Overview and Interpretation of Rate-Dependency of the Behaviour of Soft Clays

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ABSTRACT: Extensive laboratory tests and field observations show that soft clays exhibit significant rate-dependent behavior. The rate-dependency of stress-strain behavior under both 1D and 3D conditions is firstly reviewed. The applicability of five rate-dependency equations in correlating the pre-consolidation pressure and undrained shear strength is also discussed. Furthermore, the rate-dependency of the behaviour of soft clays under complex loading conditions is analysed. Finally, the uniqueness of the rate-dependency under different conditions, i.e. between 1D and 3D, between triaxial compression and extension, between different OCRs is investigated.

KEYWORDS: Pre-consolidation pressure, Shear strength, Rate-dependency, Stress-dilatancy, Over-consolidation ratio

1. INTRODUCTION

The mechanical behavior of soft clay is very complicated. Time-dependent properties of soft clay cannot be neglected due to its high clay content, high water content, large void ratio, etc. That is, the soft clays exhibit not only creep and stress relaxation behavior, but also significant strain rate-dependency of strength. In the early 1930s, based on experimental investigations, Buisma (1936) proposed that stress, strain and strength of soft clays were strongly rate-dependent. Firstly, the strain rate of field construction (10^{-2}~10^{-3}%/h) is quite different from the conventional laboratory tests conducted at 0.5~5%/h (Kabbaj et al. 1988; Hanzawa and Tanaka 1982). Moreover, in the design of geotechnical engineering, the pre-consolidation pressure and the shear strength, as key parameters, are usually obtained from standard strain rate tests which usually ignored the influence of stain rate. It will lead instability of geotechnical structures and large deformation during the construction stages and long-term deformation. Consequently, the strain rate-dependency is an important topic for soft clays.

In order to study the strain rate-dependent behavior of soft clays, extensive experimental investigations were conducted, such as 1D constant rate of strain tests (Leroueil et al. 1983; Leroueil et al. 1985; Leroueil et al. 1988; Nash et al. 1992; Cheng and Yin 2005; Graham et al. 1983; Yin and Graham 1989; Yin and Wang 2012; Yin and Karstunen 2011; Yin, 2013, 2015; etc.), triaxial undrained strain rate tests (Nash et al. 1992; Cheng and Yin 2005; Graham et al. 1983; Li et al. 2006; Vaid et al. 1979; Dan and Wang 2008; Sheahan et al. 1996; Zhu et al. 1999; Zhu and Yin 2000; Yin and Cheng 2006; Cai et al. 2006; Gao and Wang 2005; Casagrande and Wilson 1951; Yin et al. 2002; etc.) and rate-dependency tests under complex loading conditions (Prapaharan et al. 1989; Rangeard et al. 2003; Silvestri 2006; etc.). These studies concern the strain rate-dependency of specific clays under specific conditions, e.g., different stress histories, consolidation states, test types, etc. However, few work studied the uniqueness of strain rate–dependency, and there are some insufficiencies of current studies, as follows:

Most of current studies investigated separately the rate-dependency of 1D pre-consolidation pressure and triaxial undrained shear strength, while few work concerns the relationship between them.

There are few discussions on the uniqueness of rate-dependency under the triaxial compression and extension conditions and different over-consolidation ratio (OCR) conditions.

Thus, it is necessary to make a review and analysis from existing experimental results. In this paper, firstly, we summarized the strain rate-dependency of soft clays from 1D to 3D conditions, then to complex loading conditions, and deeply discussed five rate-dependancy equations. Furthermore, the uniqueness of rate-dependency behavior of soft clays between 1D and 3D, between triaxial compression and extension, between different OCR conditions were investigated.

2. REVIEW OF EXPERIMENTAL INVESTIGATIONS

Figure 1 shows typical curves of CRS tests, where the strain rate $c_3 > c_2 > c_1$ corresponds to the stress $q_3 > q_2 > q_1$. In this section, the stain rate-dependency will be summarized systematically under 1D compression, triaxial compression/extension, and unconventional complex loading conditions.

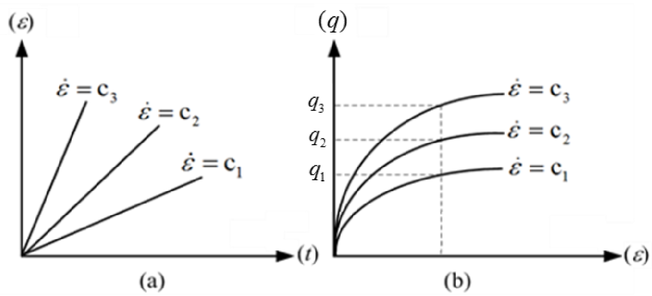

Figure 1 Schematic plot for CRS tests:
(a) strain history; (b) stress–strain relationship

2.1 One-dimensional CRS test

The 1D CRS test can be conducted by controlling the constant rate of vertical displacement. During the experimental process, we can measure the stress and deformation of specimen. Then, the stress-strain and pre-consolidation pressure-strain rate can be obtained, which is a basis of developing time-dependent constitutive models. Based on the published data of CRS tests, we investigated (1) the rate-dependency of pre-consolidation pressure, (2) normalized compression curves, and (3) the evaluation of different equations for the rate-dependency of pre-consolidation pressure.

2.1.1 Rate-dependency of pre-consolidation pressure

Extensive 1D CRS tests (Leroueil et al. 1983, 1985, 1988; Nash et al. 1992; Yin and Graham 1989; Yin and Wang 2012; Yin and Karstunen 2011; Rangeard et al. 2003; etc.) show that larger loading rate can result in larger pre-consolidation pressure σ'_p as shown in Figure 2(a). Leroueil et al. (1985) summarized systematically the strain rate-dependency of different clays by experimental observations, and pointed out that the isotache line system (Šuklje

1957) can describe the correlation between the pre-consolidation pressure and the strain rate, which can be expressed as follows:

$$\sigma_{\mathrm{p}}^{'} = f\left(\dot{\varepsilon}\right) \qquad (1)$$

Where $\dot{\varepsilon}$ is vertical strain rate; σ'_{p} is the corresponding pre-consolidation pressure. In this isotache line system as shown in Figure 2 (b), the elastic line intersects constant strain isotache lines $\dot{\varepsilon}_{\mathrm{r}}$ and $\dot{\varepsilon}$ at point A and B with $\sigma_p{}^r$ and σ_p respectively.

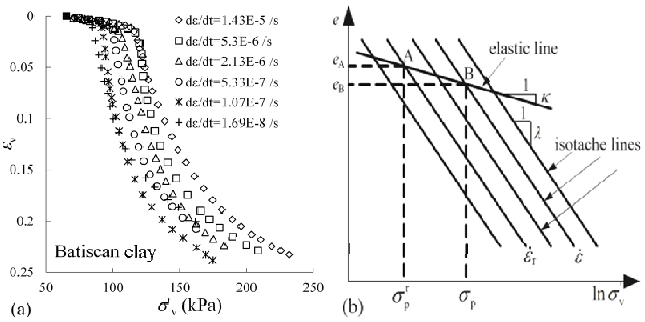

Figure 2 Stress–strain–strain-rate behavior of 1D CRS tests

Based on CRS tests on 17 different clays (Leroueil et al. 1983, 1985; Nash et al. 1992; Cheng and Yin 2005; Yin et al. 2010; Dan 2008; etc.), we plot the relationship between the pre-consolidation pressure and the strain rate in Figure 3 that shows the applied strain rate varies from 0.002 %/h to 27 %/h, and the pre-consolidation pressure σ'_{p} is proportional to the strain rate.

