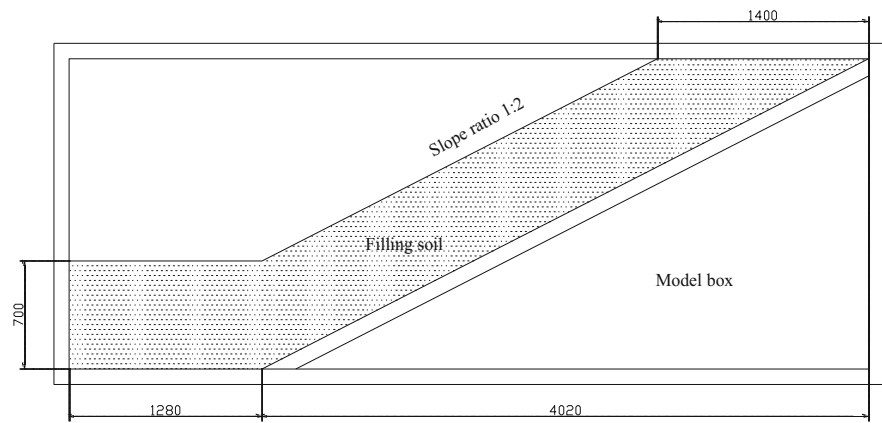
During the test, the deformation and moisture content of the slope soil were monitored. The monitoring contents and components used were as follows.

PR2/4 soil profile moisture measuring device produced by British DELTA-T was used to monitor soil moisture content, 4 moisture sensors were distributed at depths of 10, 20, 30, 40 cm, and data collection was carried out using HH2 hand-held soil moisture meter. Spring retractable displacement sensors with 50 mm measuring range and 5/1000 accuracy were used to monitor soil surface deformation. Settlement plate and

**Table 1** Strong expansive soil physical properties index

Soil type	Moisture content /%	Density/ (g/cm <sup>3</sup> )	Relative density	Liquid limit /%	Plastic limit /%	Plasticity index	Free expansion /%
Strong expansive soil	27.7	1.94	2.70	89.03	29.30	59.73	109

**Fig. 2** Model box filling soil schematic diagram (unit mm)



displacement sensors were used to monitor internal vertical deformation.

Seven typical sections of the slope were selected: slope bottom center (A'), slope foot (A), 1/6 slope height (B'), 1/3 slope height (B), 1/2 slope height (C), 2/3 slope height (D), and slope shoulder (E). The layout of the monitoring components is shown in Fig. 4.

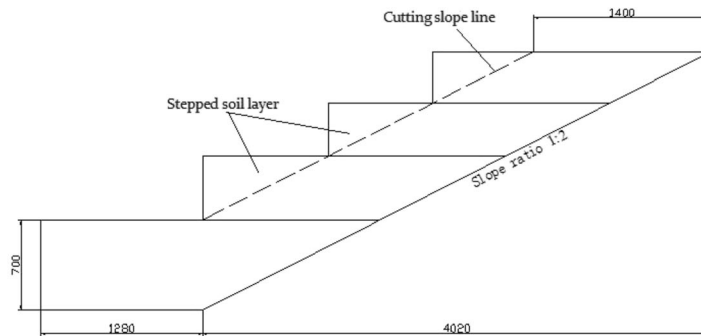
The depth of the settlement plate was 0.2 and 0.4 m, respectively. Two displacement sensors were arranged at each monitoring point on the surface of the slope to measure the horizontal and vertical displacements of the surface soil. When combined with the settlement plate, it was mounted on the platform installed at the top of the settlement plate (Fig. 5).

**Test method and process control**

Shallow fissure was one of the key factors that determine the nature of strong expansive soil slope. After filling, the slope was subjected to artificial compaction, the surface was smooth and the internal soil uniformity and compactness were also good. Therefore, the static treatment of the soil after filling ensured the uniform distribution of the moisture content inside the soil and at the same time formed an expansive soil slope with fissures.

In the different positions of the slope, a special rainfall device was used to carry out small-scale drip-type rainfall on the slope surface and the slope water naturally flew down. The rainfall device was a water pipe spanning both sides of the

