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THE MECHANISM OF INHIBITING SWELLING DEFORMATION AND SLOPE INSTABILITY OF EXPANSIVE SOILS BY REPLACEMENT METHOD

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Original scientific paper
For expansive soils slope, replacement with non-swelling clay is always the most vital treatment measure. However, there are still many unsolved problems in the replacement method, including how to determine the optimal replacement thickness, and whether there was inhibition effect on slope instability of expansive soils. In this study, a "Stress Path Triaxial Testing System" (GDS) has been applied for exploring triaxial swelling rate. It proposed a triaxial swelling rate model for expansive soils, and this model was secondary developed and embedded in ABAQUS. Different thicknesses of replacement clay have been applied in treating slopes composed by strong, medium and weak expansive soil respectively. Sensitivity analysis also has been carried out with finite element method. For the strong expansive soil slope with natural moisture content 27,5 %, the safety coefficient without clay replacement was 0,73. The safety coefficient was 0,85; 1,08 and 1,33 with the replacement thickness of 1 m, 2 m and 3 m, respectively. The results validated that the replacement method could not only effectively inhibit the swelling of expansive soils, but also correspondingly improve the slope stability. In addition, the different replacement thicknesses could bring varied increasing rate of slope safety coefficient. The increasing rate was nonlinearly changed. Finally, it demonstrated the mechanical mechanism of inhibiting effects from existing replacement method on slope instability of expansive soils. The research results are able to provide theoretical basis for practical engineering. It could be conductive to treating swelling danger from expansive soil slope.

Keywords: *replacement method, slope instability, swelling deformation, triaxial swelling rate model*

Mehanizam za sprečavanje deformacije izdizanja tla i nestabilnosti padina od ekspanzivnih tala metodom zamjene

Izvorni znanstveni članak
Za padine od ekspanzivnih tala, zamjena glinom koja ne nabrekne je uvijek najučinkovitija mjera. Ipak, još uvijek postoje neriješeni problemi u načinu zamjene, uključujući kako odrediti optimalnu debljinu zamjene i da li dolazi do nestabilnosti padina ekspanzivnih tala. U ovom je radu primijenjen "Stress Path Triaxial Testing System" (GDS) za istraživanje troosnog omjera izdizanja. Predložen je troosni model omjera izdizanja za ekspanzivna tla i taj je model razvijen u ABAQUSu. Nanesena je zamjenska glina različite debljine pri ispitivanju padina sastavljenih od čvrstog, srednjeg i slabog ekspanzivnog tla. Provedena je i analiza osjetljivosti primjenom metode konačnih elemenata. Za padinu od čvrstog ekspanzivnog tla s prirodnim sadržajem vlage od 27,5 % faktor sigurnosti bez zamjene glinom bio je 0,73. Faktor sigurnosti bio je 0,85; 1,08 i 1,33 uz odgovarajuću debljinu zamjene od 1 m, 2 m i 3 m. Rezultati su potvrdili da se metodom zamjene može ne samo spriječiti izdizanje ekspanzivnih tala već se može i odgovarajuće poboljšati stabilnost padine. Uz to, različitim debljinama zamjene mogu se postići različiti omjeri povećanja faktora sigurnosti padine. Rastući omjer se nelinearno promijenio. Konačno, pokazan je mehanički mehanizam učinaka smanjenja metodom zamjene na nestabilnost padine od ekspanzivnog tla. Rezultati istraživanja mogu pružiti teoretsku osnovu za praktično inženjerstvo u tretiranju opasnosti od izdizanja kod padina od ekspanzivnog tla.

Ključne riječi: *deformacija izdizanja tla, metoda zamjene, nestabilnost padine, troosni model omjera izdizanja*

1 Introduction

Expansive soils contain minerals such as smectite clays that are capable of absorbing water. When they absorb water, their volumes increase significantly [1]. The change of volume can apply enough force to a building or other structure and make them damage [2]. People have developed many measures to deal with the hazards of expansive soil slope [3 ÷ 7]. Replacement with non-swelling clay has been one of the most vital measures to deal with the expansive soil slope [7].

On the one hand, it could isolate the influences from eternal water, atmospheric humidity variations and so on, these factors would all influence the expansive soil slope; on the other hand, the deformation of expansive soils could be limited by the weight of replacement clay.

