Secondary development of a thermo-elastoplastic constitutive model for saturated clay in ABAQUS

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Abstract. Some projects, such as application of energy piles, underground storage of nuclear waste, geothermal development and laying of heat pipes, are necessary to consider the effect of temperature on the mechanical properties of clay. Test results have shown that clay may show two different phenomena: the shear strength of soil increases (thermal hardening) or decreases (thermal softening) with an increase in temperature. In order to describe these two different thermo-mechanical behaviors of clay, a new thermal elastoplastic constitutive model of saturated clay, in which the influence of temperature on pre-consolidation pressure and critical state parameter \( M \) of clay are taken into considerations, is proposed based on sub-loading modified Cam-clay model. The secondary development of the new model on ABAQUS was completed by preparation of the UMAT material subroutine. Through comparing the theoretical results with test results, it is known that the proposed constitutive model is capable of describing the thermal hardening and thermal softening behavior of clay well. And the correctness of the proposed constitutive model was verified. Finally, based on the proposed model, the generating mechanism of the thermal hardening and thermal softening behavior of clay are discussed macroscopically in terms of the influence degree of temperature on pre-consolidation pressure and critical state parameters.

1. Introduction

With the development and utilization of energy piles, geothermal resources, and the laying of thermal pipelines [1-4], the study of the influence of temperature on the mechanical properties of soil has become one of the important issues in geotechnical engineering.

At present, a large number of studies on the thermal characteristics of soil have been carried out at home and abroad, and fruitful results have been achieved. Campanella and Mitchell [5] proposed that the pre-consolidation pressure decreases with the increase of temperature, but the compressibility index and elastic compressibility index of soil are not affected by temperature. Hueckel [6] pointed out that the effect of temperature on the critical state parameter \( M \) and internal friction angle of saturated soil cannot be ignored. Furthermore, the numerical study of the effect of Hueckel [7] on the thermodynamic response of saturated soil shows that although the increment of internal friction caused by the increase of temperature is very moderate (the critical state parameter \( M \) is less than 20%), it has a significant effect on the effective stress path near the heat source. At the same time, the experimental results show that the effect of temperature on the shear strength of soil can show two opposite characteristics: with the increase of temperature, the peak shear strength of soil increases (thermal hardening) and the shear strength of soil decreases (thermal softening). Cekerevac & Laloui [8] carried out triaxial tests on clay with different over-consolidation ratios, and found that compared with 22°C,
when the temperature of the soil sample increased to 90℃, the shear strength increased accordingly, that is, thermal hardening occurred. Ghahremannejad [9] and Tran [10] reported similar experimental results. However, Uchaipichat [11] and Hueckel & Baldi [12] obtained the opposite conclusion by comparing the triaxial shear test results of soil samples at different temperatures, and This phenomenon is thermal softening.

At the same time, based on the test results, a large number of thermal-elastoplastic constitutive models of soil have been proposed. Based on the modified Cam-clay model, Cui [13] proposed a model which can better reflect the effect of temperature on the volume change of saturated clay. Based on the boundary model, Laloui [14] introduced the nonlinear thermoelastic relationship, and constructed the ACMEG-T model through two thermoplastic process mechanisms, which can well describe the volume change of soil during the heating process. Based on the UH model, Yao [15] considered the loading yield line (LY), and obtained the formula of the critical state parameters of saturated soil at different temperatures based on the method of over-consolidated soil potential strength, so as to establish a UH model which can consider the effect of temperature. Based on the concept of temperature equivalent stress, Zhang [16] introduced it into the sub-loading yield surface modified Cam-clay model, so that the new model can better reflect the thermal softening characteristics of geotechnical materials caused by temperature.

As we all know, the constitutive relation is one of the key factors that determine the correctness and reliability of numerical calculation. Therefore, in order to describe the thermal softening and thermal hardening of over-consolidated saturated clay macroscopically, based on the sub-loading yield surface modified Cam-clay model, considering the effect of temperature on the pre-consolidation pressure and critical state parameter $M$ of over-consolidated saturated clay, a constitutive model which can uniformly describe the different thermodynamic properties of over-consolidated saturated clay is established. Through the comparative analysis with the laboratory experimental results, it is verified that the model proposed in this paper can better reflect the two different mechanical properties of clay: thermal hardening and thermal softening at the same time.