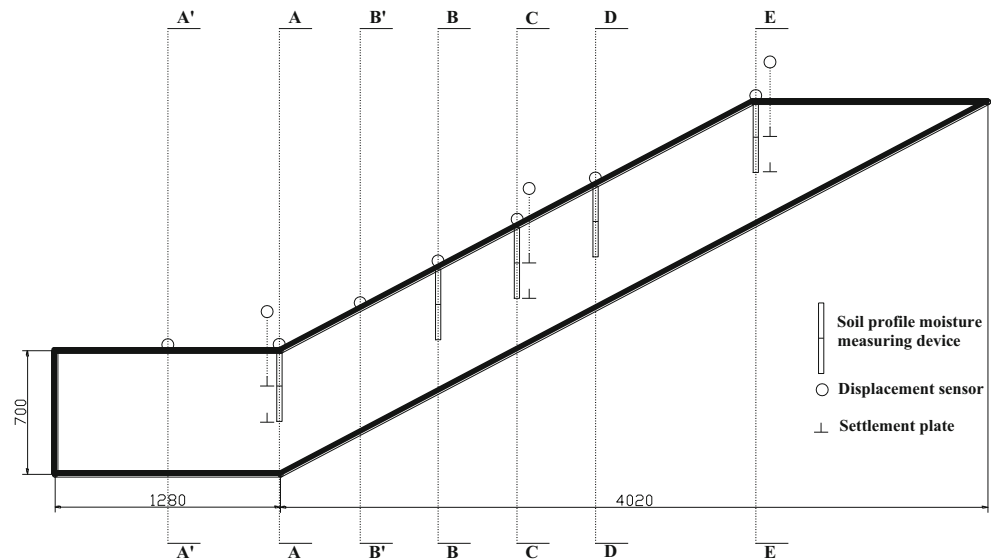
**Fig. 3** Soil filling process



Unit: mm

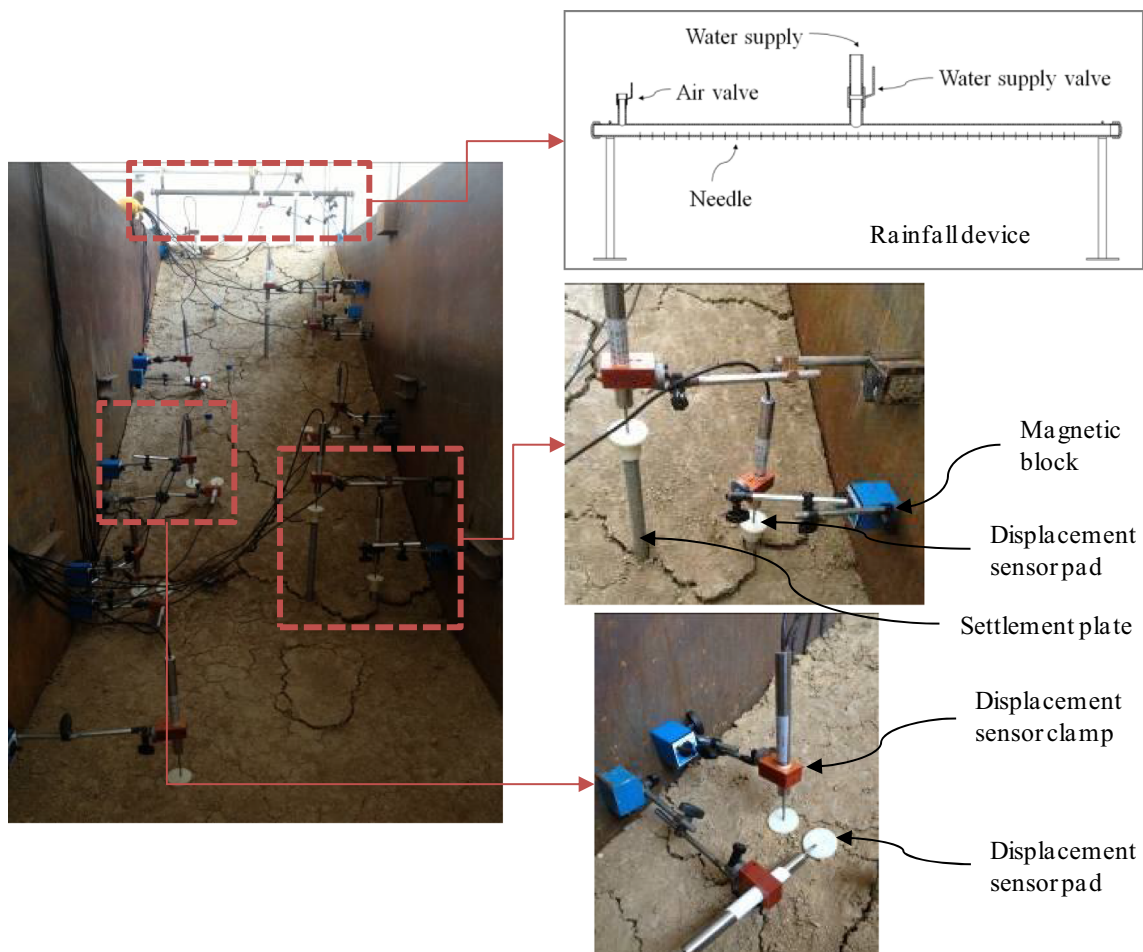


**Fig. 4** Model test monitoring components layout schematic (unit, mm)



model box (Fig. 5). One end of the water pipe was equipped with an air valve. The middle of the water pipe was connected to the water supply pipe and the flow was controlled by a valve. The water dripped into the soil through the water pipe

to the needles, ensuring the demand for low-rate water supply, and also avoiding damage to the sensors caused by the large-scale water supply. The rainfall conditions were low-intensity continuous rainfall that controlled the total amount of rainfall.



**Fig. 5** Displacement sensors layout and fixing method

The daily rainfall was 4 to 8 h, and the daily rainfall was controlled to about 10 mm, artificially simulating natural light rain.

The simulated rainfall was carried out in three stages, the first stage was the rainfall stage, which lasted for 16 days, the rainfall was 120 mm. The second stage was the natural evaporation stage, which lasted for 36 days, and the daily evaporation was measured by laboratory test, which was 0.69 mm/d. The third stage was the rainfall stage, which lasted for 14 days and the rainfall was 120 mm.

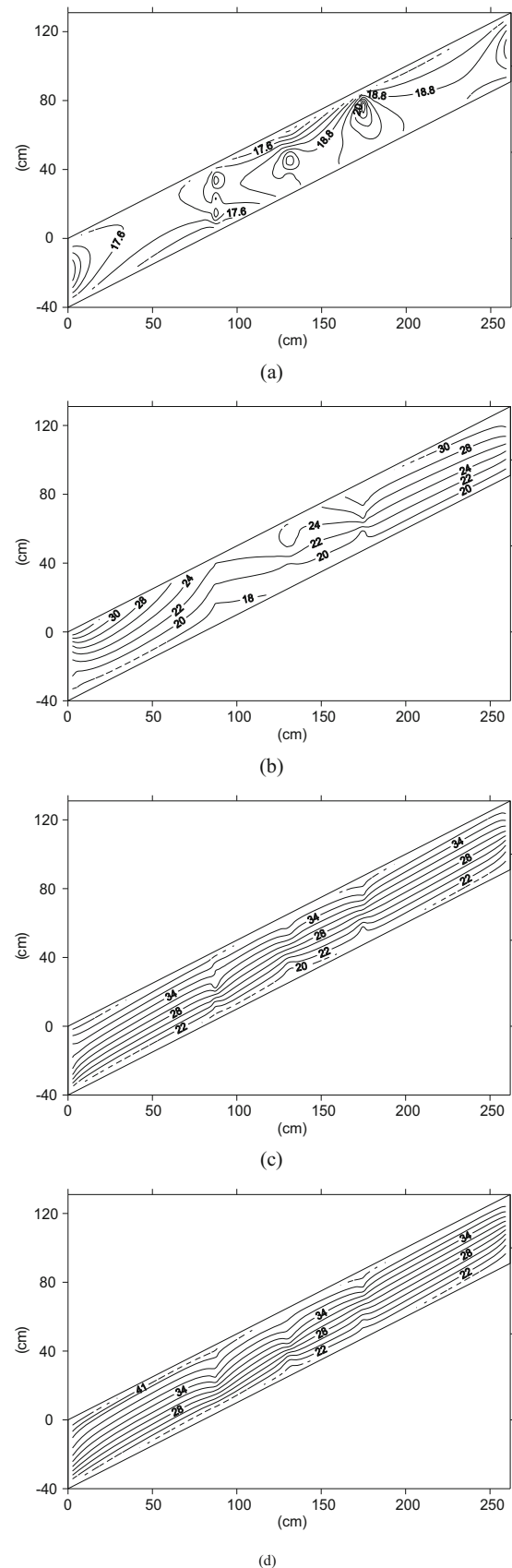
In the initial period of rainfall, intensive monitoring should be carried out for each physical quantity and the physical quantity was monitored 2 to 3 times per day. After that, each physical quantity was monitored 1 to 2 times per day. After the start of the test, the deformation characteristics of the slope should be recorded and described from time to time. If a landslide occurred, the number, location, scale, and form of the landslide should be recorded in detail.

## Variation characteristics of slope moisture content field

### Distribution of slope moisture content at different times

As the simulated rainfall progressed, water flew down the slope and gradually infiltrated into the slope soil. At different moments of rainfall, the slope moisture content distribution showed different states. The PR2/4 soil profile moisture measuring device was used in combination with surface soil sampling to test the volumetric moisture content of the slope soil at different depths. Through Kriging interpolation, the moisture content field contour map was drawn. Figure 6 shows the distribution of transient moisture content fields in the soil within 40 cm depth of the slope before the start of rainfall and at 10, 60, and 120 mm.

It can be seen that after the slope had been left for a sufficient period of time, the moisture content of the soil in the slope was basically the same at the beginning of the test, which was between 17 and 20%. When water began to infiltrate, due to the existence of a large number of fissures in the soil, the water quickly infiltrated through the fissures. When the rainfall was 10 mm, the change of the moisture content field was obvious. The soil moisture content had a layered distribution and decreased from shallow part to deep part. The moisture content of the surface soil increased, which had increased to 24% to 30%, and the moisture content of the deep soil did not change significantly. When the rainfall reached 60 mm, the contour of the soil moisture content was basically parallel to the slope surface, slightly inclined towards



**Fig. 6** Slope transient moisture distributions on different rainfall (unit, %). **a** 0 mm; **b** 10 mm; **c** 60 mm; **d** 120 mm

the foot of the slope, the soil moisture content stratification was significant, and the moisture content of each layer of soil was relatively uniform. At the end of the staged rainfall, the contour line of the soil moisture content field was similar to that of the rainfall of 60 mm, and it only increased in the soil moisture content value, indicating that the seepage had become in equilibrium and water infiltration was stable and uniform.

### Time-course variation of soil moisture content in slope

Select 5 sections of slope foot, 1/3 slope height, 1/2 slope height, 2/3 slope height, and slope shoulder as the soil moisture content field observation section. Figure 7 shows the time-course curves of soil moisture content at different depths of these 5 different sections.

It can be seen that, due to the characteristics of the rainfall device and the special simulated rainfall method, the typical time-course curve of the moisture content field showed starting stage-rapid growth stage-slow growth stage-stable stage, and the soil moisture content of different sections and different depths changed with time differently, showing their own characteristics or missing at some typical stages.