However, there are still many unsolved problems, such as how to determine the optimal thickness and whether replacement method could inhibit the failure of expansive soils slope or not. The swelling effect could not be well-reflected by limit equilibrium method. Therefore, the finite element method has been involved in this study. In order to prevent the damages, the swelling pressures should be predicted before the slopes were constructed, so the first premise was to determine the swelling rate model for expansive soils [8]. The swelling strain has been one kind of volume strain [9 ÷ 12]. Thus, the Professional Committee of the expansive soil from International Society for Rock Mechanics (ISRM) has strongly advocated the study of Triaxial Swelling rate Testing [9]. Although some swelling models have been presented [13 ÷ 15], they were either complicated or hard to be used in finite element method.

In our study, the Triaxial Swelling rate Testing has been applied to analyse the samples of expansive soils. Based on these results, it proposed a specific expression of triaxial swelling rate model for expansive soils which could be used in finite element method conveniently. Different thicknesses of replacement clay have been involved in treating with slope of expansive soils. Also the sensitivity analysis of thickness has been carried out. It demonstrated the specific mechanism of inhibiting effects on expansive deformation and slope instability by replacing of clay. The conclusion is able to provide reference for dealing with dangers from expansive soil in projects.

2 The swelling rate testing in state of triaxial stress
2.1 Experiment design

Moisture adsorption testing has been carried out with GDS Stress Path Triaxial Testing System. 1 ÷ 2 kPa water pressure has been applied to the bottom of samples for capillary absorption. To ensure the uniform moisture adsorption, the exhaust pipe has been set on the top of soil samples to discharge the gas in the pores. The specific testing procedure was as follows.

(1) Keep the samples consolidating under hydrostatic pressure, until the change of axial displacement is 0,02 mm/h;

(2) Open the water inflow controller at the bottom of samples, and use the back pressure to fill expansive soil samples;

(3) Let the samples absorbing water adequately, until the change of axial displacement is 0,01 mm/h;

The water inflow has been controlled by GDS advanced digital pressure/volume controller. The accuracy was 0,1 %.

After the moisture adsorption of sample, it generated the volume swelling. The samples were reshaped by the expansive soils collected from Nanyang, He'nan Province, China. The sample size was $d \times H = \varnothing\ 61{,}8 \times 125$ mm. Five testing samples were included in each group. The triaxial swelling rate testing was carried out in the state of three-isobaric stress.

2.2 Results analysis

For the reshaped samples of expansion soils, the swelling rate increments (volume change increments) in final state and moisture content increment in final state varied with hydrostatic pressure. For the medium expansive soil, the initial moisture content is 20,4 %, and the compaction degree is 98 %, with the pressure of 30 kPa, 60 kPa, 100 kPa, 130 kPa and 150 kPa, respectively. The test data is listed in Tab. 1.

Table 1 The relationship between swelling rate increments, moisture swelling rate increments in final state and hydrostatic pressure for remoulding samples of expansive soils

Hydrostatic pressure σ_m / kPa	Moisture content increment / %	Swelling rate increment / %
30	10,13	6,26
60	9,51	3,46
100	7,01	1,01
130	5,90	–0,40
150	5,13	–1,25

Some of the results can be obtained as follows:

(1) With the same initial moisture content and compaction degree, after full moisture adsorption, the resulted swelling rate increments in final state would be decreased with increased hydrostatic pressure. When the hydrostatic pressure was small, swelling rate increments were positive with stronger expansion effects. However, with increased hydrostatic pressure, the sample would remain in the compression state, even under sufficient moisture adsorption;

(2) Under the same initial moisture content and compaction degree, after full moisture adsorption of expansive soil, the resulted moisture content increments in final state would be decreased when the hydrostatic pressure increased. It indicated that, when the hydrostatic pressure reaches a certain level, the moisture adsorption capacity would be correspondingly weakened. It would be difficult to reach a state of full saturation.

3 The swelling rate model in state of triaxial stress

From the results, the relationship between the swelling rate increment in final state and hydrostatic pressure is obtained. The curve of relationship was plotted on semi-logarithmic coordinates (Fig. 1). For the samples with the same initial moisture content and compaction degree, after full moisture adsorption, there was a good linear relationship between the swelling rate increment in final state and the logarithm of hydrostatic pressure.