2. Elastoplastic constitutive model considering temperature effect

2.1. Temperature equivalent stress

In the indoor test, when the mean principal stress $\sigma_m$ remains unchanged, when the temperature rises from the reference temperature $T_0$ to the target temperature $T$, the geotechnical materials will produce elastic volumetric strain $\Delta \varepsilon_v^{\text{eq}}$. When the temperature is maintained at the reference temperature $T_0$, the mean principal stress $\sigma_m$ increases and the elastic volumetric strain $\Delta \varepsilon_v^{\text{eq}}$ also occurs. When $\Delta \varepsilon_v^{\text{eq}}$ and $\Delta \varepsilon_v^{\text{eq}}$ are equal, it is considered that the effect of the temperature increment $\Delta T$ on the elastic volumetric strain of the geotechnical material is consistent with the effect of the mean principal stress increment $\Delta \sigma_m$, As shown in Figure 1.

![Figure 1. Schematic map of temperature equivalent stress](image-url)
2.2. Influence of temperature on critical state parameters

In critical soil mechanics, the critical state parameter is used to represent the strength of soil. The greater the strength of the soil due to a higher value of the parameter $M$. Many scholars have carried out numbers of studies on the influence of temperature on the shear strength of soil through temperature-controlled triaxial test instruments. Further study found that temperature will affect the critical state parameters $M$. As shown in Figure 2.

![Figure 2. Effect of temperature on critical state parameter $M$](image)

In this paper, adopt a simple linear expression which proposed by Hueckel [7], to describe the influence of temperature on the critical state parameter $M$.

\[
M = M_0 + g(T - T_0) / T_0
\]

In the second item divided by reference temperature to eliminate dimensions. $M$ and $M_0$ are the critical state parameters at target temperature $T$ and reference temperature $T_0$, respectively. $g$ is the control parameters of critical state development, when $g$ is positive, it indicates that the critical state parameters $M$ of soil will increase after heating.

2.3. Elastoplastic constitutive model considering temperature effect

The modified Cam-clay model has fewer parameters and clear physical meaning. It is widely used in numerical calculations in geotechnical engineering, but it cannot describe the mechanical properties of over-consolidated soils well. In order to reflect the mechanical properties of over-consolidated soils, many scholars have proposed some constitutive models, among which the most representative ones are the boundary surface model [19] and the sub-loading modified [20]. In this paper, the influence of temperature on soil parameters is considered based on the modified Cam-clay model on the lower load surface. The new model can describe two different mechanical properties of over-consolidated saturated clay after heating.

In the sub-loading modified, the current stress state of the over-consolidated soil is always located on the yield surface of the underload and changes with the current stress, as shown in Figure 3(a). Under normal temperature, the expression of the yield function of the sub-loading modified Cam-Clay model is

\[
f_s = \ln \frac{p}{p_0} + \ln \left( \frac{q^2}{M_s^2 p^2} + 1 \right) - \frac{1}{C_p} \left( \varepsilon_v^p - \frac{\rho - \rho_0}{1 + e_0} \right) = 0
\]

Where $C_p = (\lambda - \kappa)/(1 + e_0)$, $\lambda$ is a constant compressibility index of the soil, $p$ is mean principal stress, $q$ is deviatoric stress, $p_0$ is reference mean principal stress, $\varepsilon_v^p$ is plastic volumetric strain and $\rho$ is difference of void ratio between normal and over-consolidation states, used to represent the over-consolidation state of soil. As shown in Figure 3(b), the relationship between $\rho$ and OCR can be expressed as follows.
\[ \rho = (\lambda - \kappa) \ln \text{OCR} \]  

where OCR = \( p_c/p_i \), \( p_c \) and \( p_i \) are the intersection point of the sub-loading yield surface and normal consolidation yield surface with \( p \) axis, respectively.

\[ p_c = p_{c0} \exp \left( \frac{3\alpha_r (T - T_0)(1 + e_0)}{\kappa} \right) \]  

where \( p_{c0} \) is pre-consolidation pressure at reference temperature.