At the same section, the closer to the surface soil, the faster the moisture content increased in the initial stage of water infiltration. The surface moisture content began to increase rapidly and remained unchanged for most of the time. With the increase of depth, the change of soil moisture content showed obvious hysteresis, and the situation gradually changed to slowly increased with infiltration until it remained basically unchanged. Taking the section of 1/2 slope height as an example, the moisture content of the soil within 10 cm of the surface increased the fastest at the beginning, and after reaching a certain value, it did not change with the infiltration. The initial moisture content of the soil at the depth of 20 cm increased rapidly. The moisture content of the soil at the depth of 20 to 30 cm had been in a slow growth stage from the beginning to the end of the infiltration, while the moisture content of the soil at the depth of 40 cm had never occurred obvious changes.

For different sections, from the foot to the shoulder of the slope, along the increase of the height of the slope, the growth rate of the surface soil moisture content was getting slower and slower in the initial stage and the moisture content of the deep soil was less and less obvious with time. In the 1/2 slope height, the moisture content of the soil at the depth of 20 cm slowly increased with time, and at the depth of 30 to 40 cm, the moisture content of the soil was basically unchanged with the infiltration. At the slope

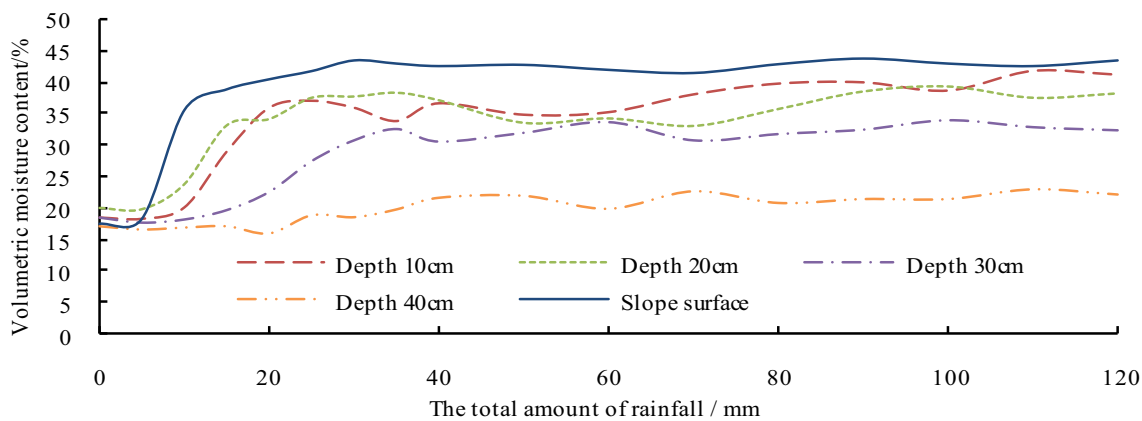
shoulder, the depth of the soil moisture content is unchanged with the infiltration decreased to 20 cm.

### Spatial distribution and variation of soil moisture content in slope

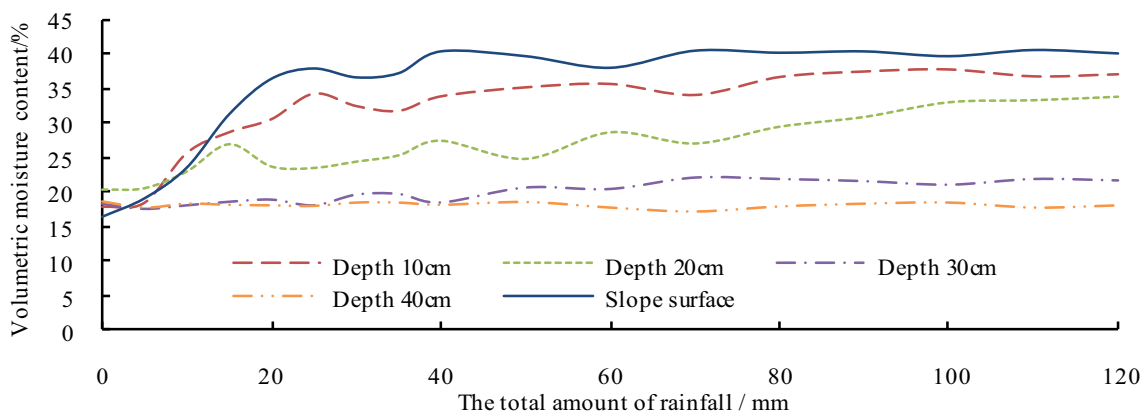
Figure 8 shows the relationships in soil moisture content distribution with rainfall in different slope sections. As can be seen,

- (1) Moisture variation in slope foot was the most significant, when the rainfall was 10 mm, the saturation of the surface soil reached about 80%. When the rainfall was 20 mm, the soil within the 30-cm depth was close to saturation. With the infiltration, in the following depth of the slope foot, the soil moisture content was stable in a highly saturated state, and the soil moisture content at 40 cm depth is slowly increased with the infiltration, and the final saturation was maintained at about 50%.
- (2) In the sections above the slope foot and below the slope shoulder, variation of soil moisture content with infiltration was basically similar. Surface soil approach saturation during rainfall was 30 mm, and then maintained the state of 80 to 90% saturation. Moisture content of soil at the depth of 15 to 25 cm continued to increase over time; finally, saturation of the soil close to the slope foot became relatively high. The moisture content of the deep soil was basically unchanged with the infiltration and was maintained near the initial value.
- (3) The moisture content of the soil changed only at a depth of 20 cm at the shoulder of the slope, and the moisture content of the soil below 20 cm remained stable at the initial value with the infiltration. The moisture content of each depth soil did not increase slowly with the infiltration, and it was stable when it increased to a certain value. The stable value of surface saturation was about 80 to 85%, and it was 55% in the depth of 20 cm and 45% below 20 cm depth.

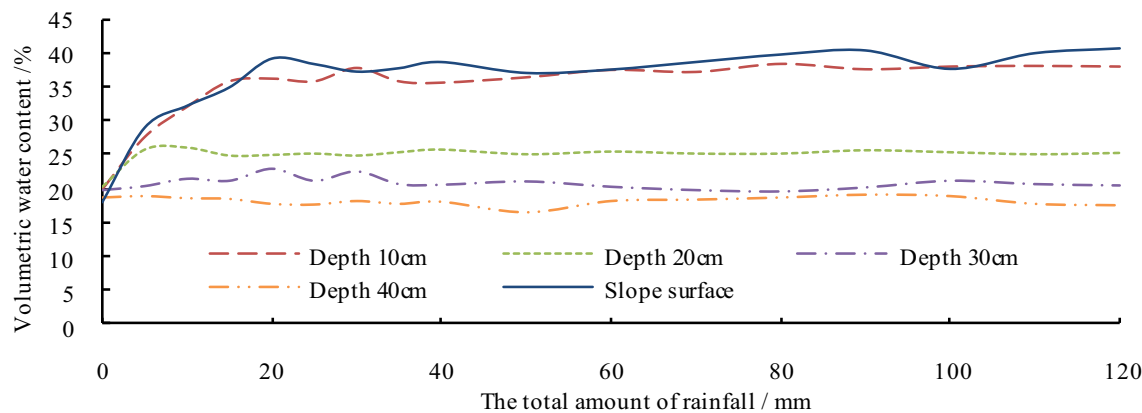
From the above analysis, it could be considered that the soil moisture content of the slope increased slowly with the infiltration, and generally reached a stable value. The occurrence of the stable value was related to the depth and rainfall. Combined with the model results, for the poor permeability strong expansive soil, under the continuous rain mode, the rainfall reached 30 mm, the surface soil moisture content was saturated and stable, and when the rainfall reached 90 mm, the overall moisture content of the slope reached a stable state.