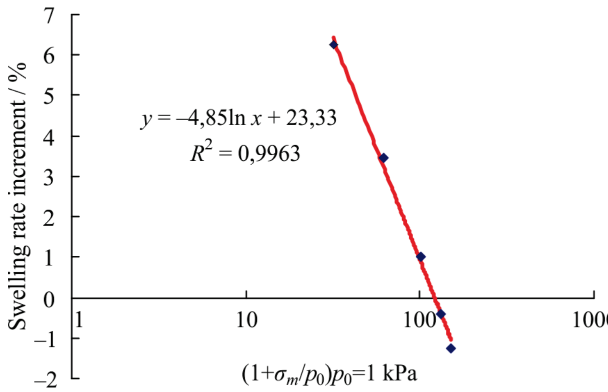


Figure 1 The semi-logarithmic curve of relationship between the swelling rate increment of expansive soil and hydrostatic pressure

Considering the testing results of multiple groups, the swelling rate in state of triaxial stress could be expressed as Eq. (1):

$$\varepsilon_v = a + b\ln\left(1 + \frac{\sigma_m}{p_0}\right), \tag{1}$$

where: ε_v was the volume swelling rate (%) after fully moisture adsorption of expansive soils, σ_m was the hydrostatic pressure (kPa), p_0 was 1 kPa, the parameters a and b were obtained from triaxial swelling rate testing. If the sample was a reshaped sample, a and b would be related to the type of soil, initial moisture content and the compaction degree. If the sample was undisturbed soil sample, a and b would be only related to the type of soil and initial moisture content.

For example, from the experimental results, for the medium expansive soil from Nanyang, with the initial moisture content of 20,4 % and compaction degree of 98 %, in the swelling rate model, $a = 23{,}33$; $b = –4{,}85$.

4 The realization of swelling rate model in finite element method

The triaxial swelling rate model was involved in finite element calculation. Once the Prandtl-Reuss flow-rule is adopted, the strain tensor increment $\{\Delta\varepsilon\}$ becomes:

$$\{\Delta\varepsilon\} = \frac{1}{3}\Delta\varepsilon_v\{I\} + \frac{3\Delta\gamma}{2q}\{S\}, \tag{2} [16]$$

where $\{I\}$ was the unit vector, $\{S\}$ was the deviatoric stress tensor, $\{\Delta\gamma\}$ was the generalized shear strain increment, and q was the generalized shear stress. Because the swelling strain was one kind of volume strain, so the last term of Eq. (2) was omitted. The finite element calculation was carried out using the initial strain method thus to acquire the stress increment. The total displacement and total stress can be further obtained by integrating up to the end of the loading period. In this way this model was embedded in the secondary development of ABAQUS [17 ÷ 19].

5 The mechanism of inhibiting swelling deformation of expansive soil and slope instability by replacement of clay

5.1 Swelling rate model and parameters

During the period 2006 to 2010, a field test of treatment measures for expansive soil canal was carried out in Nanyang, He'nan Province, by the Changjiang River Scientific Research Institute [20]. Considering the canal slope design in field testing, a slope ratio of 1:1,5 was chosen for its poor stability. The slope height was 9 m. It was assumed that the moisture content in 2 m from canal slope surface could fully absorb moisture from natural moisture content. The testing replacement conditions included no clay replacement, replacement clay thickness of 1 m, 2 m and 3 m, with slopes of strong, medium and weak expansive soils. The expansive soil types were judged according to the free swelling rate. The influence from clay replacement on expansive soil slope deformation and stability was calculated, respectively (Fig. 2). In the Figure, the hatched area is assumed as the most unfavorable moisture adsorption range. The natural moisture content was determined in field test.

According to the above triaxial swelling rate testing, the swelling rate model parameters under varied natural moisture content were obtained (Tab. 2). The natural moisture content of strong, medium and weak expansive soils were 27,5 %, 20,4 % and 21,8 %. The compaction degree was 98 %.