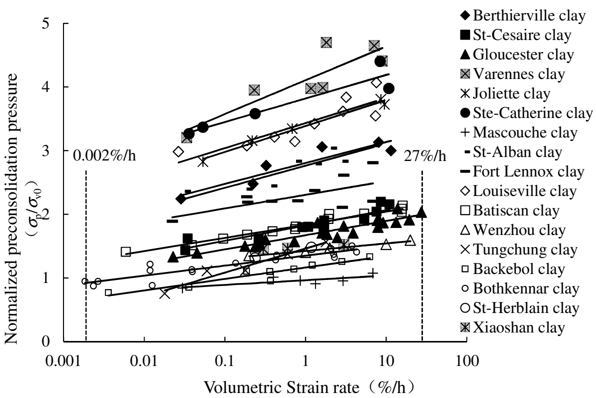

Figure 3 Pre-consolidation pressure versus applied strain-rate

Until now, test results under low strain rates (<0.01%/h) and high strain rates (>100%/h) are not available. Thus, it is difficult to determine the strain rate-dependency of pre-consolidation pressure for very low/high strain rates. The possible influence factors of the low strain rate test are as follows: (1) the time consummation of test (i.e., it needs 417 days to reach ε_v=10% under the strain rate of 0.001%/h); (2) the accuracy/difficulty of test due to limitations of equipment; (3) temperature/chemical induced inter-particle bonds during long duration of test. Additionally, the high strain rate CRS test is also influenced by such factors: (1) the rapid loading induces excess pore pressure resulting in non-homogeneous effective stress field; (2) some energy dissipation problems are not taken into account by the effective stress theory (e.g., acoustic/thermal energy); (3) some mechanical reasons, e.g. the sensor cannot record the change of pore pressure at a high speed condition. Consequently, the investigation of the rate-dependency of soft clay at very low/high strain rates is still a challenge.

2.1.2 Normalized compression curves

Leroueil et al. (1985) normalized compression curves (σ'_{v} - ε_{v}) by pre-consolidation pressure for CRS tests on 14 Canadian clays, and found that these compression curves are almost identical as Figure 4(a). Moreover, based on three oedometer tests (i.e., load duration of 1 day, 10 days and 100 days) and seven CRS tests (i.e., strain rate of 1.11×10^{-6} s^{-1} ~ 1.11×10^{-5} s^{-1}) on Vanttila clays, Yin et al. (2011) normalized compression curves obtaining similar results as Leroueil et al. Figure 4(b). Similar results can also be found for other clays (Leroueil et al. 1983, 1985, 1988; Nash et al. 1992; Cheng and Yin 2005; Graham et al. 1983; etc.). Therefore, the normalized compression behavior can be expressed as:

$$\frac{\sigma_{\mathrm{v}}^{'}}{\sigma_{\mathrm{p}}^{'}} = g\left(\varepsilon\right) \qquad (2)$$

Which indicates that the normalized compression behavior is irrelevant to the strain rate.

However, the stress developed from the initial stress to the yield state produces different strain levels. And at the yield state, higher strain rate gives bigger strain level in Figure 2(b). As a result, the normalized curves are never identical. That is, the Eq. (2) ignores the influence of strain rate on the yield strain.

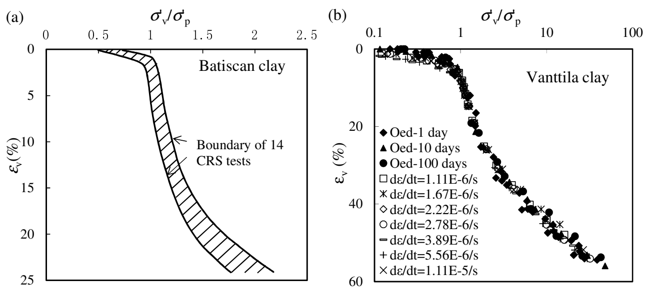

Figure 4 Normalized stress-strain relationship deduced from CRS tests

2.1.3 Evaluation of different formulations for rate-dependency of pre-consolidation pressure

As mentioned above, based on 1D CRS tests, each pre-consolidation pressure corresponds to one strain rate. For different clays the influence of strain rate on σ'_{p} is difference (Sheahan et al. 1996), as indicating by the slope of each curve in Figure 3. The rate parameter is usually used to describe quantitatively this rate-dependency of clay. Different formulations for calculating the rate parameter were defined. In this paper, we divided these rate formulations into two categories (i.e., exponential form and logarithmic form) to investigate their application and relevance (Yin et al. 2010).

(1) Exponential formulations

The exponential formulations are based on the linear relationship between the pre-consolidation pressure and the strain rate in semi-logarithmic plot. Most exponential formulations are derived from that proposed by Graham et al. (1983), who firstly introduced the rate parameter $\eta_{0.1}$ to express the effect of strain rate on the pre-consolidation pressure: a reference value $\sigma'_{p,0.1}$ corresponding to strain rate of 0.1%/h was defined, and when the strain rate increases 10 times, the rate parameter $\eta_{0.1}$ is expressed by the ratio between the increment value $\Delta\sigma'_p$ and the reference value $\sigma'_{p,0.1}$, as follows,

$$\eta_{0.1} = \Delta\sigma_{\mathrm{p}}^{'} / \sigma_{\mathrm{p},0.1}^{'} \qquad (3)$$

Based on this, a more common rate formulation (Dan and Wang 2008; Li and Peng 2005; etc.) can be expressed:

$$\eta_{\mathrm{N1}} = \frac{\left(\sigma_{\mathrm{p}}^{'} / \sigma_{\mathrm{p}}^{'\mathrm{r}} - 1\right)}{\log\left(\dot{\varepsilon} / \dot{\varepsilon}_{\mathrm{r}}\right)} \tag{4}$$

Where: σ'_{p} corresponds to strain rate $\dot{\varepsilon}$; the reference pre-consolidation pressure $\sigma_{\mathrm{p}}^{'\mathrm{r}}$ corresponds to the reference strain rate $\dot{\varepsilon}_{\mathrm{r}}$; η_{N1} is a rate parameter.

Another rate formulation was proposed by Fodil et al. (1997):

$$\eta_{\mathrm{N2}} = \frac{\left(\sigma_{\mathrm{p}}^{'} / \sigma_{\mathrm{p}}^{'\mathrm{r}} - 1\right)}{\log\left(\dot{\varepsilon} / \dot{\varepsilon}_{\mathrm{r}} + 1\right)} \tag{5}$$

If the ratio of strain rate $\dot{\varepsilon} / \dot{\varepsilon}_r = 10$ is used, the relationship between η_{N1} and η_{N2} can be obtained as:

$$\eta_{\mathrm{N1}} = \log 11 \cdot \eta_{\mathrm{N2}} \tag{6}$$

(2) Logarithmic formulations

Bases on the linear relationship between the pre-consolidation pressure and the strain rate in double logarithmic plot, three main logarithmic formulations were proposed and used (Rowe and Hinchberger 1998; Hinchberger and Rowe 2005; Shahrour and Meimon 1995; Leroueil et al. 1996; Kim and Leroueil 2001; Kutter and Sathialingam 1992; Leoni et al. 2008; Yin et al. 2010; Yin et al. 2011; Yin 2011; Mesri and Choi 1979; etc.):

$$\eta_{\mathrm{L1}} = \frac{\log\left(\sigma'_{\mathrm{p}} / \sigma_{\mathrm{p}}^{'\mathrm{r}}\right)}{\log\left(\dot{\varepsilon} / \dot{\varepsilon}_{\mathrm{r}}\right)} \ or \ \frac{\sigma'_{\mathrm{p}}}{\sigma_{\mathrm{p}}^{'\mathrm{r}}} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}^{\mathrm{r}}}\right)^{\eta_{\mathrm{L1}}} \tag{7}$$