(a)



(b)



(c)

Fig. 7 Moisture content history curves of slope at different section. **a** Slope foot; **b** slope center; **c** slope shoulder

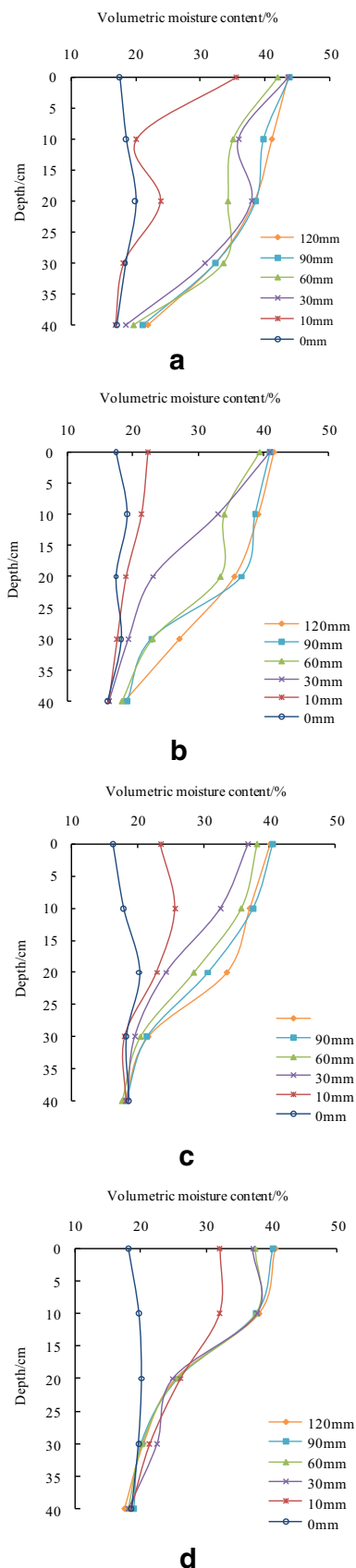
**Slope swelling deformation characteristics and evolution law**

**Fissure characteristics and soil surface state**

At the beginning of rainfall, the deformation of the soil appeared as the contraction and closure of the fissures. With the

supply of water, part of the water gradually infiltrated from the surface of the soil, and most of the water migrated rapidly through the fissures and entered the interior of the slope, causing the soil to swell and expand and the fissures to gradually close. Figure 9 shows the variation characteristics of the local fissures morphology below the slope shoulder at different stages of rainfall. It can be seen that at the initial stage of





**Fig. 8** Variation of the moisture content field in different slope sections. **a** Slope foot; **b** 1/3 Slope height; **c** slope center; **d** slope shoulder

rainfall, the change of the fissures was not obvious. When the rainfall reached 20 mm, the width of the fissures was significantly reduced compared with the rainfall of 5 mm, and the fissures with a larger width shrank significantly. The fissures contracted and the number of fissures did not change significantly. When the rainfall reached 60 mm, most of the main fissures had disappeared, and the number of fissures had been greatly reduced. After this period, the fissures in the soil had been basically closed.

With the continuous supply of water, the deformation of the soil appeared as a local and overall uplift. After the fissures were completely closed, the deformation of the soil would continue to develop in an unconstrained direction due to the swelling effect of the expansive soil. Irregular uplift occurred on the surface of the soil and became uneven. At different locations on the same section, due to the unevenness of the stress, the surface deformation of the soil was different, the part with higher degree of compaction and less fissures, due to the poor permeability of the expansive soil, which was difficult for water to infiltrate, and obvious expansion deformation occurred locally on the surface. But overall, the deformation characteristics of different parts of the slope were more obvious.

### Slope swelling deformation variation process

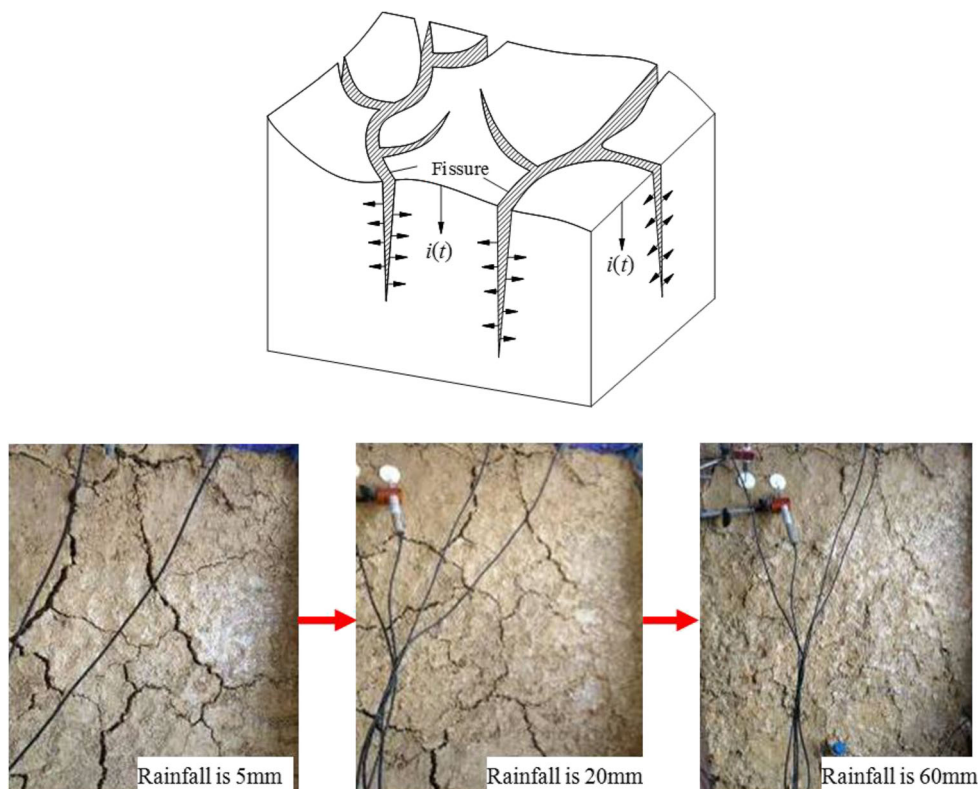
Figure 10 shows the surface displacement of the slope, it went through the starting stage-rapid growth stage-slow growth stage-stable stage, and the variation of the surface displacement and the formation mechanism were different at each stage.

At the starting stage, the deformation lagged behind the change of moisture content. The development of surface deformation took some time. At the same time, the water quickly entered the soil along the fissures, and the soil around the fissures were deformed. At this time, most of the deformation was due to the shrinkage and closure of the fissures. The expansion deformation at the stage is small, and the deformation rate was also slow, but the duration was short, generally ending when the rainfall reached 10 mm and mainly affected by the development of the fissures.

At the rapid growth stage, the closure of the fissures caused the lateral constraint of the soil deformation, and the deformation of the soil developed towards the free direction. At this stage, the soil swelling effect was obvious. This stage lasted until the rainfall reached 30 to 40 mm, which was mainly affected by the expansion and contraction characteristics and permeability characteristics of the soil.

At the slow growth stage, the infiltration amount was restricted by the soil permeability coefficient and the surface runoff, and gradually became smaller. The soil was near saturation, most of the deformation had been completed, and the residual deformation was small. This stage was the main stage

**Fig. 9** Fissures morphology of the slope surface at different rainfall times



of soil deformation, which lasted for a long time, but the amount of deformation was small and it was still affected by the expansion and contraction characteristics and permeability characteristics of the soil.

At the stable stage, the seepage field of the slope had reached a stable state, moisture content remained unchanged, and swelling deformation basically stopped.

### Spatial distribution of slope swelling deformation

Figure 11 shows surface deformations at different locations of the slope at different rainfall moments.

When the rainfall was 10 mm, the vertical displacement of each point on the slope was small and similar, which was less than 5 mm. When the rainfall reached 30 mm and later, the vertical displacement distribution of the slope gradually decreased from the slope foot to the slope shoulder. The deformation of the slope foot was about 3 times of the deformation of the slope shoulder. The vertical displacement was basically linear distribution along the slope. When the rainfall was 120 mm, the vertical displacement reached 30 mm at the slope foot and 12 mm at the slope shoulder.