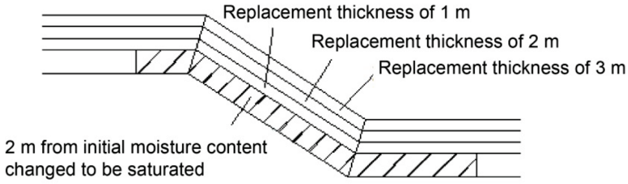


Figure 2 The scheme of treatment with varied thicknesses of replacement clay (Height: 9 m, Slope ratio: 1:1.5)

Saturated strength parameter was determined by Strength parameter. The elastic modulus was determined by secant modulus during the peak strain of soil body. The confining pressure of soil body within 5 m from surface layer was less than 100 kPa. The elastic modulus of soil body could be selected as the secant modulus of stress-strain curve in saturated triaxial CD test, under the confining pressure of 100 kPa. From the testing, the parameters of strength and deformation were obtained (Tab. 3).

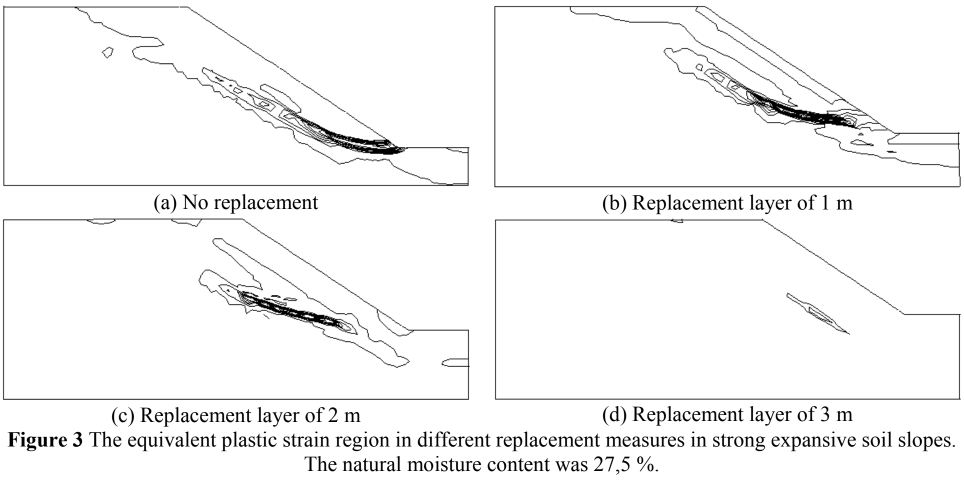
The replacement thickness in the actual engineering was usually 1 ÷ 3 m, but it was hard to determine the optimal replacement thickness. The replacements were carried out for treating strong, medium and weak soil slopes. The results were demonstrated respectively to study the appropriate replacement thickness for treating different types of expansive soil slopes.

Table 2 Parameter *a* and *b* in triaxial swelling rate model

Soil type	Initial moisture content / %	Compaction degree / %	*a*	*b*
Weak expansive soil	21,8	98	4,67	–0,87
Medium expansive soil	20,4	98	23,33	–4,85
Strong expansive soil	27,5	98	29,10	–5,77

Table 3 The parameters of strength and deformation

Soil type	Density / g/cm^3	Saturated triaxial CD		Elastic modulus	Poisson's ratio
		C / kPa	Φ / °	MPa	
Replacement clay	2,00	30,0	23,0	4,00	0,3
Weak expansive soil	2,02	21,9	27,0	5,25	0,3
Medium expansive soil	2,00	43,8	28,0	4,85	0,3
Strong expansive soil	1,90	35,7	13,2	3,50	0,3



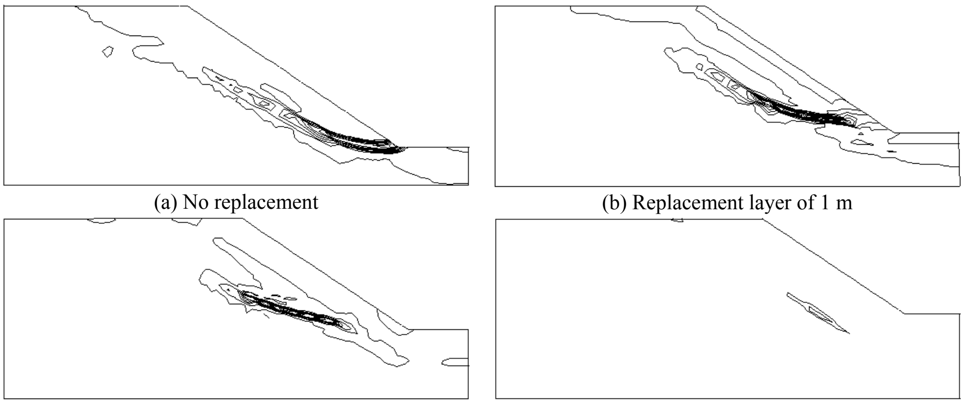
(a) No replacement (b) Replacement layer of 1 m

(c) Replacement layer of 2 m (d) Replacement layer of 3 m

Figure 3 The equivalent plastic strain region in different replacement measures in strong expansive soil slopes. The natural moisture content was 27,5 %.

