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A 1D model considering the combined effect of strain-rate and temperature for soft soil

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Abstract. Strain-rate and temperature have significant effects on the one-dimensional (1D) compression behavior of soils. This paper focuses on the bonding degradation effect of soil structure on the time and temperature dependent behavior of soft structured clay. The strain-rate and temperature dependency of preconsolidation pressure are investigated in double logarithm plane and a thermal viscoplastic model considering the combined effect of strain-rate and temperature is developed to describe the mechanical behavior of unstructured clay. By incorporating the bonding degradation, the model is extended that can be suitable for structured clay. The extended model is used to simulate CRS (Constant Rate of Strain) tests conducted on structural Berthierville clay with different strain-rates and temperatures. The comparisons between predicted and experimental results show that the extended model can reasonably describe the effect of bonding degradation on the stain-rate and temperature dependent behavior of soft structural clay under 1D condition. Although the model is proposed for 1D analysis, it can be a good base for developing a more general 3D model.

Keywords: structured clay; strain-rate; bonding degradation; temperature; viscoplasticity

1. Introduction

Natural soft clays are subjected to action of heat under many different circumstances, for instance, the nuclear waste isolation, heat energy storage, geothermal development, etc. The compressibility of soft clays will be changed accordingly. A variety of oedometer tests have been conducted to study the effect of temperature on soft clays (Bai and Shi 2017, Tsutsumi and Tanaka 2012, Abuel-Naga *et al.* 2007, Marques *et al.* 2004, Sultan *et al.* 2002, Boudali *et al.* 1994). Based on the experiments, the first conceptional model for the temperature dependency of clay was proposed by Campanella and Mitchell (1968). After that, several constitutive models that describe the influence of temperature on the mechanical behavior have been proposed in the literature (Yashima *et al.* 1998, Laloui *et al.* 2008, Laloui and Cekerevac 2003, Abuel-Naga *et al.* 2007).

Besides, the compressibility of soft clays is also largely dependent on the strain-rate. After studying 1D compression behavior of soft clays on a variety of tests, Leroueil et al. (1985) concluded that the behavior is controlled by a unique effective stress-strain-strain rate relationship. The relationship between the preconsolidation pressure (the maximum effective vertical overburden stress that a particular soil sample has sustained in the past) and strain-rate can be functioned by some expressions (Laloui *et al.* 2008, Leroueil *et al.* 1985, Graham *et al.* 1983, Karstunen and Yin 2010, Yin *et al.* 2010, 2011). Based on that, some viscoplastic models have been developed (Chen *et al.* 2014, Yao *et al.*, 2013, Yin and Wang 2012, Yin *et al.* 2015, 2017). These models usually are based on Perzyna's overstress theory.

As studied above, several models have been proposed to describe the influence of strain rate and temperature separately on the mechanical behavior. However, few of them can capture the combined effect of strain-rate and temperature on the compression behavior at 1D condition of soft clay. Furthermore, inter-particle bonds are usually existing in soft clays referred as soil structure which refers to the arrangement of soil particles (Mitchell and Soga, 2005). Temperature-controlled oedometer tests (Ng *et al*. 2018) and triaxial tests (Hueckel *et al*. 1998) on saturated clays with variable structures gave different stress-strain behaviors. The experimental results also indicate that a significant progressive loss of bond will be happened during straining induced by the mechanical and/or thermal loads. The large differences observed between the compression curves for intact and reconstituted samples are caused by the bonding degradation, as experimented by many researches (Yin *et al*. 2011, Zhu *et al*. 2017). Thus, the combined effect of strain-rate and temperature on the mechanical behavior of soft structured clay should also take into account of bonding degradation.

In this paper, we focus on the 1D behavior which can bring fundamental features for more general mechanical behavior. From the practical point of view, the 1D condition is also the case for some embankments, airports, etc. Firstly, a 1D model for unstructured clay is developed based on the combined effect of strain rate and temperature on the

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preconsolidation pressure. Then, the effect of bonding degradation of soil structure on the compression behavior of soft clay at a varying strain rates and temperatures are investigated. The bonding degradation of structure is incorporated into the strain-rate and thermal based model. Finally, the calibration of the model parameters is discussed and simulations are carried out on CRS tests for Berthierville clay (Boudali *et al*. 1994).