Many experimental results show that when the temperature rises from the reference temperature \( T_0 \) to the target temperature \( T \), the pre-consolidation pressure \( p_c \) will decrease \([8,21]\), as shown in Figure 4. The pre-consolidation pressure determines the yield surface size of soil in the elastoplastic constitutive model. The decrease of its value will cause the shrinkage of the yield surface of the model, which will affect the stress-strain relationship of the soil. Therefore, this paper will introduce the concept of temperature equivalent stress to reflect the influence of temperature on pre-consolidation pressure, to describe the thermal behavior of temperature on saturated clay. Similar to the temperature equivalent stress from (3), the expression of pre-consolidation pressure at different temperatures is

\[ p_c = p_{c0} \exp \left( \frac{3\alpha_r (T - T_0)(1 + e_0)}{\kappa} \right) \]  

Based on equation (4), Figure 5 shows the curve of the pre-consolidation pressure \( p_c \) during the heating process under different linear thermal expansion coefficient \( \alpha_r \) and the elastic compressibility \( \kappa \). Figure 5(a) and Figure 5(b) show that when the linear thermal expansion coefficient increases or the elastic compressibility \( \kappa \) is smaller, the pre-consolidation pressure decays faster.

![Figure 3. Schematic diagram of the sub-loading concept of over-consolidation remolded soil](image)

![Figure 4. Effect of temperature on the pre-consolidation pressure](image)
Thus, the initial over-consolidation ratio of soil after heating can be obtained from

\[ OCR_T = \frac{p_\alpha}{p_c} = \frac{p_c}{p_c} \exp\left(\frac{3\alpha_T (T - T_c)(1 + e_0)}{\kappa}\right) / p_i \]  

(5)

Based on the pre-consolidation pressure \( p_c \) and the critical state parameter \( M \) are affected by temperature, the yield surface of the sub-loading yield surface modified Cam-clay model can be expressed as

\[ f_T = \ln \frac{p}{p_0} + \ln \left(\frac{q^2}{M^2 p_T^2 + 1}\right) - \frac{1}{C_p} \left( e_v^p - \frac{\rho_T}{1 + e_0} \right) = 0 \]  

(6)

where \( \rho_T = (\lambda - \kappa) \ln OCR_T, M = M_0 + g(T - T_c) / T_0 \).

This paper uses the associative flow rule to determine plastic flow direction, so the increment of plastic strain can be expressed as

\[ de_v^p = A \frac{\partial f_T}{\partial e_v^p} \]  

\[ de_p^p = A \frac{\partial f_T}{\partial e_p^p} \]  

(7)

where \( A \) is plastic factor, \( A \geq 0 \).

The plasticity factor \( A \) can be obtained from the overall consistency condition

\[ df_T = \frac{\partial f_T}{\partial \sigma_y} d\sigma_y + \frac{\partial f_T}{\partial e_v^p} de_v^p + \frac{\partial f_T}{\partial M} dM + \frac{\partial f_T}{\partial \rho_T} d\rho_T = 0 \]  

(8)

To expand (8) further, then we can obtain the following result

\[ df_T = \frac{\partial f_T}{\partial \sigma_y} d\sigma_y - \frac{1}{C_p} A \frac{\partial f_T}{\partial e_v^p} - \frac{g}{M T_0} \frac{2q^2}{q^2 + M^2 p^2} dT + \frac{1}{C_p} \frac{d\rho_T}{1 + e_0} = 0 \]  

(9)

In order to obtain the plasticity factor \( A \) and calculate the plastic strain increment, the development equation of \( \rho_T \) must be given. This paper is based on the relational equation proposed...
by Nakai [22], and takes into account the influence of temperature on the dissipation rate of over-consolidation ratio, the expression is as follows

$$-\frac{1}{1+e_0}d\rho_r = \frac{a\rho_r^2}{\bar{p}}A$$

where \( \bar{p} = p\exp\left(3\alpha_T(1+e_0)(T-T_0)\right) \).