5.2 The influence of replacement thickness on the equivalent plastic strain region

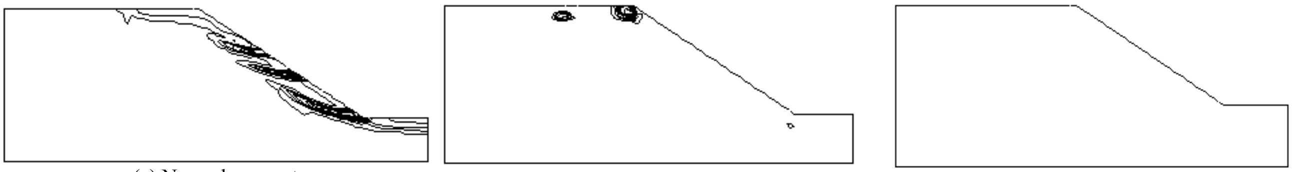
For the 2 m moisture adsorption range, after full moisture adsorption from natural moisture content, the equivalent plastic strain regions were observed in the replacement measures in strong, medium and weak expansive soil slopes (Figs. 3 ÷ 5). From the results we could see, for the strong expansive soil slope in natural state, small plastic zone could be observed with replacement layer of 3 m. For the medium expansive soil slope in natural state, no plastic zone could be found with replacement layer of 2 m. However, for the weak expansive soil slope, no plastic zone existed with replacement layer of 1 m, so the replacement layer of 1 m was sufficient under this condition.



(a) No replacement (b) Replacement layer of 1 m

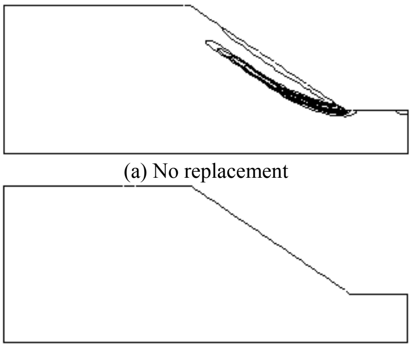
(c) Replacement layer of 2 m (d) Replacement layer of 3 m

Figure 3 The equivalent plastic strain region in different replacement measures in strong expansive soil slopes. The natural moisture content was 27,5 %.



(a) No replacement (b) Replacement layer of 1 m (c) Replacement layer of 2 m

Figure 4 The equivalent plastic strain region in different replacement measures in medium expansive soil slopes. The natural moisture content was 20,4 %



(a) No replacement

(b) Replacement layer of 1 m

Figure 5 The equivalent plastic strain region in different replacement measures in weak expansive soil slopes. The natural moisture content was 21,8 %.

5.3 The influence of replacement thickness on the slope displacement

Under the natural moisture content, for the strong, medium and weak expansive soils, the normal displacement (uplift) curves of slopes were different (Figs. 6 ÷ 8). With the increased replacement layer, the normal displacement of slope gradually decreased. For strong expansive soil, the normal displacement of slope was 7,0 cm with the replacement layer of 3 m. For medium expansive soil, the normal displacement of slope was about 6,5 cm with the replacement layer of 2 m. For weak expansive soil, the normal displacement of slope was about 2,5 cm with the replacement layer of 1 m.

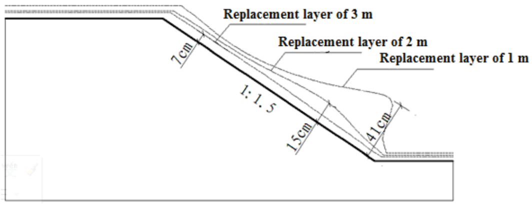


Figure 6 The normal displacement of slope with strong expansive soil, the natural moisture content was 27,5 %.