$$\eta_{\mathrm{L2}} = \frac{\log\left(\sigma'_{\mathrm{p}} / \sigma_{\mathrm{p}}^{'\mathrm{r}}\right)}{\log\left(\dot{\varepsilon} / \dot{\varepsilon}_{\mathrm{r}} + 1\right)} \ or \ \frac{\sigma'_{\mathrm{p}}}{\sigma_{\mathrm{p}}^{'\mathrm{r}}} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}^{\mathrm{r}}} + 1\right)^{\eta_{\mathrm{L2}}} \tag{8}$$

$$\eta_{\mathrm{L3}} = \frac{\log\left(\sigma_{\mathrm{p}}^{'} / \sigma_{\mathrm{p}}^{'\mathrm{r}} - 1\right)}{\log\left(\dot{\varepsilon} / \dot{\varepsilon}_{\mathrm{r}}\right)} \ or \ \frac{\sigma'_{\mathrm{p}}}{\sigma_{\mathrm{p}}^{'\mathrm{r}}} - 1 = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}^{\mathrm{r}}}\right)^{\eta_{\mathrm{L3}}} \tag{9}$$

Where η_{L1}, η_{L2} and η_{L3} are rate parameters according to logarithmic formulations. For the case that $\dot{\varepsilon} / \dot{\varepsilon}_r = 10$, the relations among three rate parameters (η_{L1}, η_{L2} and η_{L3}) are:

$$\eta_{\mathrm{L2}} = \frac{\eta_{\mathrm{L1}}}{\log 11} \ and \ \eta_{L3} = \log\left(10^{\eta_{\mathrm{L1}}} - 1\right) \tag{10}$$

(3) Comparisons of rate formulations

Taking the Bastican clay as example, the relationship between the pre-consolidation pressure and the strain rate is shown in Figure 5(a), and the fitting curves by five rate formulations as Eqs. (4)-(5) and Eqs. (7)-(9) are plotted in Figure 5(b-f). It shows that, Eq. (4) and Eq. (7) can obtain a good curve fitting with higher values of regression coefficient R^2; Eq. (5) and Eq. (8) can only be used in the condition of $\dot{\varepsilon} / \dot{\varepsilon}_{\mathrm{r}} + 1$; Eq. (9) can only be used in the range $\sigma_{\mathrm{p}}^{'} / \sigma_{\mathrm{p}}^{'\mathrm{r}} - 1 < 0$. Consequently, from both the practical point of view and curve fitting, Eq. (4) and Eq. (7) are better than others.

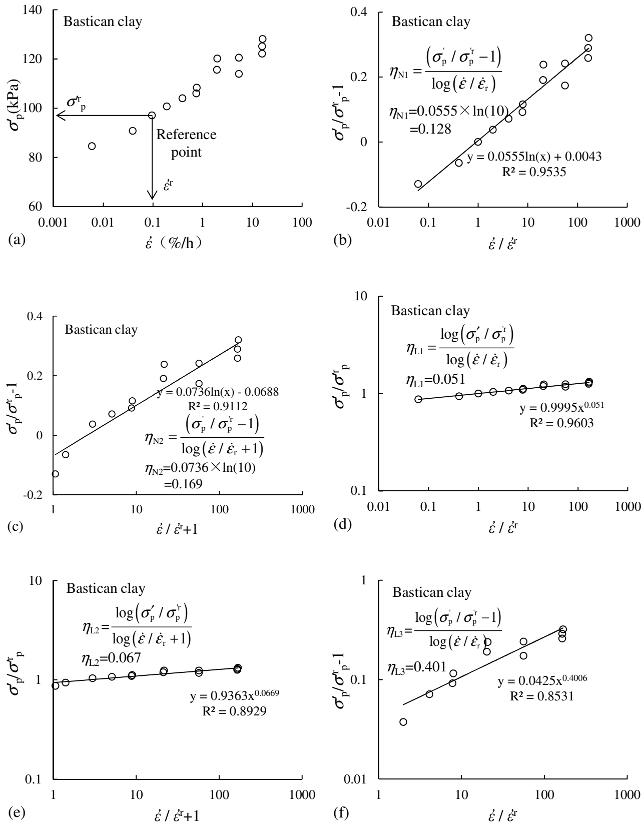

Figure 5 Comparison of pre-consolidation - rate formulations

Similarly, all clays in Figure 3 are fitted by above formulations, with parameters and regression coefficient R^2 summarized in Table 1. Comparing each regression coefficient R^2, Eq. (4) and Eq. (7) have best applicability. Consequently, the rate parameter η_{N1} and η_{L1} can well reflect the strain rate-dependency of soft clays.

According to the Casagrande plasticity chart in Figure 6, these clays can be divided into different areas as low plasticity inorganic clays (CL), high plasticity inorganic clays (CH), high plasticity fine sandy and opaque clay (OH). In order to investigate the relationship between rate parameters and Atterberg limits of clays (deleting the huge difference of Tungchung clay), we summarized the maximum, minimum, and average value of rate parameter η_{N1} and η_{L1} in Figure 6. The average value of rate parameters in the OH region is maximum, the CH region followed, and the CL region is the smallest one. Furthermore, we plotted the relationship between rate parameters and the liquid limit Figure 7(a) and the plasticity index Figure 7(b). Comparing the regression coefficient R^2 of linear fitting formula, the rate parameter has a certain linear relation to liquid limit and plasticity index of clays, and rate parameter fitted by liquid limit is much better than that by plasticity index.

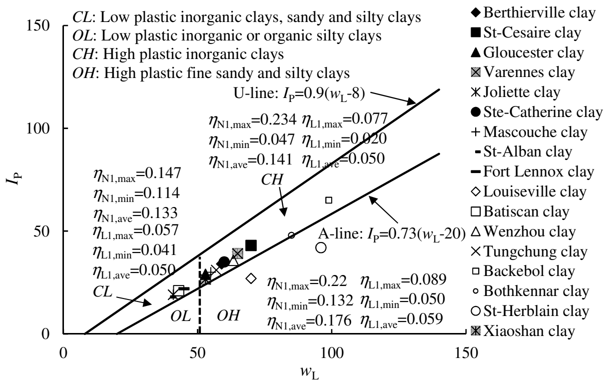

Figure 6 Classification of selected soils in plasticity chart

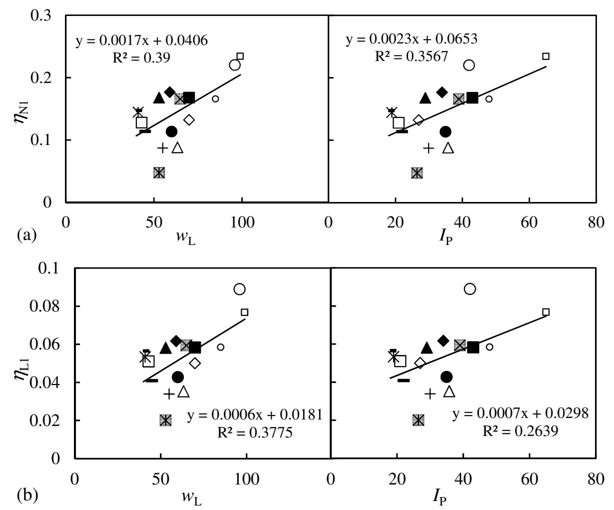

Figure 7 Relationship between rate parameters and liquid limit and plasticity index

Moreover, according to 1D CRS tests and conventional oedometer tests, Mesri and Choi (1979) proposed that rate parameters are related to the secondary consolidation coefficient C_α and the compression index C_c, as follows:

$$\sigma_p^{'} / \sigma_p^{'r} = \left(\dot{\varepsilon} / \dot{\varepsilon}^{r}\right)^{C_\alpha / C_c} \tag{11}$$

Combining Eq. (7) and Eq. (11), it can be easily derived that:

$$\eta_{L1} = C_\alpha / C_c \tag{12}$$

However, Kutter and Sathialingam (1992), Leoni et al. (2008), Yin et al. (2010) considered that Eq. (13) is more consistent with experimental observations as,

$$\eta_{L1} = C_\alpha / \left(C_c - C_s\right) \tag{13}$$

Generally, C_c is ten times to C_s, and then the values of η_{L1} between Eq. (12) and Eq. (13) are close. However, few papers provided both the data of rate parameters and C_α/C_c. Consequently, the correlation between rate parameters and the secondary consolidation coefficient needs further investigations.