Combining equations (9) and (10), we can obtain the plasticity factor \( A \)

$$A = \frac{\frac{\partial f_T}{\partial \sigma_y} d\sigma_y - \frac{g}{MT_e} q^2 + M^2 p^2 dT}{1 + \left(\frac{\frac{\partial f_T}{\partial \sigma_y} + a\rho_r^2}{\bar{p}}\right)}$$

Based on Hooke's Law, the stress increment can be expressed as

$$d\sigma_y = E_{ijkl}(d\varepsilon_{ij} - d\varepsilon_{ij}^p)$$

$$E_{ijkl} = E(\delta_{ij} + \delta_{kl} + \delta_{il} + \delta_{jk})$$

$$\Gamma = \frac{\nu E}{(1+\nu)(1-2\nu)}G = \frac{E}{2(1+\nu)}$$

where, the shear modulus \( G \) is corrected by the expression proposed by Likitlersuang [23].

$$G = sf(e)p_p \left(\frac{p}{p_a}\right)^n$$

Where \( p_a \) is atmospheric pressure, usually 100 kPa, \( n \) and \( s \) are material parameters. According to reference [23], The value ranges of \( s \) and \( n \) are between 10 to 10\(^3\) and 0 to 1, respectively. \( f(e) \) is a function of void ratio, the \( f(e) \) takes the form of

$$f(e) = \frac{(2.973 - e)^2}{1+e}$$

The loading and unloading criterion of the constitutive model is

$$\begin{cases} \text{load: } \left\|d\varepsilon_y^p\right\| > 0, \quad \left\{\begin{array}{l} A > 0, \frac{\partial f_T}{\partial \sigma_y} d\sigma_y > 0 \quad \text{hardening} \vspace{0.5em} \rule{0pt}{1.5em} A > 0, \frac{\partial f_T}{\partial \sigma_y} d\sigma_y < 0 \quad \text{softening} \end{array}\right. \\
\text{unload: } \left\|d\varepsilon_y^p\right\| = 0, \quad A \leq 0 \end{cases}$$

In this paper, considering the influence of temperature on the pre-consolidation pressure \( p_c \) and the critical state parameter \( M \) of clay, develop of a new constitutive model to describe the thermal behavior of soil on the sub-loading yield surface modified Cam-clay model. The new model preserves all the parameters of the original model, and adds four parameters, namely the linear elastic thermal expansion coefficient \( \alpha_T \), the critical state development control parameter \( M \), and the material parameters \( s \) and \( n \) used to correct the shear modulus. The meaning of model parameters is shown in Table 1.
Table 1. Physical meaning of model parameters

| Model parameter | Physical meaning                      |
|-----------------|--------------------------------------|
| $\nu$           | Poisson's ratio                      |
| $\kappa$        | Elastic compressibility               |
| $e_0$           | Void ratio under reference stress    |
| $\alpha_T$      | Linear elastic thermal expansion coef.|
| $R_f$           | Critical stress ratio                |
| $\lambda$       | Compressibility index of the soil    |
| $g$             | Control parameters of critical state development |
| $a$             | Control parameters of over-consolidation development |
| $s$             | Material parameters of shear modulus 1 |
| $n$             | Material parameters of shear modulus 2 |

3. Secondary development and validation of the model

ABAQUS is a common commercial finite element software. Based on the above theoretical derivation. The UMAT subroutine of the new model is written by Fortran language to make the secondary development in ABAQUS. In order to verify the correctness of the program, the triaxial shear test of soil is simulated and compared with the theoretical value of the model. And simulation and comparison the triaxial tests of soil under different temperature conditions to verify whether the proposed constitutive model can describe the mechanical properties of thermal hardening and thermal softening of soil.

3.1. Verification of UAMT subroutine

The main function of UMAT material subroutine is to input model parameters and state variables such as stress, strain increment and temperature. The UMAT material subroutine will calculation of stress increment by stress integration, and give the elastic-plastic Constitutive of the next strain increment. Therefore, the stress integration method plays an important role in the accuracy of the calculated results. This paper uses the modified Euler method introduced by Potts [24]. The preparation of material subroutines has been reported in many references [25-27], so this paper does not introduce them in detail.

The process of simulated triaxial shear test is as follows: (1) Establish a cube model. (2) Give the soil model parameters (as shown in table 2). (3) Component assembly and analysis step setting, simulation adopt automatic increase step. (4) Setting the initial conditions. The bottom of the soil sample was fixed, the initial effective stress was 100 kPa, and the initial temperature fields were set as the reference temperatures of 20°C, 40°C and 60°C. (5) Grid division. triaxial shear test is simply regarded as unit experiment, so only one unit is needed. (6) Calculation and post-processing.