2. Strain-rate and temperature dependency of the preconsolidation pressure

2.1 Strain-rate dependency of the preconsolidation pressure

The mechanical behavior of soft clay is strain-rate dependency. In one-dimensional condition, the strain rate-dependency of the preconsolidation pressure (σ'_p) has been attracted much attentions since last decade. CRS test results show that larger loading rate can result in larger preconsolidation pressure (Leroueil *et al.* 1983, 1985, 1988; Rangeard 2002; Yin *et al.* 2017). Fig. 1 plots log(σ'_p/σ'_{v0}) against log($\dot{\varepsilon}_v$) for clays reported in literature (the preconsolidation pressure normalized by in situ vertical stress versus vertical strain rate). It can be seen that the relationship between log σ'_p/σ'_{v0}) and log($\dot{\varepsilon}_v$) is essentially linear for each clay. Thus, the effect of strain-rate on σ'_p can be represented by parameter β, which can be estimated from the slope of the best-fit line from the data points. Thereby, the preconsolidation pressure σ'_p corresponding to $\dot{\varepsilon}_v$ can be obtained by

$$\frac{\sigma'_p}{\sigma'^r_p} = \left(\frac{\dot{\varepsilon}_v}{\dot{\varepsilon}^r_v}\right)^{1/\beta} \tag{1}$$

where σ'^r_p is the reference preconsolidation pressure corresponding to reference strain rate $\dot{\varepsilon}^r_v$.

2.2 Temperature dependency of the preconsolidation pressure

The influence of temperature on preconsolidation pressure have been studied by oedometer tests and isotropic compression tests with constant strain-rate and variable temperatures. All of the experimental results show that the preconsolidation pressure will decrease with an elevated temperature (Boudali *et al.* 1994, Tanaka 1995, Eiksson 1989, Moritz 1995, Marques *et al.* 2004, Abuel-Naga *et al.* 2007). Fig. 2 presents the normalized preconsolidation pressure with temperature. The regression analyses indicate that it is also reasonable to assume a linear relationship between log(σ'_p/σ''_p) and log(T/T^r), firstly proposed by Moritz (1995). Thus, the relationship between the preconsolidation pressure and temperature can be fitted by the following equation

$$\frac{\sigma'_p}{\sigma'^r_p} = \left(\frac{T}{T^r}\right)^{\theta} \tag{2}$$

where θ is a thermal parameter; σ'_p and σ'^r_p are the preconsolidation pressures at temperature T and the

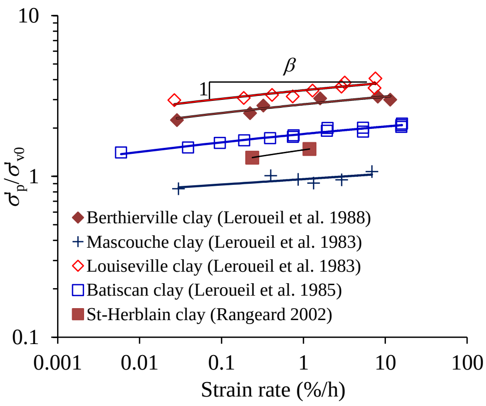


Fig. 1 Effect of strain-rate on the preconsolidation pressure at the same temperature for each clay

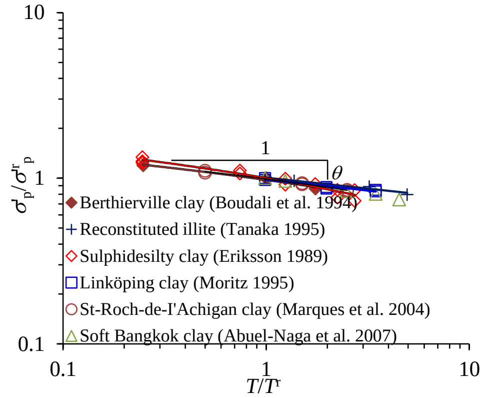


Fig. 2 Effect of temperature on the preconsolidation pressure at the same strain-rate for each clay

reference temperature T^r, respectively.

2.3 Combined effect of strain-rate and temperature on the preconsolidation pressure

As indicated above, the preconsolidation pressure is associating with strain-rate and temperature and can be written as a function of strain rate and temperature. Furthermore, the experiments considering the coupling effect of strain rate and temperature (Boudali *et al.* 1994, Marques 2004, Jarad *et al.* 2017) show that β is essentially independent of temperature and, θ is independent of strain rate. Thus, the preconsolidation pressure can be written as follows

$$\sigma'_p = f_1(\dot{\varepsilon}_v) f_2(T) \tag{3}$$

Considering Eqs. (1)-(2), the evolution of the preconsolidation pressure with respect to strain rate and temperature can be expressed as

$$\sigma'_{p,T} = \sigma'^r_{p,T^r} \left(\frac{\dot{\varepsilon}_v}{\dot{\varepsilon}^r_v}\right)^{1/\beta} \left(\frac{T}{T^r}\right)^{\theta} \tag{4}$$

where $\sigma'_{p,T}$ is the preconsolidation pressure corresponding to the test conducted with strain-rate $\dot{\varepsilon}_v$ and at temperature T; σ'^r_{p,T^r} is the preconsolidation pressure corresponding to the reference strain rate $\dot{\varepsilon}^r_v$ and temperature T^r.