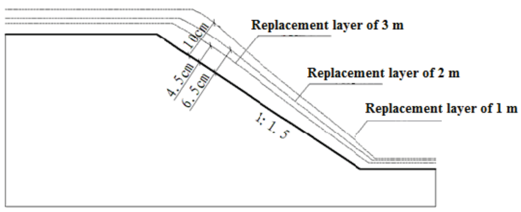


Figure 7 The normal displacement of slope with medium expansive soil, the natural moisture content was 20,4 %.

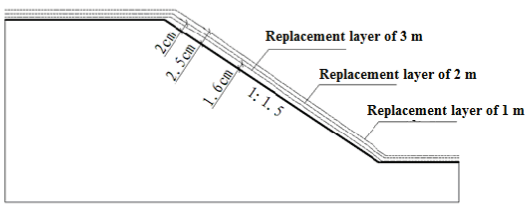


Figure 8 The normal displacement of slope with weak expansive soil, the natural moisture content was 21,8 %.

5.4 The influence of replacement thickness on the slope stress

In order to observe the stress clearly, local coordinate system was established (Fig. 9). The stress results of strong expansive soils were listed as follows. The tension stress symbol is positive, and the pressure stress symbol is negative.

(1) The X direction stress σ_x (Fig. 10).

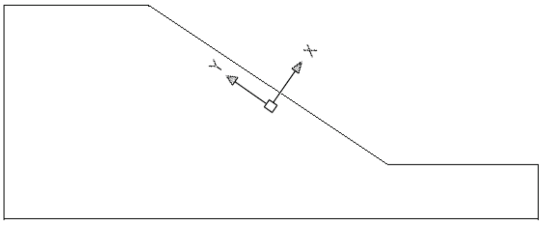
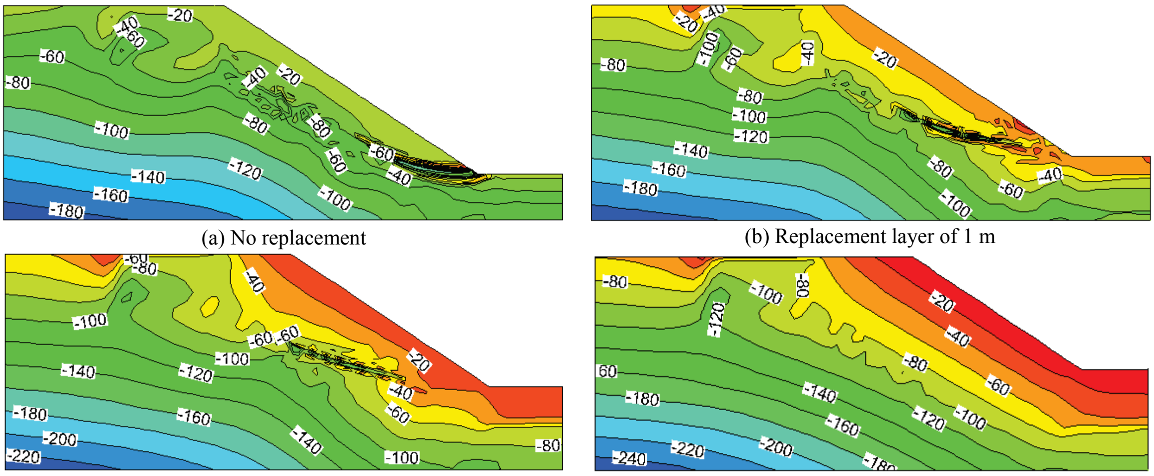