All rate parameters have some relevance under the above two coordinate systems. Therefore, combining Eq. (4) with Eq. (7), the relationship between η_{N1} and η_{L1} can be derived as follows:

$$\begin{cases} \sigma_p^{'}/\sigma_p^{'r} = \eta_{N1}\log\left(\dot{\varepsilon}/\dot{\varepsilon}_r\right)+1 \\ \sigma_p^{'}/\sigma_p^{'r} = \left(\dot{\varepsilon}/\dot{\varepsilon}_r\right)^{\eta_{L1}} \end{cases} \tag{14}$$

When $\dot{\varepsilon} / \dot{\varepsilon}_r = 10$, according Eq. (4) and (7), Eq. (14) can be changed as this following:

$$\eta_{N1} = 10^{\eta_{L1}} - 1 \tag{15}$$

For soft clays, C_α/C_c varies from 0.03 to 0.09 (Mesri and Godlewski 1977). Thus, the parameter η_{L1} varies form 3% to 9%, and η_{N1} varies from 7.2% to 23%. Moreover, these results are also consistent with the range of η_{L1} (2% ~ 8.9%) and η_{N1} (4.7% ~ 23.4%) presented in Table 1 apart from Tungchung clay.

Table 1 Physical characteristics and rate parameters for selected clays

clays	w_L	w_P	I_P	η_{N1}	R^2	η_{N2}	R^2	η_{L1}	R^2	η_{L2}	R^2	η_{L3}	R^2
Berthierville clay	59	25	34	0.176	0.8592	0.190	0.8237	0.062	0.8491	0.066	0.8078	0.187	0.6681
St-Cesaire clay	70	27	43	0.168	0.8527	0.192	0.8774	0.058	0.8728	0.066	0.8913	0.260	0.8765
Gloucester clay	53	24	29	0.168	0.8779	0.179	0.8800	0.058	0.8957	0.062	0.8925	0.319	0.8561
Varennes clay	65	26	39	0.166	0.7595	0.184	0.7361	0.059	0.7803	0.066	0.7507	0.173	0.4914
Joliette clay	41	22	19	0.144	0.9861	0.160	0.9701	0.053	0.9794	0.059	0.9576	0.268	0.9781
Ste-Catherine clay	60	25	35	0.113	0.8748	0.126	0.8698	0.043	0.8937	0.048	0.8862	0.382	0.9030
Mascouche clay	55	25	30	0.087	0.5587	0.098	0.5443	0.034	0.5764	0.038	0.5581	0.116	0.0774
St-Alban clay	40	22	18	0.147	0.8161	0.169	0.8422	0.057	0.8234	0.065	0.8473	0.847	0.7854
Fort Lennox clay	45	23	22	0.114	0.4363	0.123	0.4245	0.041	0.4573	0.043	0.4397	0.128	0.1538
Louiseville clay	70	43	27	0.132	0.7441	0.149	0.7738	0.050	0.7722	0.056	0.8000	0.588	0.8452
Batiscan clay	43	22	21	0.128	0.9535	0.169	0.9112	0.051	0.9603	0.067	0.8929	0.401	0.8531
Wenzhou clay	63.4	27.6	35.8	0.088	0.9688	0.102	0.9773	0.035	0.9722	0.041	0.9774	0.169	0.8870
Tungchung clay	57	26	31	0.500	0.0640	0.574	0.9345	0.146	0.9206	0.166	0.8858	0.265	0.9191
Backebol clay	99	34	65	0.234	0.8980	0.256	0.9091	0.077	0.9085	0.084	0.9117	0.335	0.7807
Bothkennar clay	85	37	48	0.116	0.8580	0.176	0.8522	0.058	0.8366	0.062	0.8267	0.174	0.7799
St-Herblain clay	96	54	42	0.22	1.0000	0.322	1.0000	0.089	1.0000	0.130	1.0000	-	-
Xiaoshan clay	53	26.5	26.5	0.047	0.9611	0.028	0.9831	0.020	0.9619	0.027	0.9836	1.38	1.0000

2.2 Triaxial CRS test

The triaxial CRS tests can be conducted by controlling vertical strain rate with constant confining pressure. Different strain rates can be applied to investigate the rate-dependency of undrained shear strength. Comparing with the 1D CRS test, the triaxial CRS test can control lateral stresses to simulate different loading paths. To eliminate the excess pore water pressure, the strain rate for triaxial drained test must lower than 0.18%/h. As a result, drained test cannot be applied for the investigation of rate-dependency. Thus, the triaxial CRS test is usually conducted under the undrained condition. Similar to the 1D CRS test, we investigated (1) the rate-dependency of undrained shear strength, (2) the normalized stress-strain curves and (3) the evaluation of different formulations for rate-dependency of undrained strength.

2.2.1 Rate-dependency of undrained strength

The undrained strength is a mechanical property of soft clays, which relates closely to the design of engineering and the safety of construction. Bjerrum (1967) proposed firstly that the triaxial undrained strength relates to strain rate, and then many studies summarized various data of triaxial CRS tests and proposed that the undrained strength was increasing with strain rate (i.e. when strain rate increased 10 times, the corresponding undrained strength increased roughly between 5%~20%) (Dan and Wang 2008; Sheahan et al. 1996; Zhu et al. 1999; Zhu and Yin 2000; Vaid and Campanella 1977; Lefebvre and Leboeuf 1987; Kulhawy and Mayne 1990; Richardson and Whitman 1963; Sorensen et al. 2007; etc.). However, the increase range of undrained strength is slightly relevant with the consolidation state, consolidation stress and experimental types, but relates with the physical mechanical properties of clays.

In order to describe the relationship between undrained strengths S_u and strain rate, we summarized published data on 17 selected clays in Figure 8 (Cheng and Yin 2005; Graham et al. 1983; Vaid 1979; Sheahan et al. 1996; Zhu et al. 199; Yin and Cheng 2006; Fodil et al. 1997; Hinchberger and Rowe 2005; Yin et al. 2010; Dan 2008; Vaid and Campanella 1977; Díaz-Rodríguez et al. 2009; Nakase and Kamei 1986; Qi et al. 2008). It shows that the strain rate varies from 0.003%/h to 800%/h, and the undrained strength S_u is generally proportional to the strain rates. For the low strain rate (<0.01%/h) and the high strain rate (>100%/h), the triaxial CRS test has the similar problem to the 1D-CRS tests mentioned above. Thus, it is difficult to determine the undrained shear strength S_u under these two extreme ranges of strain rate.