At each stage of rainfall, the horizontal displacement of the slope was generally smaller at the upper part of the slope and larger at the lower part of the slope. When the rainfall reached 120 mm, the maximum horizontal displacement occurred at 1/6 slope height, about 13 mm. This was because the horizontal

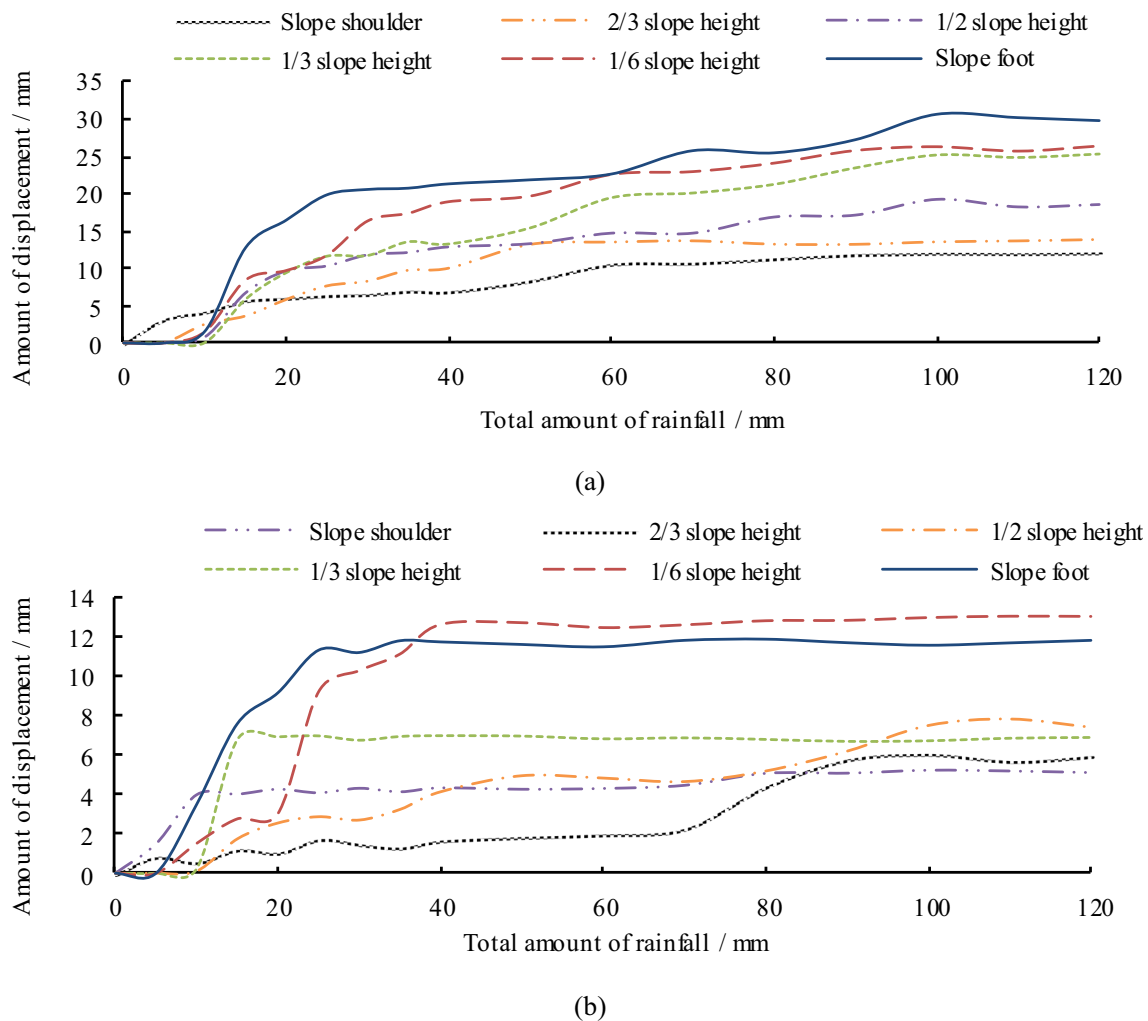
deformation of the slope foot was laterally constrained by the surrounding soil, while the vertical deformation could be developed. The horizontal displacements in the middle and upper parts of the slope are not much different, about 5 to 8 mm, and the horizontal displacement was about 1/3 to 1/2 of the vertical displacement.

Figure 12 shows the deep vertical displacements of slope shoulder, slope central, and slope foot at different times. The vertical displacement decreased rapidly with depth, the closer to the slope foot, the more obvious the vertical displacement attenuation with the depth. Vertical displacement at the surface of the slope foot was about six times of that at 20 cm depth and 7 to 8 times of that at 40 cm depth; vertical displacement at the surface of the slope shoulder was 4 times of that at 20 cm depth and about 6 times of that at 40 cm depth.

### Evolution law of fissure during dehumidification of the slope

Evaporation started after the rainfall, slope soil was dehumidified under the condition of the daily evaporation of 0.69 mm for 52 days.

According to the monitoring results, the water was lost during the evaporation process, but there was no considerable vertical displacement and horizontal displacement on the slope surface. The maximum attenuation of the slope displacement was only about 2 mm. The shrinkage effect of expansive



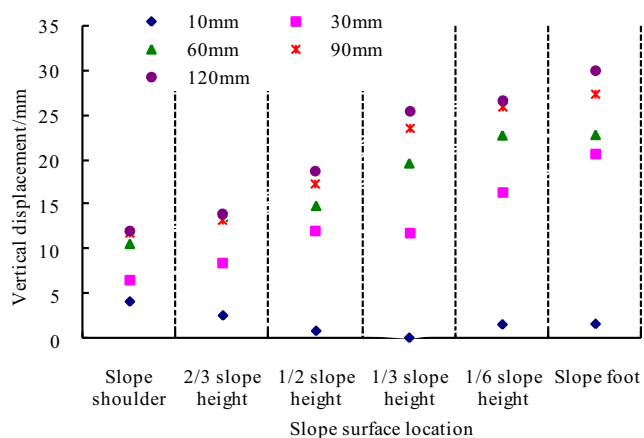
**Fig. 10** Slope surface swelling deformation curves. **a** Vertical displacement; **b** horizontal displacement

soil was very obvious. After losing water, the volume was rapidly reduced and shrinkage occurred. This shrinkage effect was manifested by fissures propagation and propagation. The evolution of fissures in soil is generally divided into three stages: fissures generation, fissures propagation, and fissures stability. When the stress state at a certain point in the soil met certain conditions, fissures began to occur. Under the condition of continued water loss, the fissures would expand in the direction of expansion, accompanied by new fissures. In the process of fissures generation and development, when the fissures developed to a certain extent, continuous changes in the direction of expansion would occur, and at the same time, new fissures continued to be generated, resulting in continuous changes in the stress field, which in turn led to parts where the stress met the conditions for fissure development and new fissures appeared. Eventually, the fissures continued to develop and cut each other, forming a complex fissure network. Taking the surface of the slope as the reference surface, the normal deformation of each point did not occur, but it showed significant tangential deformation, which caused the soil area

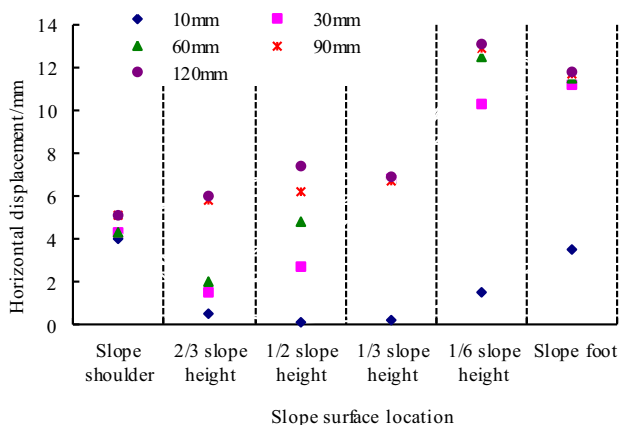
on the slope surface to decrease and the volume of the soil to shrink.