Figure 9 The local coordinate system



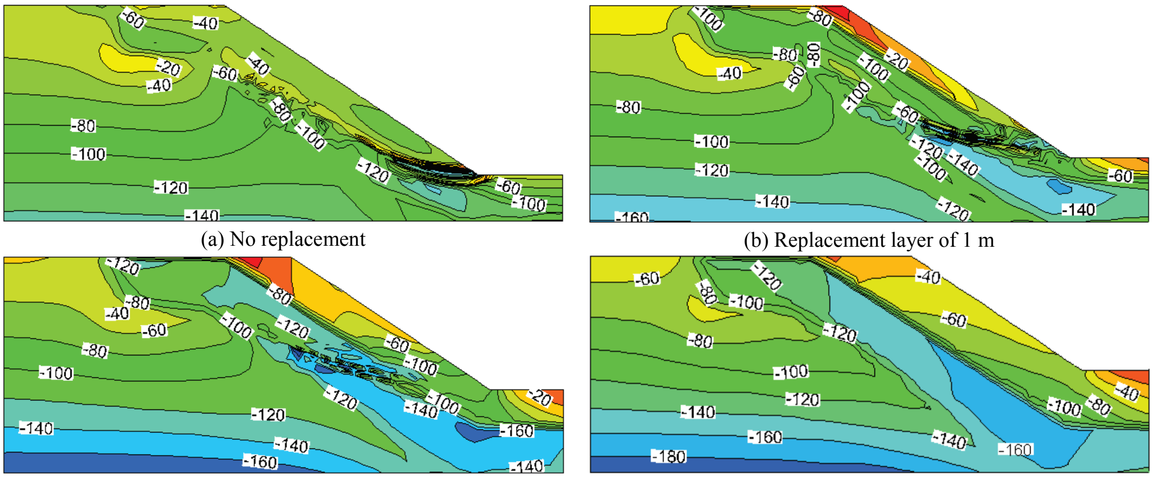
(a) No replacement (b) Replacement layer of 1 m

(c) Replacement layer of 2 m (d) Replacement layer of 3 m

Figure 10 The X direction stress σ_x in different replacement measures in strong expansive soil slopes (kPa)

After full moisture adsorption from natural moisture content, the X direction stress σ_x was observed in the strong expansive soil slopes (Fig. 10). From the results we could see, σ_x was basically self weight stress distribution, but the weight of replacement clay could significantly increase the σ_x in the protected soil body. According to the Eq. (1), the greater the hydrostatic pressure is, the smaller the expansibility is, so the swelling potential of protected soil body under different thickness of replacement clay is different.

(2) The Y direction stress σ_y (Fig. 11).



(a) No replacement (b) Replacement layer of 1 m

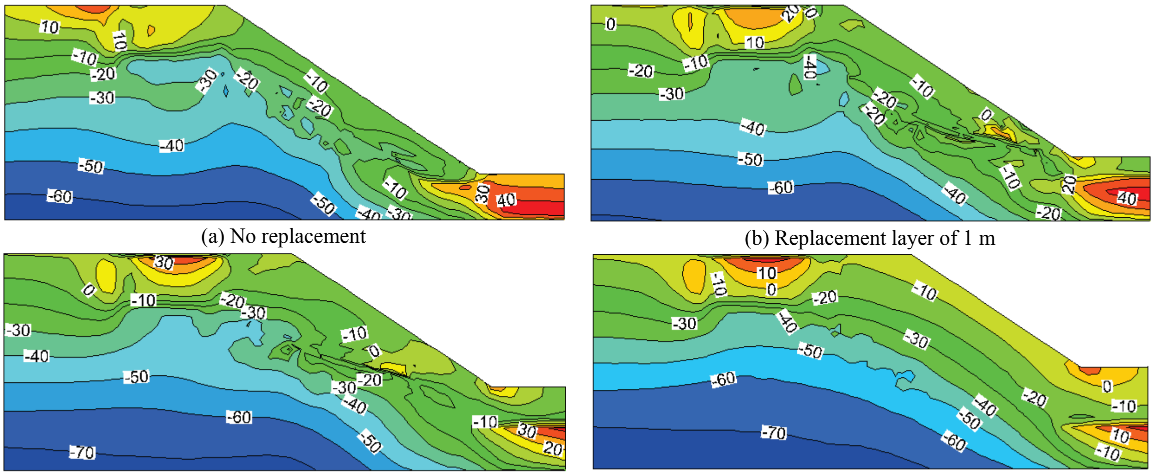
(c) Replacement layer of 2 m (d) Replacement layer of 3 m

Figure 11 The Y direction stress σ_y in different replacement measures in strong expansive soil slopes (kPa)

After full moisture adsorption from natural moisture content, the Y direction stress σ_y was observed in the strong expansive soil slopes (Fig. 11). From the results we could see, the σ_y was changed most significantly in the protected soil body. With the water content gradually changing, the σ_y of the protected soil body was increased heavily, thus the shear stress τ_{xy} was increasing. When the shear stress was more than its shear strength, the contour line with high stress concentration was formed, which showed that the swelling process would obviously cause the slope stress redistribution.

(3) The shear stress τ_{xy} (Fig. 12).