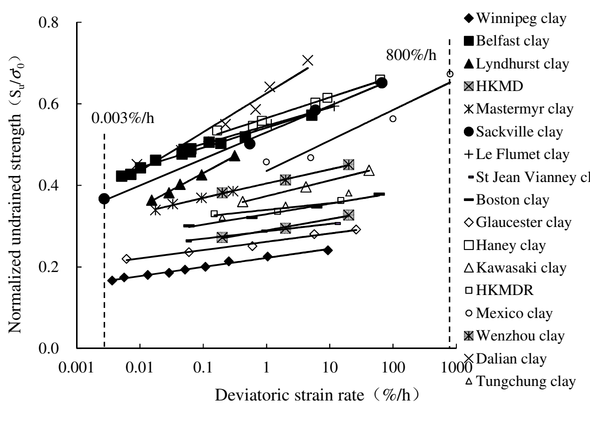

Figure 8 Relationship between Normalized undrained shear strength versus Deviatoric strain rate

2.2.2 Normalized stress-strain curves

Similar to the 1D CRS test, the triaxial CRS test also has the unique normalized behavior of stress-strain curves. Differently, existing studies show that the strain level corresponding to the peak strength in triaxial undrained test is almost identical for different strain rates (Vaid et al. 1979; Zhu and Yin 2000; Díaz-Rodríguez et al. 2009; etc.). Thus, the normalized behavior of the triaxial CRS tests is theoretically better than the 1D CRS tests. Taking Hong Kong clays as example, the triaxial compression and extension strengths are gradually increasing with strain rate Figure 9(a), and normalized stress-strain curves by different strain rates are almost identical as shown in Figure 9(b). Consequently, the stress-strain curves of triaxial CRS test with different strain rates have a good normalized behavior.

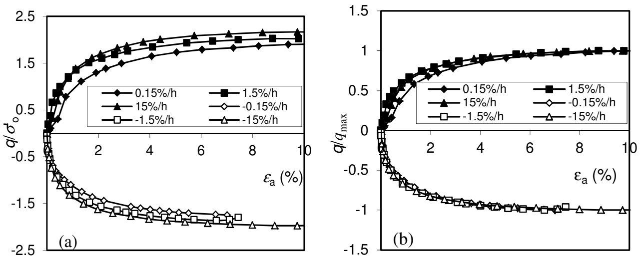

Figure 9 Normalized stress strain relationship for triaxial CRS compression and extension tests: (a) Normalized deviatoric stress by confined pressure versus axial strain; (b) Normalized deviatoric stress by maximum values versus axial strain

2.2.3 Evaluation of different formulations for rate-dependency of undrained strength

Similar to the method of 1D CRS test, rate parameters can be used to describe the effect of strain rate on different undrained strengths, and formulations for rate-dependency have the same form as the 1D CRS test. Therefore, rate formulations can be divided into two categories: the exponential form and the logarithmic form.

The exponential form rate formulation is expressed as:

$$\rho_{N1} = \frac{\left(q_{peak}/q_{peak}^{r} - 1\right)}{\log\left(\dot{\varepsilon}/\dot{\varepsilon}_r\right)} \tag{16}$$

$$\rho_{N2} = \frac{\left(q_{peak}/q_{peak}^{r} - 1\right)}{\log\left(\dot{\varepsilon}/\dot{\varepsilon}_r + 1\right)} \tag{17}$$

Where the peak shear stress q_{peak} corresponds to the deviatoric strain rate $\dot{\varepsilon}$; the reference peak shear stress q_{peak}^{r} corresponds to the reference deviatoric strain rate $\dot{\varepsilon}_r$; the undrained strength is $S_u = q_{peak}/2$.

If $\dot{\varepsilon}/\dot{\varepsilon}_r = 10$ is used, the relationship between ρ_{N1} and ρ_{N2} can be derived as follows:

$$\rho_{N1} = \log 11 \cdot \rho_{N2} \tag{18}$$

The logarithmic form rate formulation is expressed as:

$$\rho_{L1} = \frac{\log\left(q_{peak}/q_{peak}^{r}\right)}{\log\left(\dot{\varepsilon}/\dot{\varepsilon}^{r}\right)} \quad and \quad \frac{q_{peak}}{q_{peak}^{r}} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}^{r}}\right)^{\rho_{L1}} \tag{19}$$

$$\rho_{L2} = \frac{\log\left(q_{peak}/q_{peak}^{r}\right)}{\log\left(\dot{\varepsilon}/\dot{\varepsilon}_r + 1\right)} \quad and \quad \frac{q_{peak}}{q_{peak}^{r}} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}^{r}} + 1\right)^{\rho_{L2}} \tag{20}$$

$$\rho_{L3}=\frac{\log\left(q_{peak}/q^{r}_{peak}-1\right)}{\log\left(\dot{\varepsilon}/\dot{\varepsilon}_{r}\right)} \; and \; \frac{q_{peak}}{q^{r}_{peak}}-1=\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}^{r}}\right)^{\rho_{L3}} \tag{21}$$

When $\dot{\varepsilon}/\dot{\varepsilon}_r=10$, the relationship among ρ_{L1}, ρ_{L2} and ρ_{L3} as follows:

$$\rho_{L2}=\frac{\rho_{L1}}{\log 11} \; and \; \rho_{L3}=\log\left(10^{\rho_{L1}}-1\right) \tag{22}$$

Taking the Winnipeg clay as example in Figure 10(a), the fitting curves by five rate formulations are plotted in Figure 10(b)-(f). It shows that, Eq. (16)-(17) and Eq. (19)-(21) can obtain a good curve fitting with the higher value of regression coefficient R^2. In addition, Eq. (17) and Eq. (20) can only be used under the condition of $\dot{\varepsilon}/\dot{\varepsilon}_r+1$ and the Eq. (21) can only be used when $\dot{\varepsilon}>\dot{\varepsilon}_r$. Therefore, from practical point of view and curve fitting, Eq. (16) and Eq. (19) are better than others.

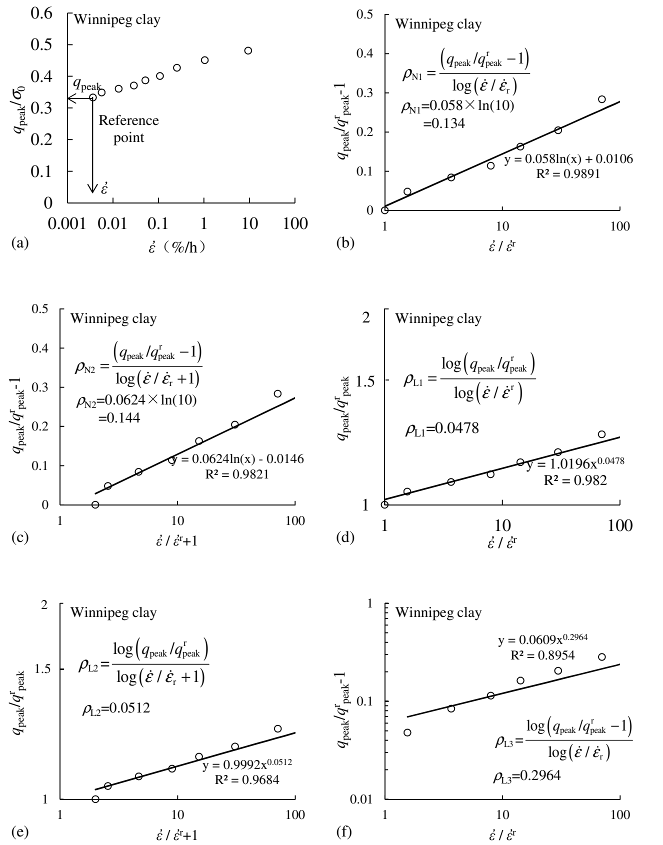

Figure 10 Comparison of rate formulation for triaxial undrained shear strength

Similarly, each clay in Figure 8 is fitted by above formulations, and the results are summarized in Table 2. By comparing each regression coefficient R^2, we can find Eq. (16) and Eq. (19) have the best applicability. Consequently, the rate parameter ρ_{N1} and ρ_{L1} can well reflect the strain rate-dependency of soft clays.