Table 2. Material parameters of some examples

| $\nu$ | $R = \sigma_1 / \sigma_3$ | $\lambda$ | $\kappa$ | $e_0$ | $s$ | $n$ | $g$ | $\alpha / ^{\circ}C^{-1}$ | $a$ |
|-------|-----------------|--------|--------|------|----|----|----|------------------|----|
| 0.30  | 3.0             | 0.1    | 0.02   | 0.9  | 500| 0.6| 0.5| -1.0x10^{-5}     | 500|

Figure 6 is the comparison between the theoretical value of triaxial shear test at different temperatures and the results calculated by ABAQUS. Its show that the theoretical value and the simulation result have a high degree of consistency, indicating that the UMAT subroutine is correct. Next, the temperature-controlled triaxial experimental calculation model will be established in ABAQUS to verify the effectiveness of the proposed model.
3.2. Thermal softening verification of saturated clay

Uchaipichat \cite{11} carried out triaxial drainage shear tests of Bourke clay at different temperatures. The experiment first performed isotropic compression and unloading at 25°C to make the over-consolidation ratio of the soil sample reach the target value (OCR = 1.33, 2.0 and 4.0). Then keep constant confining pressure, and heating samples to 40°C and 60°C under drained conditions, and then conduct shear test.

The parameters used in the model calculation are listed in Table 3. The method of determining the parameters can refer to the literature \cite{22}. According to the experimental results, we can obtain the value of parameters \( \lambda, \kappa, e_0, \nu, R_f, \) and \( g \). As shown in Figure 7(a), the experimental data of pre-consolidation pressure changing with temperature are simulated, and then we can obtain \( \alpha_c = -6.0 \times 10^{-8} \). Other parameters can be determined by comparison with experimental data. Figure 7(b) is the \( e - \log p \) curve at different temperatures. The \( e - \log p \) curve gradually shifts downward with the increase of temperature. The theoretical simulation results can better describe the thermal characteristics of soil. Figure 7(c)~(e) is the comparison of triaxial shear test results and theoretical simulation results under different temperatures and OCR conditions. The results show that the shear strength of the soil tends to decrease with the increase in temperature, and this phenomenon is called thermal softening. As the degree of over-consolidation increases, the volumetric strain of the soil sample will change from shear shrinkage to dilatancy, and the temperature will affect the dilatancy characteristics. Through the comparison of simulation and test results, it can be seen that based on the same set of parameters, the finite element calculation results are agreement with the experimental results under different working conditions. Verified the effectiveness of the model.
Figure 7. Comparison results of test and calculation at different temperatures and cell pressures (test data from Uchaipichat [11])

Table 3. Material parameters of Bourke Silt

| ν    | R = σ₀/σ₃ | λ   | κ   | ε₀   | s  | n  | g   | αₜ/°C⁻¹ | a   |
|------|------------|-----|-----|------|----|----|-----|---------|-----|
| 0.30 | 3.0        | 0.09| 0.006| 0.635| 900| 0.9| 0   | -6.0×10⁻⁶ | 2500 |

3.3. Verification of thermal hardening of saturated clay

Laloui [8] used kaolin to conduct a temperature-controlled triaxial drainage shear test to study the effect of temperature on the shear strength of clay. In order to ensure that the sample is in a saturated state during the experiment, a constant back pressure of 100 kPa is applied to the sample. At the same time, in order to ensure that the test does not produce excessive pore water pressure during the heating process, the soil is slowly heated at a heating rate of 10°C every 3 hours. The samples were subjected to shear tests at 22°C and 90°C, respectively.

The calculation parameters of the model are listed in Table 4. The value of parameters λ, κ, ε₀, ν, Rₛ and g are determined based on the test results, while the remaining parameters are determined by simulation and comparison of the shear test results. Figure 8 shows the comparison between the kaolin temperature control triaxial test and the finite element simulation results. The experimental results show that the shear strength of saturated soil samples with different over-consolidation ratios increases after heating, resulting in thermal hardening. And, from the figure, using the same set of parameters, this model can better predict the drainage triaxial stress-strain characteristics of soil samples with different over-consolidation ratios at different temperatures.
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\( \sigma = 200 \text{ kPa}, \quad \text{OCR} = 3.0 \)

\( \sigma = 100 \text{ kPa}, \quad \text{OCR} = 6.0 \)

\( \sigma = 50 \text{ kPa}, \quad \text{OCR} = 12.0 \)