3. Elasto-thermal-viscoplastic (ETVP) model for unstructured clay

3.1 Modeling assumptions

The constitutive model is developed based on the following assumptions, which appear to be reasonable from the available literature.

a) The compression and recompression coefficients (i.e., λ and κ) are independent of temperature. Increase and decrease in temperature may produce changes in the bonding of clay particles and the viscocity of absorbed water. These changes alternately produce more or less changes in compressibility. The experiments conducted by (Campanella and Mitchell 1968, Tsutsumi and Tanaka 2012, Jarad *et al.* 2017) show that the variations of λ and κ with temperature are negligible.

b) The volumetric strain during drained heating under overconsolidated conditions is neglected. It is well-established in the literature that overconsolidated soils tend to expand during drained heating. Considering that the strain under a constant effective stress remains small (Coccia and McCartney 2016, Cekerevac and Laloui 2004, Abuel-Naga *et al.* 2007), and the emphasis of this paper, the initial void ratio e_0 will remains constant when clays suffering a change of temperature in overconsolidation range.

3.2 Proposed ETVP model for unstructured clay

According to the experimental observations, the temperature induced volumetric change of normal consolidation soils can be considered independent of stress level in 1D condition. Following the conventional elasto-viscoplastic approach, the total strain rate contains two parts: the elastic and viscoplastic strains rate

$$\dot{\varepsilon}_{v,T} = \dot{\varepsilon}^{e}_{v,T} + \dot{\varepsilon}^{vp}_{v,T} \tag{5}$$

where $\dot{\varepsilon}_{v,T}$ denotes the combined effect corresponding to strain rate $\dot{\varepsilon}_{v}$ and temperature T. The superscripts e and vp represent elastic and viscoplastic components, respectively. The elastic strain rate is expressed as

$$\dot{\varepsilon}^{e}_{v,T} = \frac{\kappa}{1+e_0}\frac{\dot{\sigma}'_{v,T}}{\sigma'_{v,T}} \tag{6}$$

where e_0 is the initial void ratio, $\sigma'_{v,T}$ is the effective vertical stress at temperature T, and κ is the slope of recompression lines in e-log σ'_v space. .

Similarly, the viscoplastic strain rate can be derived from the ε_v-ln(σ'_v) curve at $\dot{\varepsilon}_{v,T}$ and expressed as

$$\dot{\varepsilon}^{vp}_{v,T} = \frac{\lambda-\kappa}{1+e_0}\frac{\dot{\sigma}'_{v,T}}{\sigma'_{v,T}} \tag{7}$$

where λ is the slope of compression lines in e-logσ'_v space (Fig. 3). Then, combing Eqs. (5)-(7), the total strain rate could be rewritten as

$$\dot{\varepsilon}^{vp}_{v,T} = \frac{\lambda-\kappa}{1+e_0}\frac{\dot{\sigma}'_{v,T}}{\sigma'_{v,T}} \tag{8}$$

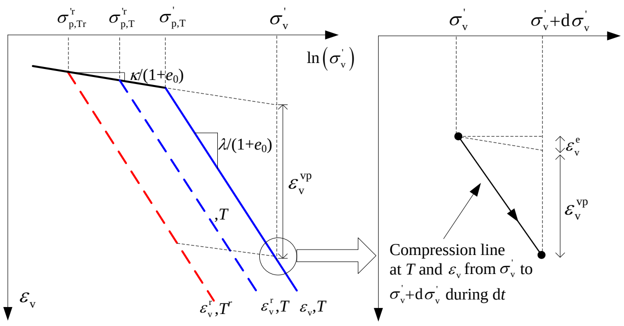


Fig. 3 Principle of the strain-rate and temperature based model

Substituting Eq. (8) into Eq. (1), the viscoplastic strain rate can be rewritten as