According to the Casagrande plasticity chart as shown in Figure 11, these clays can be divided into different areas as low plasticity inorganic clays (CL), high plasticity inorganic clays (CH), high plasticity fine sandy and opaque clay (OH). In order to investigate the relationship between the rate parameters and the characteristic of viscosity, we summarized the maximum, minimum, and average value of rate parameters ρ_{N1} and ρ_{L1} in each areas. It shows that the average value of rate parameters in the CH area is the maximum, then the OH area follows, and the CL area is the minimum.

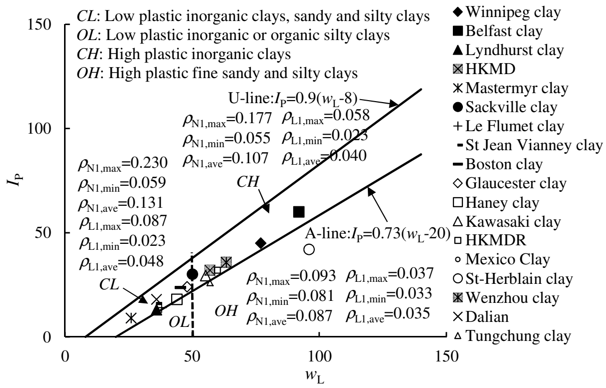

Figure 11 Classification of selected soils in plasticity chart

Furthermore, we plotted the rate parameter versus the liquid limit in Figure 12(a), and versus the plasticity index in Figure 12(b). Comparing the regression coefficient R^2 between linear fitting formulations, we can find the rate parameters ρ_{N1} and ρ_{L1} have a certain linear relation with liquid limit and plasticity index, and the rate parameter fitted by the plasticity index is much better than by the liquid limit.

Moreover, the relationship between ρ_{N1} and ρ_{L1} can be derived by Eq. (16) and Eq. (19) :

$$\begin{cases} q_{peak}/q^{r}_{peak}=\rho_{N1}\cdot\log(\dot{\varepsilon}/\dot{\varepsilon}_r)+1 \\ q_{peak}/q^{r}_{peak}=(\dot{\varepsilon}/\dot{\varepsilon}_r)^{\rho_{L1}} \end{cases} \tag{23}$$

In the case of $\dot{\varepsilon}/\dot{\varepsilon}_r=10$, Eq. (23) can be derived as follows:

$$\rho_{L1}=\log\left(\rho_{N1}+1\right) \tag{24}$$

As mentioned above, the parameter ρ_{N1} of soft clays generally varies from 5% to 20%. Thus, it is consistent with the range in Table 2 (ρ_{N1}=5.5~23%, ρ_{L1}=2.3~8.7 %).

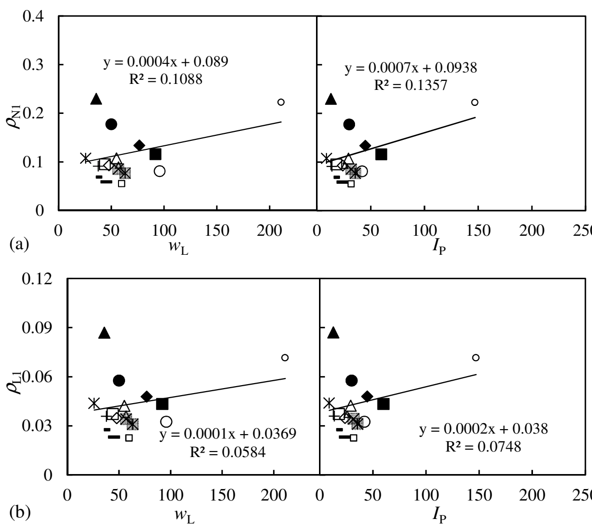

Figure 12 Relationship between ρ_{N1}, ρ_{L1} and w_L, I_P

Table 2 Physical characteristics and rate parameters for selected clays

Clays	w_L	w_P	I_P	ρ_{N1}	R^2	ρ_{N2}	R^2	ρ_{L1}	R^2	ρ_{L2}	R^2	ρ_{L3}	R^2
Winnipeg clay	77	32	$45^{\dagger}$	0.134	0.9801	0.144	0.9821	0.048	0.9820	0.051	0.9684	0.296	0.8954
Belfast clay	$92^{\dagger}$	32	$60^{\dagger}$	0.116	0.9752	0.126	0.9518	0.043	0.9615	0.047	0.9303	0.418	0.6321
Lyndhurst clay	36	23	13	0.230	0.9957	0.286	0.9914	0.087	0.9954	0.108	0.9841	0.688	0.9087
HKMD natural clay	57	25	32	0.085	0.993	0.099	0.992	0.034	0.994	0.040	0.990	0.330	1.000*
Mastermyr clay	26	17	$9^{\dagger}$	0.108	0.9894	0.136	0.9689	0.044	0.9855	0.055	0.9621	0.519	0.9763
Sackville clay	50.1	20	30.1	0.177	0.9963	0.191	0.9987	0.058	0.9971	0.062	0.9933	0.155	0.9720
Le Flumet clay	38	24	14	0.091	0.9988	0.102	0.9942	0.036	0.9979	0.040	0.9903	0.421	0.9581
St Jean Vianney clay	36	20	16	0.069	0.9954	0.078	0.9814	0.028	0.9921	0.031	0.9754	0.213	1.000*
Boston clay	45.4	21.7	23.7	0.059	0.954	0.064	0.959	0.023	0.957	0.025	0.959	0.348	0.951
Glaucester clay	48	24	24	0.093	0.9833	0.100	0.9894	0.035	0.9791	0.037	0.9913	0.249	0.9815
Heney clay	44	26	18	0.095	0.9855	0.106	0.9959	0.037	0.9880	0.042	0.9950	0.486	0.9022
Kawasaki clay	55.3	25.9	29.4	0.107	0.9985	0.125	0.9987	0.042	0.9999	0.049	0.9959	0.332	1.000*
HKMD remolded clay	60	32	28	0.055	0.956	0.065	0.967	0.023	0.959	0.027	0.968	0.442	1.000*
Mexico clay	211	63.9	147.1	0.222	0.873	0.242	0.862	0.072	0.863	0.078	0.849	0.521	0.924
St-Herblain clay	96	54	42	0.093	1.0000	0.109	0.9950	0.037	0.9996	0.043	0.9910	0.305	1.000*
Wenzhou clay	63.4	27.6	35.8	0.077	0.991	0.090	0.999	0.031	0.987	0.036	0.999	0.378	1.000*
Dalian clay	36	18	18	0.210	0.9606	0.236	0.9790	0.073	0.9788	0.082	0.9900	0.438	0.9535
Tungchung clay	57	26	31	0.093	1.000	0.109	0.994	0.037	0.999	0.043	0.990	0.301	1.000*

2.3 CRS test under complex stress condition

The stress state of soft clay in the practice engineering is more complicated than in the conventional laboratory (Yin et al. 2008, 2009, 2011, 2012; Karstunen and Yin 2010; Karstunen et al. 2012; etc.). Thus, it is necessary to conduct tests under special stress conditions, such as some unconventional laboratory tests, etc.