Figure 8. Comparison results of triaxial drain test and calculation of Kaolin at different temperature (test data from Laloui [8])

| Material parameters of Kaolin | \( \nu \) | \( \frac{R_f}{\sigma_1} \) | \( \lambda \) | \( \kappa \) | \( e_0 \) | \( s \) | \( n \) | \( g \) | \( \alpha_T/\text{C}^{-1} \) | \( a \) |
|-----------------------------|---------|-----------------|--------|--------|------|----|----|-----|-----------------|-----|
|                             | 0.30    | 2.1             | 0.104  | 0.045  | 0.93 | 450| 0.5| 0.02 | -2.0 \times 10^6 | 120 |

4. The occurrence conditions of thermal hardening and softening

Through the comparison of the above experimental and calculated results, it is found that the model proposed in this paper can well describe the opposite thermal characteristics of thermal softening and thermal hardening of saturated clay. This section will further explore the conditions of thermal hardening and thermal softening of clay based on the new model. In the new constitutive model, the parameter \( g \) controls the change of \( M \) value during the heating process of clay. The higher the \( g \) value, the greater the critical state parameter value of the soil after heating. Under the framework of critical soil mechanics, when the other parameters are constant, the larger the \( M \) value is, the higher the shear strength of clay is. On the other hand, based on the model, it is known that the change of linear thermal expansion coefficient \( \alpha_T \) will have a great influence on the change of pre-consolidation pressure caused by temperature. When the value of \( \alpha_T \) increases, the attenuation of pre-consolidation pressure caused by temperature will accelerate (see figure 5a), resulting in the shrinkage of the yield surface of the soil, thus making the clay show a lower shear strength.

Figure 9 shows the stress-strain curves of four examples, of which example 1 is the result at the reference temperature of 20°C and the rest is the result at 60°C. In the four examples, only the critical state development control parameter \( g \) or the linear thermal expansion coefficient \( \alpha_T \) is changed, and the other model parameters are the same. The example 1 is the calculation result at the reference
temperature, $p_c$ and $M$ will not be affected by temperature, so it can be regarded as a reference object for the strength change of clay after increasing temperature. By comparing examples 1, 2 and 3, it is found that the shear strength of examples 2 and 3 increases with the increase of temperature, that is, the clay has thermal hardening, and the shear strength will further increase when the value of $\alpha_T$ decreases. Compared with example 1 and 4, the $g$ value of example 4 is lower than that of example 2, and the clay shows thermal softening after heating. The reason is that the value of $g$ and $\alpha_T$ from example 2 to 4 is not 0, and the clay is affected by the temperature on the pre-consolidation pressure and the critical state parameter $M$ at the same time. Therefore, the final performance of clay is thermal hardening or thermal softening depends on the specific gravity of the influence of temperature on the pre-consolidation pressure and the critical state parameter $M$. If the pre-consolidation pressure is more affected by temperature, thermal softening will occur, otherwise it will be thermal hardening.

![Figure 9. Four examples of stress-strain theoretical curve](image)

5. Conclusion

(1). Considering the effect of temperature on pre-consolidation pressure $p_c$ and critical state parameter $M$, and based on the sub-loading yield surface modified Cam-clay model, a constitutive model which can uniformly reflect the thermal hardening and thermal softening characteristics of saturated clay with different over-consolidation ratio is established. Based on the sub-loading yield surface modified Cam-clay model, the new model adds four parameters, namely, the critical state development control parameter $g$ of the linear thermal expansion coefficient $\alpha_T$, and two material parameters $s$ and $n$ which control the shear modulus.

(2). The constitutive model is written as a UMAT subroutine, and the secondary development of ABAQUS is completed, and the triaxial shear experiments at different temperatures are simulated. The results are compared with the theoretical values, and the subroutine is verified to be correct.

(3). The finite element simulation results can well reproduce the temperature-controlled triaxial experimental results of saturated clay by Uchaipichat [11] and Laloui [8], which shows that the proposed model can uniformly describe the two different mechanical properties of thermal softening and thermal hardening.

(4). Based on the proposed model, the causes of thermal hardening or thermal softening of saturated clay are explored. When the clay is heated, if the pre-consolidation pressure is more affected by temperature, the soil shows the phenomenon of thermal softening; on the contrary, it may show thermal hardening.
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