$$\dot{\varepsilon}^{vp}_{v,T} = \dot{\varepsilon}^{r}_{v,T}\frac{\lambda-\kappa}{\lambda}\left(\frac{\sigma'_{p,T}}{\sigma'^{r}_{p,T}}\right)^{\beta} \tag{9}$$

where $\sigma'_{p,T}$ and $\sigma'^{r}_{p,T}$ are the preconsolidation pressures corresponding to $\dot{\varepsilon}_{v,T}$ and $\dot{\varepsilon}^{r}_{v,T}$, respectively. $\dot{\varepsilon}^{r}_{v,T}$ denotes test conducting at the reference strain rate $\dot{\varepsilon}^{r}_{v}$ and temperature T. Along the compression line corresponding to the strain rate $\dot{\varepsilon}_{v,T}$ (Fig. 3), the current vertical stress $\sigma'_{v,T}$ at an accumulated viscoplastic strain $\varepsilon^{vp}_{v,T}$ can be derived as

$$\sigma'_{v,T} = \sigma'_{p,T}\exp\left(\frac{1+e_0}{\lambda-\kappa}\varepsilon^{vp}_{v,T}\right) \tag{10}$$

Taking the tests experimented at temperature T^r as the reference, $\sigma'^{r}_{p,T}$ in Eq.(9) can be expressed as

$$\sigma'^{r}_{p,T} = \sigma'^{r}_{p,T^r}\left(\frac{T}{T^r}\right)^{\theta} \tag{11}$$

where σ'^{r}_{p,T^r} denotes the preconsolidation pressure corresponding to corresponding to $\dot{\varepsilon}^{r}_{v,T^r}$ which denotes reference strain rate $\dot{\varepsilon}^{r}_{v}$ and reference temperature T^r (Fig. 3). Substituting Eqs. (10)-(11) into Eq. (9), the viscoplastic strain rate at T is expressed as

$$\dot{\varepsilon}^{vp}_{v,T} = \dot{\varepsilon}^{r}_{v,T^r}\frac{\lambda-\kappa}{\lambda}\left(\frac{\sigma'_{v,T}}{\sigma'^{r}_{p,T^r}\left(\frac{T}{T^r}\right)^{\theta}\exp\left(\frac{1+e_0}{\lambda-\kappa}\varepsilon^{vp}_{v,T}\right)}\right)^{\beta} \tag{12}$$

Thus, eight model parameters (e_0, λ, κ, β, θ, T^r, $\dot{\varepsilon}^{r}_{v,T^r}$, σ'^{r}_{p,T^r}) are required for the model and all the parameters can be determined straightforwardly from the temperature controlled CRS test.

3.3 Simulated one-dimensional behaviour

In order to validate the proposed ETVP model, numerical simulations for assumed CRS tests were performed at two temperatures (T = 20°C and 60°C) and two strain rates ($\dot{\varepsilon}_{v,T}$ = 1.07×10^{-5}/s and 1.07×10^{-8}/s). The results are plotted in Fig. 4 and the parameters adopted for the simulations are listed in the plot. The simulated temperature and strain-rate dependent behavior agrees with the common experimental phenomena on unstructured clay, as expected by the model's principle. For example, the

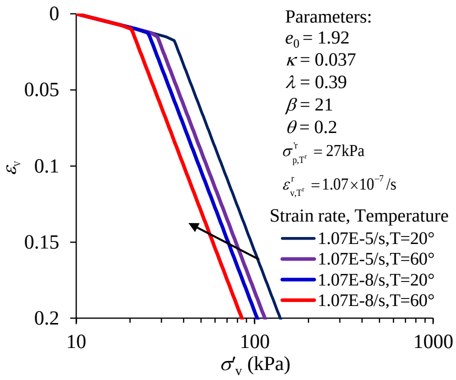
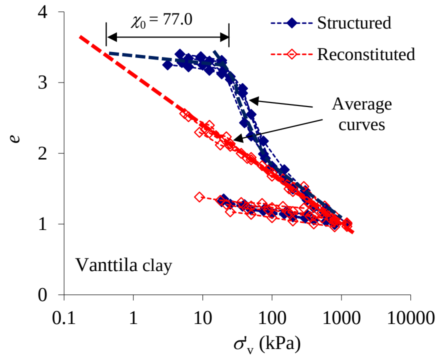
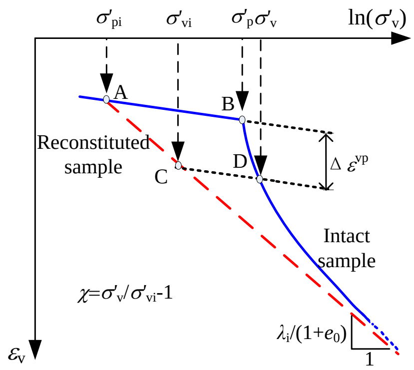