The vane shear test is an in-situ simple test that can rapidly measure the shear strengths of soft clays and is widely used to study the soft clays of Chinese coastal areas. Rangeard et al. (2003) studied the influence of shear rate on the strength of Saint Herblain clay as Figure 13(a) in multistage vane rotation speeds varying from 0.06°/s, 0.2°/s to 1.2°/s. The result shows that the maximum shear strength occurs in the range from 20° to 30°, and the normalized strength related with the vane rotation speed and the cumulative rotation angle. Additionally, the rate-dependency of soft clays also can be measured easily by the pressio-triax apparatus. Rangeard et al. (2003), Yin (2006) conducted CRS pressio-triax tests (see Figure 13(b) that can well control boundary conditions and the homogeneity of soft clays. Based on that, Yin and Hicher (2008) derived the viscous parameters of soft clays, and summarized the experimental data that the parameters obtained by the pressio-triax tests are identical with oedometer and triaxial tests. Moreover, Prevost (1976), Prapaharan et al. (1989) and Silvestri (2006) analyzed the cavity expansion theory under the axisymmetric loading, and derived the analytical solution of the effect of strain rates on undrained strength by pressuremeter tests.

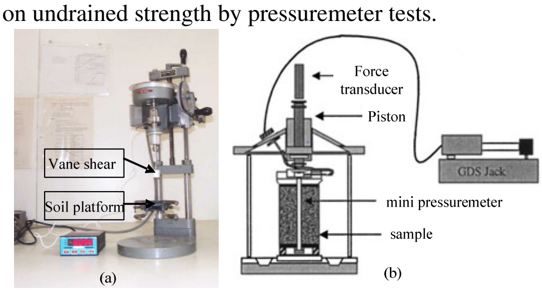

Figure 13 (a) Vane shear apparatus of laboratory;
(b) Modified pressio-triax apparatus

3. DISCUSSION ON THE UNIQUENESS OF RATE-DEPENDENCY

At present, studies have widely described the experimental phenomena of rate-dependency and the general research methods, but less investigated the characteristics of rate parameters and the relationship between CRS tests under different conditions. Therefore, the uniqueness of rate-dependency is questionable and needs to be investigated as follows: (1) the uniqueness of rate-dependency between undrained strength and pre-consolidation pressure; (2) the uniqueness of rate-dependency for shear strength between the triaxial compression and extension conditions; (3) the uniqueness of rate-dependency for undrained strength with different OCRs.

3.1 Uniqueness of the rate-dependency between 1D and 3D conditions

In this paper, Wenzhou natural clay was investigated to study the rate-dependency between 1D and 3D conditions. Firstly, we plotted the 1D pre-consolidation pressure with the axial strain rate in Figure 14(a), and the triaxial undrained strength with the axial strain rate in Figure 14(b), with the corresponding strain rate parameters η_{N1} = 8.8 %, η_{L1} = 3.5 %, ρ_{N1} = 7.7 %, ρ_{L1} = 3.4 % calculated respectively by Eq. (4), Eq. (7), Eq. (16) and Eq. (19). Secondly, the 1D pre-consolidation pressures and triaxial undrained shear strengths were normalized by the strength at the strain rate of 0.2%/h, and plotted in Figure 14(c). It shows that the normalized strength has a good linear correlation with the logarithm of axial strain rate for both conditions. That is, the Wenzhou clay has a good uniqueness of the rate-dependency under the 1D and 3D conditions.

However, the normalized strengths of the St-Herblain clay (Yin et al. 2010; Yin 2006) and Hong Kong Tungchung natural clay (Cheng and Yin 2005) have a big diversity under 1D and 3D conditions as shown in Figure 15. Investigating the reason, for one thing, the rate parameters of the 1D CRS tests of St-Herblain clays have no statistical meaning, because it only has two experimental data of strain rate, and the experimental results also is scattered; For another thing, the rate parameters η_{N1} = 50% of Tungchung clays is much higher than the general range of η_{N1} (4.7% ~ 23.4%), and the study of Cheng and Yin (2005) also lack the illustration of the inhomogeneity property of the natural clay or the investigations of other reasons.

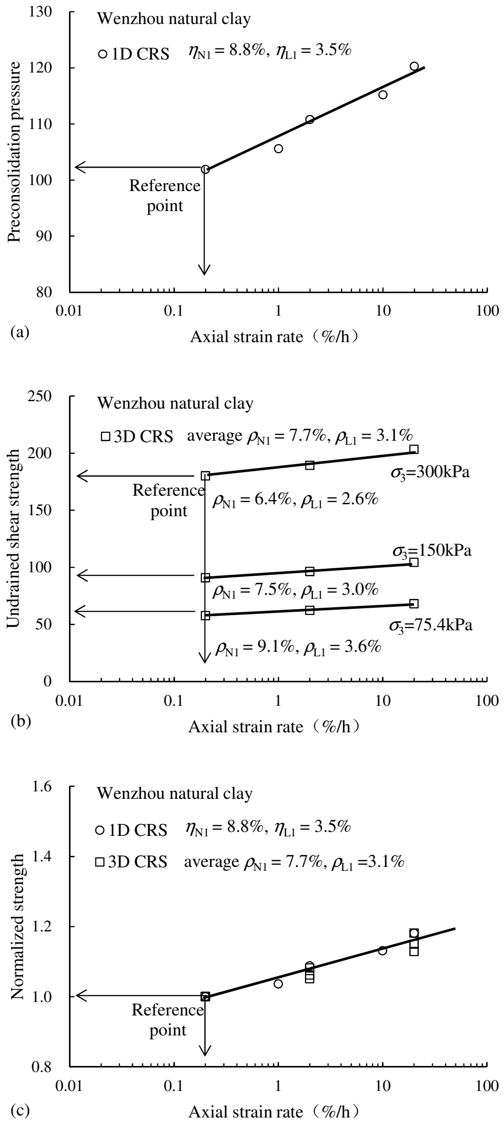

Figure 14 1D and 3D strain rate effect for Wenzhou clay

3.2 Uniqueness of the rate-dependency between triaxial compression and extension conditions

In practice, the clay can be loaded in compression (e.g. embankment) or extension (e.g. excavation) during constructions (Wang et al. 2008), and the deformation behavior can be significantly influenced by the speed of construction. Thus we studied the triaxial tests of Wenzhou natural clay (Dan and Wang 2008), Mastemyr natural clay (Graham et al. 1983), Hong Kong remolded and natural clay (Zhu and Yin 2000; Yin and Cheng 2006), and Kawasaki remolded clay (Nakase and Kamei 1986) to investigate the uniqueness of rate-dependency between triaxial compression and extension tests.

Based on above normalized method, we summarized logarithmic relationship between the normalized strength and the axial strain rate under the triaxial compression and extension conditions as shown in Figure 16.

The result shows that: for Wenzhou clays, Mastemyr clay and Hong Kong natural clay, the rate-dependency of triaxial compression and extension tests has a good uniqueness; for Hong Kong remolded clay comparing the general ranges of ρ_{N1} from 5.5% to 22.9% mentioned above, the parameter ρ_{N1} = 4.9% is low , thus the rate-dependency has big scatters between the triaxial compression and extension conditions; for Kawasaki remolded clay, when the extension rate is 42%/h, the scattered value of strength under extension makes the rate parameter ρ_{N1} = 21.2 %, and thus it also has a bad uniqueness between triaxial compression and extension conditions.

Above all, the rate-dependency of triaxial compression and extension generally have a good uniqueness, but also needs more experimental verification in the future study.