### Correlation between the deformation field and the moisture content field

The volumetric moisture content increment was used as the seepage variable, and the initial soil moisture content of the slope was taken as the initial zero point. At different times during the rainfall, the soil moisture content increment value at different depths was extracted from each typical section and compared with surface deformation of the same section (Fig. 13). Under unconstrained conditions, the surface deformation could be arbitrarily developed and the increase of moisture content was the dominant factor causing the deformation of the soil, and the surface deformation was actually the macroscopic performance of the accumulation of the internal soil deformation. Therefore, the larger the accumulated moisture increment, the greater the surface deformation, and deformation affected by this law was more significant. At the



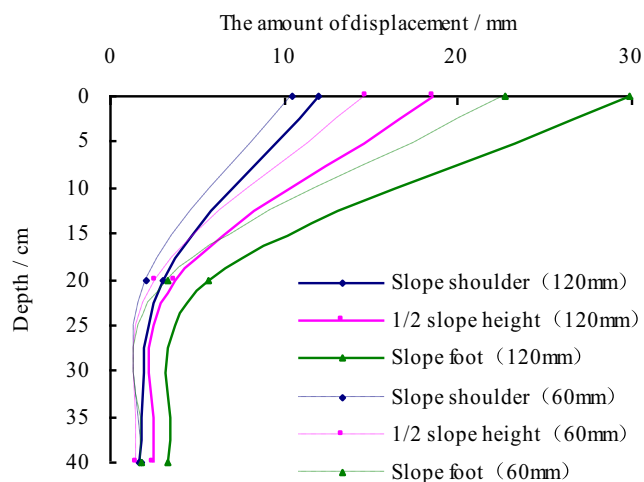
(a)



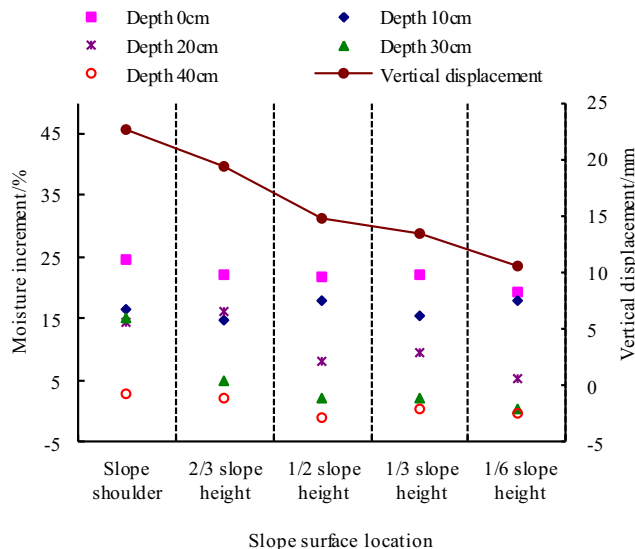
(b)

**Fig. 11** Surface displacement distribution characteristics of slopes at different times. **a** Vertical displacement; **b** horizontal displacement

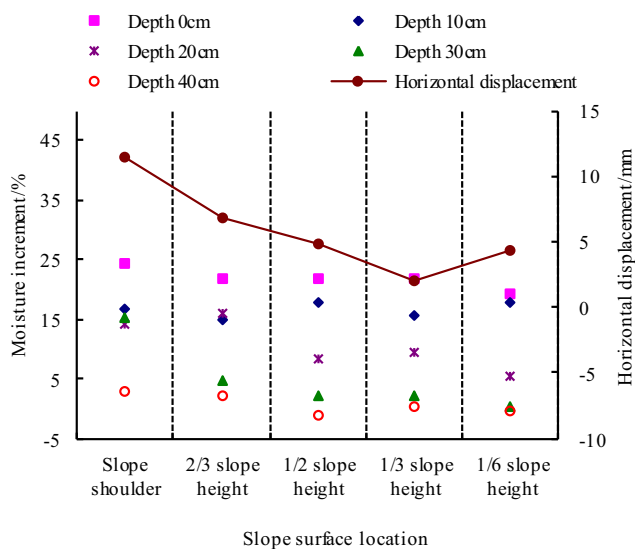
same section of the slope, the change of the moisture content in the internal soil was the same, but the vertical deformation was more affected by the change of the moisture content than the horizontal deformation. The swelling effect was expressed



**Fig. 12** Curve of vertical displacement versus depth



(a)



(b)

**Fig. 13** Relationships between the surface deformation and the moisture content. **a** Vertical (rainfall is 60 mm); **b** horizontal (rainfall is 60 mm)

in the form of deformation without external constraints, and it will be expressed in the form of stress when the deformation is limited by the external constraints. Therefore, the expansive soil expands after water absorption and the internal stress field of the slope changes. The vertical stress does not change much, only in the vicinity of the slope surface, the saturation zone expands due to the infiltration, and the vertical stress in the local area increases slightly. However, the horizontal stress and shear stress increase significantly and the stress redistribution occurs.

At some moment during the test, the instant incremental moisture contents of soil at the depth of 0 to 40 cm of each section of the slope were averaged and compared with the

slope surface vertical displacement. The results are shown in Fig. 14.

Vertical displacements basic had the linear relationship with the average incremental moisture content, and vertical displacements of the different sections with the same average incremental moisture content were similar, concentrated within a certain range. The linear relationships between vertical displacement  $s_1$  and the average incremental moisture content  $\Delta\bar{w}$  of each section could be gotten:

Slope foot:

$$s_1 = 1.7983\Delta\bar{w} - 3.4911, R = 0.9625 \quad (1)$$

1/3 slope height:

$$s_1 = 1.7333\Delta\bar{w} - 2.2933, R = 0.9676 \quad (2)$$

1/2 slope height:

$$s_1 = 1.8054\Delta\bar{w} - 3.1901, R = 0.9810 \quad (3)$$

2/3 slope height:

$$s_1 = 1.9466\Delta\bar{w} - 7.3363, R = 0.9432 \quad (4)$$

Slope shoulder:

$$s_1 = 2.1137\Delta\bar{w} - 9.2171, R = 0.7424 \quad (5)$$

The swelling effect of expansive soil must be closely related to the change of the moisture in the soil. In the areas where the moisture content changed drastically, the expansion of the soil was correspondingly larger. Therefore, the expansion of the soil in the saturated-unsaturated boundary region and the wet-dry interface played an important controlling role in the swelling effect. The number and extent of these areas affected the deformation of the expansive soil, which was reflected in the deformation of the slope surface. It could be seen from the relationship between the increase of the moisture content in

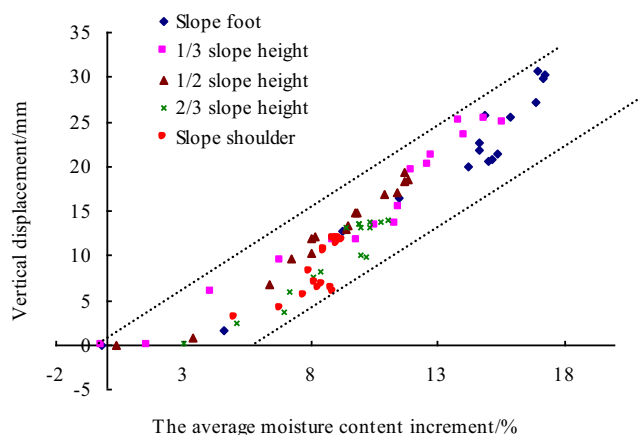
various parts of the slope and the vertical deformation of the surface that the slope angles of the linear relationships were smaller at the bottom and the lower part of the slope, that was because when the infiltration in the soil reached a certain level, the range of the soil at the bottom and the lower part of the slope which reached saturation was the largest, the seepage in the saturated soil was basically stable, and the soil no longer absorbed water and expanded. Although the moisture content of the soil changed greatly, the surface deformation was relatively small. The closer to the upper part of the slope until to the slope shoulder, the larger the slope angle of the linear relationship, indicating that in the middle and upper part of the slope, the steep infiltration could be maintained for a long time. Most of the deep soils had not reached saturation, and there were some areas where the moisture content changes drastically, such as the saturated-unsaturated boundary regions and the wet-dry interfaces, so the swelling effect was more significantly affected by the changes of moisture content.