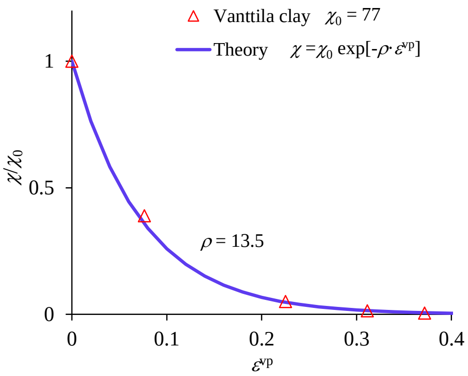
Fig. 4 Simulations for CRS tests at different strain rates and temperatures



(a) Compression curves for structured and unstructured Vanttila clay



(b) Illustration of the bonding degradation with viscoplastic strain



(c) Evolution of bonding ratio with viscoplastic strain

Fig. 5 Bonding effect on the compressibility and the evolution of bonding ratio

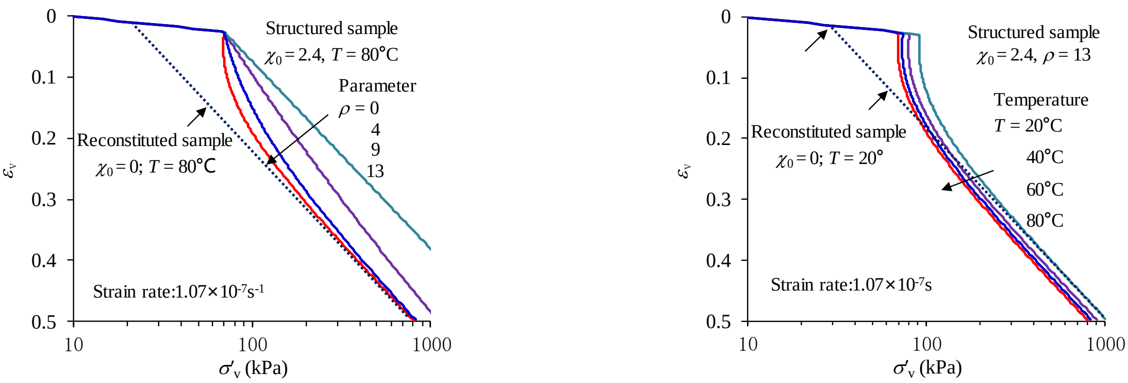
simulated relationship between the preconsolidation pressure and temperature corresponds to input value of θ. Certainly, the simulated relationship between the preconsolidation pressure and strain-rate coincides with the input β.

4. ETVP model for structured clay

4.1 Bonding effect

During oedometer tests, the difference of compression curves obtained on structured and reconstituted clay are caused by bonding degradation as shown in Fig. 5(a) for Vanttila clay. The structures between soil particles for structured clay will be eliminated gradually during straining. Tests under different temperatures also show that temperature doesn't change the shape of the compression curves, for instance, tests on intact Berthierville clay (Boudali *et al.* 1994) and Linköping clay (Moritz 1995). Thus, we assume that the process of bonding degradation is in independent of temperature and only relate to the strain level. Fig. 5(b) shows the schematic plot of the stress-strain curve at a constant strain rate and arbitrary temperature T for soft structured clay. For a given viscoplastic strain level ε_v^{vp}, the bond degradation results in the current stress σ'_v reaching point D.

Corresponding to the same viscoplastic strain, we define an intrinsic stress σ'_{vi}, which is the stress for the reconstituted sample at the same strain rate and



(a) Compression curves obtained with temperature T = 80°C and different values of ρ varying from 0 to 13

(b) Simulated curves obtained with ρ = 13 and different temperatures from 20°C to 80°C