After full moisture adsorption from natural moisture content, the shear stress τ_{xy} was observed in the strong expansive soil slopes (Fig. 12). From the results we could see, the expansibility of slope with replacement layer of 3 m was very weak. Even if the swelling potential had been given to full play, the maximum shear stress had not exceeded the shear strength, thus no shear band was formed.



(a) No replacement (b) Replacement layer of 1 m

(c) Replacement layer of 2 m (d) Replacement layer of 3 m

Figure 12 The shear stress τ_{xy} in different replacement measures in strong expansive soil slopes (kPa)

5.5 The mechanism of inhibiting effects on expansive soil instability from different replacement thickness

For the treatment measures with different replacement thickness, the stability analysis has been calculated. The calculation has involved "the analysis method of expansive soil slope stability with the consideration of expansibility" proposed by Prof. Zhan-lin Cheng in the Changjiang River Scientific Research Institute [20]. The stability safety coefficient of canal slope in each measure has been calculated (Tab. 4). The stability safety coefficient of strong expansive soil canal slope without considering the expansibility has also been calculated (Tab. 5). However when the expansibility was omitted, the stability safety coefficient was almost the same, that was clearly wrong.

In the results, the finite element considering expansibility could truly reflect the influence of expansion effects on canal slope stability. The safety coefficient of slope would increase with improved replacement thickness.

Table 4 The stability safety coefficient of canal slope in different replacement thickness

Conditions	Natural moisture content / %	No replacement	Replacement layer of 1 m	Replacement layer of 2 m	Replacement layer of 3 m
Weak expansive soil	21,8	1,09	1,37	1,64	1,84
Medium expansive soil	20,4	0,88	1,20	1,70	1,83
Strong expansive soil	27,5	0,73	0,85	1,08	1,33

Table 5 The stability safety coefficient of canal slope without considering the expansibility

Conditions	Natural moisture content / %	No replacement	Replacement layer of 1 m	Replacement layer of 2 m	Replacement layer of 3 m
Strong expansive soil	27,5	2,00	1,98	1,97	1,96

For the strong expansive soil slope, when the natural moisture content was 27,5 %, the safety coefficient without clay replacement was 0,73. It was 0,85 with the replacement thickness of 1 m, the increment of safety coefficient was relatively small. The safety coefficient was 1,08 and 1,33 with the replacement thickness of 2 m and 3 m, respectively. It indicated that the replacement clay would bring increased safety coefficient, however, the increase increment was nonlinearly changed with the replacement thickness. In the same region, when the moisture content changed from initial moisture content to saturated state, the thicker replacement layer significantly enhanced the stability of expansive soil slope.

The specific reason has been demonstrated. The hydrostatic pressure in protected soil body has been increased by the weight of replacement clay. From the formula of swelling rate model we can see that the expansibility of soil body was not only related to the initial moisture content, but also to the suffered hydrostatic pressure. Larger hydrostatic pressure could result in smaller swelling. Thus, even if the 2 m moisture adsorption range from the bottom was completely saturated, under the gravity of different replacement thickness, the expansibility at the bottom could also be varied. When the replacement thickness was thicker, the inhibition of swelling would be greater with increasing stability.

6 Conclusions

The mechanism of influences from replacement thickness on expansive soil slopes has been investigated for deformation and stability. The following conclusions could be explored:

(1) It validated that the replacement treatment could effectively inhibit the swelling deformation of expansive soils. In addition, the stability of expansive soil slopes could be correspondingly increased. The replacement clay would bring increased safety coefficient, however, the increase increment was nonlinearly changed with the replacement thickness;

(2) It demonstrated that the mechanical mechanism of inhibition effect from replacement method on swelling

instability of expansive soil slope. The expansibility of soil body was not only related to the moisture content, but also to the suffered hydrostatic pressure. Higher hydrostatic pressure would result in smaller expansibility. Thicker replacement layer would result in greater inhibition effects to the expansibility. Thus, the safety coefficient would be improved.

(3) It proved that the replacement method could effectively inhibit the slope instability caused by swelling deformation. The swelling rate model and relevant parameters could be obtained from triaxial swelling rate testing. In addition, the most unfavourable conditions could be calculated with finite element. Finally, cost-optimal replacement thickness could be determined by integrating the calculation results from deformation and stability.

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