Because the linear relationships of each section between vertical displacement and the average incremental moisture content were close, the correlation coefficients were high. The slopes and intercepts of these linear equations were averaged respectively. The following formula could be used for estimating the surface vertical deformation of expansive soil slope under the condition of known the moisture content field.

$$s_1 = 1.88\Delta\bar{w} - 5.11 \quad (\Delta\bar{w} > 3\%) \quad (6)$$

## Discussions

For the instability of expansive soil slopes, the fissurability, overconsolidation of expansive soil, and soil strength softening after moisture absorption are generally considered to be the main causes of this problem. Fissures of various types and sizes in the soil not only destroy the structure and homogeneity of the soil but also accelerate the infiltration of water. The dry-wet cycle further leads to the development of fissures and reduces the strength of the soil. In addition, overconsolidation causes slope excavation unloading expansion and strain softening, which results in an increase in shear stress, a decrease in soil strength, and eventually a landslide. In the slope stability analysis, the effect of the above factors is comprehensively reflected by the decrease of the shear strength. However, a large number of engineering examples show that expansive soil landslides can still occur at very slow slope ratios. In this case, even if the shear strength of the soil is set to the residual strength, the stability calculation shows that the safety factor of the slope is still high. Theoretically, no sliding will occur in the slope, but in fact a landslide does occur (Cheng et al. 2014). In the Nanyang Basin area, expansive soil landslides often have a common feature, that is, when the surface of the



**Fig. 14** Correlations between surface vertical displacement with average moisture content increment

slope is protected and fissures are not developed, the slope also partially or entirely slides, and the depth of the sliding surface is basically within 2 m. For these landslides, the strength index obtained from the test is used for stability calculation and the safety factor is much greater than 1.0. The safety factor calculated using the residual strength index is also greater than 1.0, which cannot reflect the true state of the landslide.

The deformation and instability mechanism of shallow expansive soil slope was analyzed based on the test results and phenomena, combined with engineering slope investigation and numerical analysis.

In the semi-infinite space state, water is uniformly infiltrated, although the expansive soil expands and increases in volume after water absorption, the soil is in an iso-stress state, on the same plane, the expansion is the same everywhere in the soil, and no obvious shear stress is generated inside the soil, so that instability failure does not occur.

After excavation forms an expansive soil slope, affected by atmospheric environment, wet and dry cycles, and other factors, a dense fissure network is formed in the shallow layer of the soil, and these fissures are mostly small fissures formed by expansion and shrinkage, not the structural fissures that control the stability of the slope, but these fissures provide good channels for water infiltration. Water infiltrates into the interior of the slope through fissures and soil, and the expansive soil changes from unsaturated to saturated within a certain range of the shallow slope. The model test revealed that the infiltration was limited to the range of several tens of centimeters below the slope surface, which was much smaller than the depth of atmospheric influence of natural slopes (2 to 3 m), and was related to the duration of the model test. The natural slope is a macroscopic state that finally forms after several years of dry and wet cycles, and the duration of the model test is only hundreds of hours. However, the moisture content distribution and change process caused by rainfall infiltration on the slope revealed by the model test was sufficient to provide a reference for the actual slope. The test results showed that even for homogeneous expansive soil slopes, the soil moisture content of the slope caused by rainfall also showed obvious uneven spatial and temporal distribution. The moisture content in the surface layer of the soil near the middle and lower slopes firstly increased; under the suction of the deep unsaturated soil, it gradually expanded to the deep and upper part of the slope. The depth of water infiltration in the lower part of the slope was relatively large. The infiltration further occurred with the rainfall, the wetting front in the soil continuously moved downward, and the saturated-unsaturated infiltration zone expanded deep into the slope. When the shallow soil reached saturation and a local saturation zone was formed, the soil moisture content in the deep slope tended to change slowly. Therefore, the external hydraulic action causes an uneven distribution of the slope moisture content field.

From the results of a large number of tests, after the moisture content of the expansive soil changes, its strength decrease is very obvious and there is no doubt that the slope stability is affected by it. However, for shallow landslides of expansive soil, practice has also proved that considering only the decrease in strength still cannot truly reflect the fact that the slope of the expansive soil is not stable, especially for the situation of low groundwater level, rainfall will only cause temporary saturation area or stagnation area of the shallow slope, it is not possible to form a stable infiltration line. It can be seen that there are other key factors that affect and control the shallow sliding of the expansive soil slopes.

If the swelling effect of expansive soil is considered, the situation is different. The slope deformation process is basically synchronized with the rainfall process. The expansion deformation mainly occurs during the rainfall period. Although the deformation occurs during the intermittent rainfall period, the deformation is very slow. Due to the spatio-temporal inhomogeneity of the distribution of soil moisture content in the slope, the expansion and development of different parts of the slope are not synchronized, and the magnitude of the expansion is greatly different. The soil in the middle and lower slope where the moisture content changes first, its swelling deformation also increases first.

The expansive soil expands after water absorption and the internal stress field of the slope changes. According to the investigation and statistics of dozens of landslides in the project, combined with some numerical simulation studies (Ding 2014), it can be found that after the expansion of the expansive soil, the vertical stress does not change much, only in the vicinity of the slope surface, the saturation zone expands due to the infiltration, and the vertical stress in the local area increases slightly. However, the horizontal stress and shear stress increase significantly, and the stress redistribution occurs. Controlled by the moisture content of the soil, the effects of this stress concentration are mainly in two regions, one is the saturated-unsaturated boundary region and the other is the wet-dry interface. After the soil absorbs water, the stress concentration zone is formed in the saturated-unsaturated boundary region and the wet-dry interface, and a large shear stress is generated, resulting in local shear deformation. With the infiltration, the expansion deformation expands with the saturated-unsaturated infiltration zone and the wet-dry interface to the deep part of the slope, forming multiple shear planes, and the slope is unstable.

In addition, since the expansion deformation of expansive soil is controlled by the moisture content of the soil, it also has obvious spatial and temporal heterogeneity. The stress concentration zone is first formed near the foot of the slope, and local deformation and sliding occur. As the infiltration progresses, the soil expansion causes the stress concentration zone to expand until it penetrates. Finally, a stress concentration zone penetrating the slope is formed, resulting in the

overall sliding of the slope. This sliding failure mode creates multiple shear failure surfaces with significant traction sliding characteristics. This is consistent with the shallow landslide characteristics of expansive soil slopes observed in a large number of engineering practices.

Therefore, the swelling effect of expansive soil is the most fundamental reason for the shallow sliding of the slopes, and the fissurability and soil strength softening after moisture absorption promote the occurrence of the sliding.

## Conclusions

Strong expansive soil suffers moisture action leading to swelling deformation at a very limited depth. Based on that, large-scale physical model test on expansive soil slope swelling at a shallow depth was carried out. A wedge-shaped model box with a bevel at the bottom was designed and a low-rate water supply rainfall device with needles was used to supply small-scale drip-type rainfall. The characteristics of moisture infiltration, surface and deep deformation of different parts of the slope, and relationship between soil deformation and changes of moisture content were analyzed. It was found that the moisture content and the surface displacement of the slope showed starting stage, rapid growth stage, slow growth stage, and stable stage. The closer the soil was to the surface layer, the more quickly it became saturated in the initial stage of infiltration. As the height along the slope increased, the rate of increase of the moisture content in the surface layer became slower and slower. With the increase of the depth in the soil, the change of moisture content showed obvious hysteresis. The moisture changed at the slope foot was the most significant, and the infiltration depth and saturation zone became smaller as the slope height increased. Surface displacement increases from slope foot to slope shoulder and significantly attenuate towards the depth. Horizontal displacement is about 1/3–1/2 of the vertical displacement. The larger the increment of the soil moisture, the greater the surface deformation. Soil shows dehydration shrinkage with fissures first appearing in the soil surface and expands downward with continuing evaporation. The vertical deformation was more affected by the change of the moisture content than the horizontal deformation. Vertical displacements basic had the linear relationship with the average incremental moisture content, which showed some differences in different parts of the slope, because the expansion of the soil in the saturated-unsaturated boundary region and the wet-dry interface played an important controlling role in the swelling effect.