Fig. 6 Simulations for CRS tests considering bonding degradation

temperature. We assume that the different between the current stress and intrinsic stress in due to the existing of the soil structure. Thus, a bonding ratio $\chi = \sigma'_v/\sigma'_{vi} - 1$ is proposed. The current stress σ'_v during straining can be expressed by

$$\sigma'_v = (1+\chi)\sigma'_{vi} \tag{13}$$

Initially, the bonding ratio $\chi = \chi_0 = \sigma'_p/\sigma'_{pi} - 1$, with σ'_p.and σ'_{pi} denoting the preconsolidation pressures of intact and reconstituted samples. Following with the increasing of strain, the bonds are broken gradually and χ decreases from its initial value χ_0 ultimately towards zero when the bonds are completely destroyed as present in Fig. 5a. Substituting Eq. (2) into Eq. (13), we can find that bonding ratio χ is a temperature independent parameter following with the assumptions of this study. According to definition, bonding ratio and the corresponding viscoplastic strain are measured during compression and plotted in Fig. 5c for Vanttila clay. Based on the results, we propose the following the relationship to express the attenuation of bonding ratio

$$\chi = \chi_0 e^{-\rho\varepsilon^{vp}_{v,T}} \tag{14}$$

where the parameter ρ controls the rate of bonding degradation (ρ = 13.5 for Vanttila clay in Fig. 5c). As stated above that bonding ratio is independent with temperature, a constant ρ is adopted here. Actually, the intrinsic stress σ'_{vi} in Eq. (13) can be regarded as the reference stress as indicated in Eq. (1) and the bonding ratio can be regarded as scaling parameter. Thus, to take account the influence of soil structure, Eq. (12) is extended as

$$\dot{\varepsilon}^{vp}_{v,T} = \dot{\varepsilon}^{r}_{v,T^r}\frac{\lambda_i-\kappa}{\lambda_i}\times \left(\frac{\sigma'_{v,T}}{\sigma'^{r}_{p,T^r}(1+\chi_0 e^{-\rho\varepsilon^{vp}_{v,T}})(\frac{T}{T^r})^{\theta}\exp(\frac{1+e_0}{\lambda_i-\kappa}\varepsilon^{vp}_{v,T})}\right)^{\beta} \tag{15}$$

Considering that λ is used in Eq. (12), to avoid confusion, λ_i is adopted here which denotes the slope of the intrinsic normal compression line in the e-ln(σ'_v) plane for a reconstituted sample. Combining with the elastic strain rate in Eq.(6), the stress-strain curve for a given strain rate and temperature can be obtained. We used the same parameters within the previous case for Fig. 4, and assign parameters χ_0 =2.4. Fig. 6(a) plots the curves obtained with temperature T = 80°C and different values of ρ varying from 0 to 13. Fig. 6b shows the curves obtained with ρ=13 and different temperatures from 20°C to 80°C. The two figures represent the combined effect of strain-rate and temperature on the compression behavior of soft structured clay considering bonding degradation. Two additional parameters χ_0 and ρ are required comparing with the model for reconstituted clay, and can be measured from oedometer tests.

4.2 Model parameters

The present model combined strain-rate and temperature involves a number of parameters which can be divided into four groups.

a) Parameters related to compressibility: initial void ratio (e_0), the intrinsic slope of the compression line (λ_i), the slope of the recompression line (κ), and the reference preconsolidation pressure (σ'^{r}_{p,T^r}) at reference strain rate $\dot{\varepsilon}^{r}_{v}$ and reference temperature T^r. The values of λ_i and κ can be measured from oedometer tests on reconstituted and intact samples, respectively. σ'^{r}_{p,T^r} can be obtained at the intersection of compression curves for reconstituted and intact samples, as shown in Fig. 5(b). Due to the thermal expansion is neglected in this paper, e_0 can be measured initially at the reference temperature condition.

b) Parameter related to bonding degradation: the initial bonding ratio χ_0 and the parameter ρ. The value of χ_0 can be measured from oedometer tests on intact and reconstituted sample conducted at the same temperature and strain rate. It needs to point out that for the parameter χ_0, high quality intact sample are required. The parameter ρ representing the bonding degradation rate can be derived from Eqs. (13)-(14)