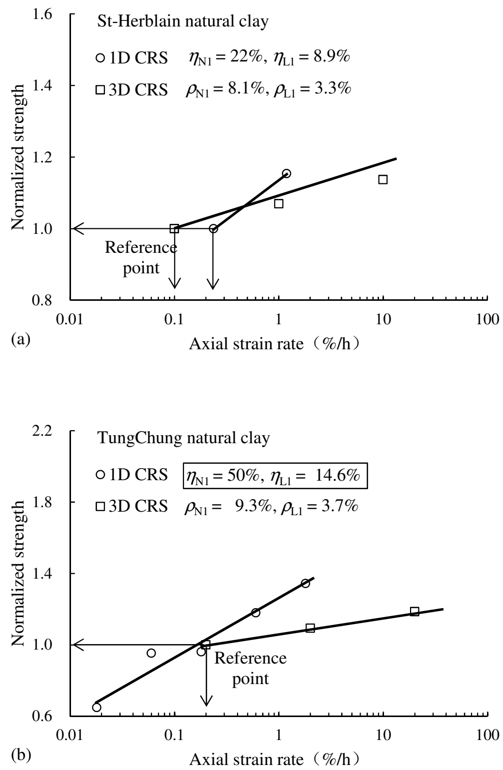

Figure 15 1D and 3D rate effect for St-Herblain and Tungchung clays

3.3 Uniqueness of the rate-dependency with different OCRs

At present, the study of the mechanical property for the over-consolidation clay is an important topic of soil mechanics. However, in the past, few experiments consider both the influence between the strain rate and the OCRs on the undrained strength, and the main experimental studies include the research of Hong Kong natural clay (Zhu and Yin 2000), Boston clay (Sheahan et al. 1996) and Mexico clay (Díaz-Rodríguez et al. 2009), etc.

As the same research method, the rate parameters ρ_{N1} and ρ_{L1} under different OCRs were calculated firstly, and then the normalized strength with the axial strain rate was plotted in Figure 17. The result shows that Boston clay and Mexico clay have big scatters under different OCRs, but Hong Kong remolded clay is slightly better. Since the experimental data is limited, the uniqueness of rate-dependency for soft clays with different OCRs also needs more experimental verification.

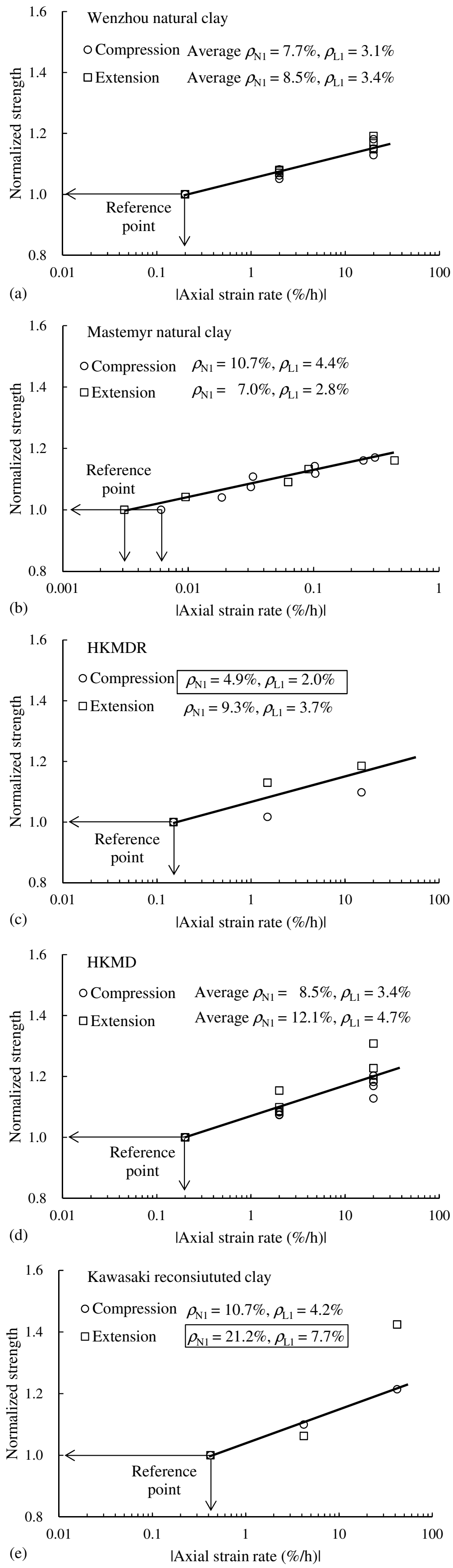

Figure 16 Normalized compression and extension strength versus axial strain rate

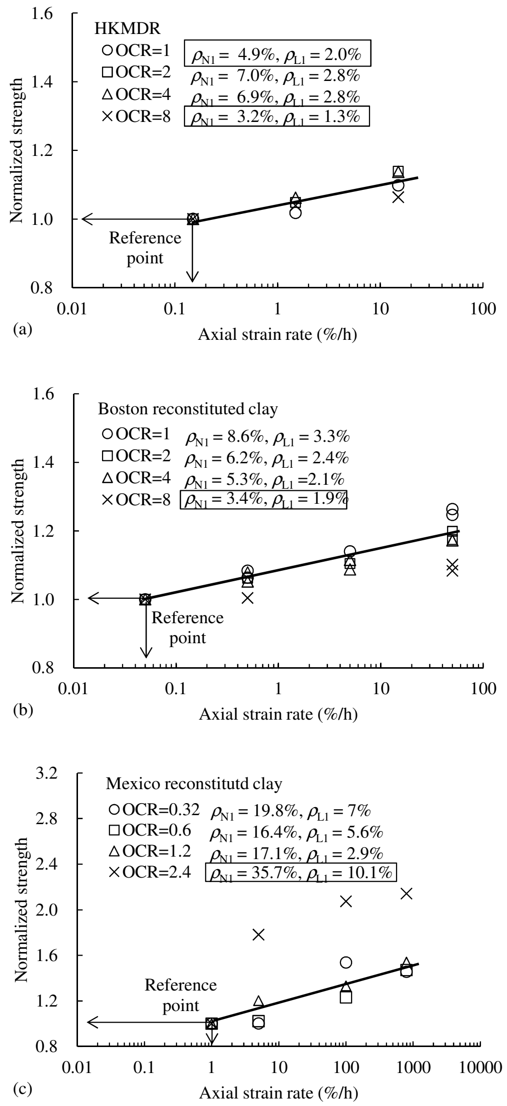

Figure 17 Normalized compression strength versus axial strain rate for different OCRs

4. CONCLUSION

This paper deeply investigated the uniqueness of strain rate-dependency of clay, systematically discussed the characteristic of rate-dependency of clay, and achieved following conclusions:

The pre-consolidation pressure and the undrained shear strength of soft clays are both rate-dependent. The range of rate parameters are summarized as η_{L1} 2%~8.9%, η_{N1} 4.7%~23.4%, ρ_{L1} 5.5%~23% and ρ_{N1} 2.3% ~ 8.7%.

According to the relationship between the pre-consolidation pressure and the strain rate, the exponential rate formulation Eq. (4) and the logarithmic rate formulation Eq. (7) have good applicability. For the undrained shear strength the rate formulations Eq. (16) and Eq. (19) can well represent the rate-dependency. Moreover the relationship between rate parameters and Atterberg limits was summarized in this paper.

For the uniqueness of strain rate-dependency, this paper investigated 1D and 3D conditions, triaxial compression and extension conditions, and different OCRs based on current experimental results, and all results show that the uniqueness of strain rate-dependency still needs further experimental verification.

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