The external hydraulic action causes an uneven distribution of the slope moisture content field, which will cause the expansive soil to expand, the vertical stress does not change much, the horizontal stress and shear stress increase significantly, and the stress redistribution occurs. The stress

concentration zone is formed in the unsaturated-saturated boundary region and the wet-dry interface, causing local shear failure, and gradually expanding to the deep part of the slope, eventually forming multiple shear planes, and the slope is unstable. So the swelling effect of expansive soil is the most fundamental reason for the shallow sliding of the slopes, and the fissurability and soil strength softening after moisture absorption promote the occurrence of the sliding.

**Funding information** This study was funded by the National Natural Science Foundation of China (No. 41702337 and No. 51579236).

## References

- Abduljawad SN, Hameed RA, Al-Sulaimani GJ, Basunbul IA, Safar MM (1992) Expansive soils in eastern province of Saudi Arabia. In: Proceedings of 7th international conference on expansive soils, Dallas, Texas, pp 426–431
- Ai-Homoud AS, Khoury H, Al-Omari YA (1996) Mineralogical and engineering properties of problematic expansive clayey beds causing landslides. *Bull Int Assoc Eng Geol* 22(1):13–31
- Al-Shamrani MA, Al-Mhaidib AI (1999) Prediction of potential vertical swell of expansive soils using a triaxial stress path cell. *Q J Eng Geol* 32:45–54
- Al-Shamrani MA, Dhowian AW (2003) Experimental study of lateral restraint effects on the potential heave of expansive soils. *Eng Geol* 69(1–2):63–81
- Bao CG (2004) Behavior of unsaturated soil and stability of expansive soil slope. *Chin J Geotech Eng* 26(1):1–15 (in Chinese)
- Basma AA (1991) Estimating uplift of foundations due to expansion: a case history. *Geotech Eng* 22:217–231
- Basma AA, Azm SAH, Abdallah IHM, Mohamed AA (1996) Swelling-shrinkage behavior of natural expansive clays. *Appl Clay Sci* 11(2–4):211–227
- Chen R, Ng CWW (2005) Wetting and anisotropic consolidation behavior of an expansive clay. In: Proceedings of the international symposium on advanced experimental unsaturated soil mechanics. Taylor and Francis Group, UK, pp 157–162
- Cheng ZL, Ding JH, Rao XB, Cheng YH, Xu H (2014) Physical model tests on expansive soil slopes. *Chin J Geotech Eng* 36(4):716–723
- Dafalla MA, Shamrani MA (2012) Expansive soil properties in a semi-arid region. *Res J Environ Earth Sci* 4(11):930–938
- Dakshanamurthy V (1979) A stress-controlled study of swelling characteristics of compacted expansive clays. *Geotech Test J* 2(1):57–60
- Dhowian AW (1981) Characteristics of Al-Ghatt collapsing and swelling soils. Symposium on geotechnical problems in Saudi Arabia, vol 1, 3–32, Riyadh
- Ding JH (2014) Research on failure mechanism of shallow instability of expansive soil slope and geogrid-confined effect on swelling deformation. Ph.D. Thesis, Zhejiang University, Hangzhou, p 97
- Gadre AD, Chandrasekaran VS (1994) Swelling of black cotton soil using centrifuge modeling. *J Geotech Eng* 120:914–919
- He P, Li SC, Xiao J, Zhang QQ, Xu F, Zhang J (2018) Shallow sliding failure prediction model of expansive soil slope based on gaussian process theory and its engineering application. *KSCE J Civ Eng* 22(5):1709–1719
- Houston S, Dye H, Zapata C, Walsh K, Houston W (2011) Study of expansive soils and residential foundations on expansive soils in Arizona. *J Perform Constr Facil* 25(1):31–44
- Huang RQ, Wu LZ (2007) Stability analysis of unsaturated expansive soil slope. *Earth Sci Front* 14(6):129–133 (in Chinese)

- Kong LW, Wang M, Guo AG, Wang Y (2017) Effect of drying environment on engineering properties of an expansive soil and its microstructure. *J Mt Sci* 14(6):1194–1201
- Liao SW (1984) *Expansive soil and railway engineering*. China Railway Publishing Press, Beijing
- Liu TH (1997) *Expansive soil problems in engineering construction*. China Architecture and Building Press, Beijing
- Liu LW, Zheng JL, Miao W (2008) Researches on characteristics of swell and shrinking active zone of expansive soil and failure mechanism of landslides. *Chin J Geotech Eng* 30(1):28–33 (in Chinese)
- Meisina C (2004) Swelling-shrinking properties of weathered clayey soils associated with shallow landslides. *Q J Eng Geol Hydrogeol* 37(2): 77–94
- Mutaz E, Dafalla MA (2014) Chemical analysis and X-ray diffraction assessment of stabilized expansive soils. *Bull Eng Geol Environ* 73(4):1063–1072
- Mutaz E, Al-Shamrani M, Puppala AJ, Dafalla M (2011) Evaluation of chemical stabilization of a highly expansive clayey soil. *Transp Res Board J* 2204:148–157
- Ng CWW, Zhan LT, Bao CG, Fredlund DG, Gong BW (2003) Performance of an unsaturated expansive soil slope subjected to artificial rainfall infiltration. *Géotechnique* 53(2):143–157
- Ruwaih IA (1984) Case studies on swelling soils in Saudi Arabia. In: *Proceedings of 5th international conference on expansive soils*, Adelaide, South Australia, pp 348–353
- Shi B, Jiang HT, Liu ZB, Fang HY (2002) Engineering geological characteristics of expansive soils in China. *Eng Geol* 67(1–2):63–71
- Sivapullaiah PV, Sitharam TG, Subbarao KS (1987) Modified free swell index for clays. *Geotech Test J* 10(2):80–85
- Sridharan A, Rao SM, Sashi S (1990) Classification of expansive soils by sediment volume method. *Geotech Test J* 13(4):375–380
- Tisot JP, Aboushok M (1983) Triaxial study of swelling characteristics. In: *proceedings 7th Asian regional conference on soil mechanics and foundation engineering*, Vol. 1:94–97
- Xeidakis G, Koudoumakis P, Tsirambides A (2004) Road construction on swelling soils: the case of Strymi soils, Rhodope, Thrace, northern Greece. *Bull Eng Geol Environ* 63(2):93–101
- Yilmaz I, Kaynar O (2011) Multiple regression, ANN (RBF, MLP) and ANFIS models for prediction of swell potential of clayey soils. *Expert Syst Appl* 38(5):5958–5966
- Yin ZZ, Xu B (2011) Slope stability of expansive soil under fissure influence. *Chin J Geotech Eng* 33(3):454–459 (in Chinese)
- Yin ZZ, Wei J, Yuan JP, Cao XS (2010) Mechanism of slope slide of expansive soil and reinforcement for the slope. *J Hydraul Eng* 41(1): 1–6 (in Chinese)
- Zhan LT, Ng Charles WW, Fredlund Del G (2007) Field study of rainfall infiltration into a grassed unsaturated expansive soil slope. *Can Geotech J* 44:392–408
- Zhou J, Xu HZ, Hu WJ (2013) Impact of wetting-drying cycle effects on stability of expansive soil slopes. *Chin J Geotech Eng* 35(S2):152–156 (in Chinese)