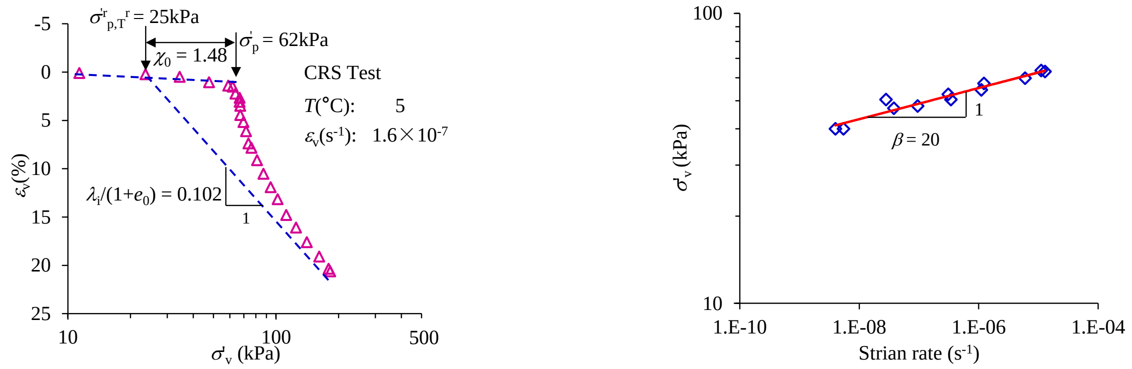
$$\rho = -\ln\{\frac{1}{\chi_0}[\frac{\sigma'_v}{\sigma'_{vi}} - 1]\}\frac{1}{\varepsilon^{vp}_{v,T}} \tag{16}$$

where ε^{vp}_{v} is the volumetric viscoplastic strain corresponding to the current stress σ'_v (see Fig. 5(b)) at arbitrary temperature. Thus, the parameter ρ can be

Table 1 Values of model parameters and state variables for Berthierville clay

Clay	e_0	λ_i	κ	σ'^{r}_{p,T^r} (kPa)	$\dot{\varepsilon}^r_v$ (s^{-1})	β	T^r (°)	θ	χ_0	ρ
Berthierville[a)]	1.7	0.275	0.019	25	1.6×10^{-7}	20	5	0.14	1.5	15
Berthierville[b)]	1.7	0.65	0.019	25	1.6×10^{-7}	20	5	0.14	1.5	0

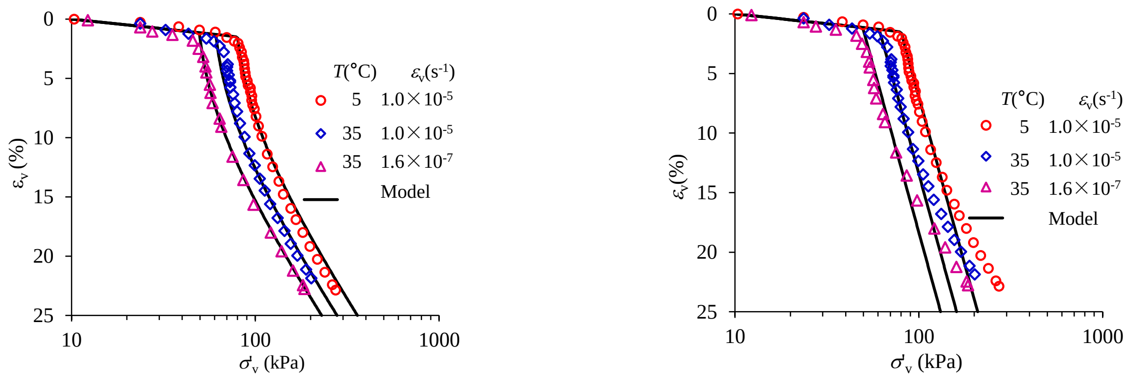
Note: a) Considering bonding degradation; b) no considering bonding degradation



(a) CRS test at a constant strain-rate and 5°C

(b) Determination of parameter β

Fig. 7 Determination of parameters from CRS tests



(a) Predictions considering bonding degradation

(b) Predictions with ρ=0

Fig. 8 Comparison between experimental and predicted results

calculated by selecting a post-yield point on the compression curve.

c) Parameters related to strain rate: reference strain-rate ($\dot{\varepsilon}^r_v$) and strain-rate parameter (β) corresponding to σ'^{r}_{p,T^r}. β can be measured directly from CRS oedometer tests on reconstituted or intact samples at different strain rate. Qu *et al.* (2010) investigated multi-rates laboratory tests on clays and given that β varies approximately from 10 to 50. As studied in previous section, β is constant during the bonding degradation process.

d) Parameters related to temperature: reference temperature (T^r) and thermal parameter (θ) corresponding to σ'^{r}_{p,T^r}. θ can also be obtained directly from CRS compression curves on reconstituted or intact samples at different temperature. Wang *et al.* (2016) investigated the value of θ for seven clays and summarized that the θ varies from 0.125 to 0194. Furthermore, θ can be obtained by empirical correlation of liquid limit (w_L) expressed as

$$\theta = 0.1072 + 0.0008 w_L \tag{17}$$

Thus, θ can also be obtained by correlating without carrying out temperature-controlled tests.Furthermore, all parameters can also be identified by the optimization-based inverse approach only using the conventional laboratory temperature-controlled tests (Jin *et al.* 2017a, b, 2018 and Yin *et al.* 2017, 2018), such as the oedometer test and triaxial test.

5. Experimental validation

In order to evaluate the model ability to reproduce the behavior of soft structured clay, simulations were performed for CRS tests. The predicted results were compared with that experimentally observed from intact Berthierville clay.

Boudali (1995) presented a set of 1D CRS tests on Berthierville clay with different strain-rates and temperatures. The clay properties are as follows: water content w = 63%, plastic limit w_p = 22%, liquid limit w_L = 45%, and the average e_0 =1.7. CRS tests were performed by displacement and temperature control corresponding to

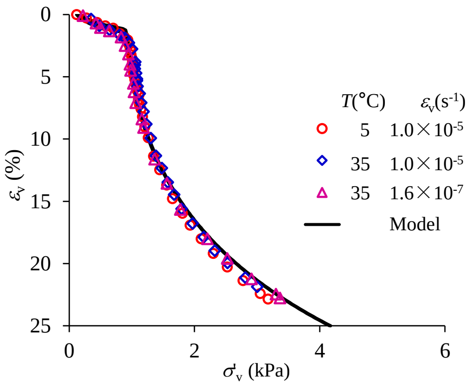


Fig. 9 The unique vertical effective stress- strain-train rate-temperature relationship

strain rate from 1.0×10-5 s^{-1} to 1.6×10-7 s^{-1} and temperature from 5°C to 35°C. The CRS oedometer test selected to calibrate the parameter is shown in Fig. 7(a), conducted at 5°C and 1.6×10-7 s^{-1}. The reference preconsolidation pressure σ'^{r}_{p,T^r}= 62 kPa can be measured. The parameter λ_i = 0.275 is determined at a strain level 20% since there is no data available on reconstituted clay. The parameter κ= 0.019 is measured from the slope of compression line before yield stress. The value ρ=15 was calculated by selecting a stress strain point in Fig. 7(a) and adopting Eq. (16). The rate-dependency parameter β was measured by plotting the preconsolidation pressure versus strain-rate of intact samples as shown in Fig. 7(b) (Leroueil *et al.* 1988). The temperature dependent parameter θ=0.14 can be approximately calculated by Eq.(17) with w_L. All the values of parameters are summarized in Table 1. The second set of parameters do not consider bonding degradation (by setting ρ=0). The value of λ=0.66 was measured from the compression curve of intact clay corresponding to a vertical strain range of 3%-9% as shown in Fig. 7(a).

Fig. 8 shows the comparison between experimental and predicted results. The predictions with bonding degradation show good agreement with the experimental results for the shape of the compression curves conducted at different strain rates and temperatures (Fig. 8(a)). On the other hand, the predictions with ρ=0 do not fit well the compression curves (Fig. 8(b)). Thus, it can be concluded that it is necessary to account for the bonding degradation for modelling the combined effect of strain-rate and temperature for soft structured clay.

6. Discussion

Leroueil *et al.* (1985) found that the 1D compression behavior is controlled by a unique vertical effective stress - vertical strain - vertical strain rate (σ'_v-ε_v-$\dot{\varepsilon}_v$) relationship. That is, when the vertical effective stress in normalized with respect to the preconsolidation pressure associated with the current strain rate, the compression results fall on a unique curve. Fig. 9 reproduced the experimental and simulated compression curves in Fig. 8a conducted at different strain rates and temperatures by normalizing with the associating preconsolidation pressure. The normalized compression results also fall on a unique curve. Thus, the proposed model combining with strain-rate and temperature allows for complete determination of the σ'_v-ε_v-$\dot{\varepsilon}_v$ -T relationship for soft structured clay.

7. Conclusions

The strain-rate and temperature dependent behavior of soft structured clay has been investigated based on experimental observations from CRS tests. Considering the influence of bonding degradation on the compressibility, a strain rate and temperature combined model has been developed. The determination of model parameters is straightforward. Numerical simulations have been conducted to examine the predictive ability of the model for soft structured clay.

Experimental verification has been carried out for CRS test on Berthierville clay at different strain-rates and temperatures. The bonding degradation effect has been highlighted by comparing predictions with and without considering bonding degradation. The comparisons between predicted and measured results demonstrate that the proposed model can well reproduce the strain rate and temperature dependent behavior of soft structure clay under one dimensional loading condition. Future work will be done to extend the proposed model into three dimensional general stress space.

Acknowledgments

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