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The Effect of the Strain Rate on Soft Soil Behaviour under Cyclic Loading

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ABSTRACT

In this paper, cyclic triaxial loading tests were conducted on specimens of soft clay with varying cyclic stresses and frequencies to investigate the performance of soft soil subgrade subjected to cyclic loading. The laboratory results indicate that given the same level of cyclic stress, the stability of clay subgrade is primarily dependent on the loading time with no consistent frequency/train speed effect. There exists a critical level of cyclic stress between 60 and 80% of the monotonic shear strength, above which failure may occur regardless of the loading frequency. The nature that soils behave dependently on cyclic stress level rather than loading frequency was investigated through the strain rate during cyclic loading, which is considered responsible for the cyclic response of soft clays under various loading conditions. For loading frequencies ranging from 0.1 to 5 Hz, it was found that the strain rate depended on the cyclic stress ratio rather than the loading frequency, which implies that the cyclic stress level plays a more important role in influencing the cyclic performance of soft soil subgrade.

Keywords: soft clay, cyclic loading, cyclic stress ratio, loading frequency, strain rate

1 INTRODUCTION

The performance of soft clays under train induced cyclic loading is gaining increasing attention since the accumulation of excessive subgrade plastic deformation and excess pore pressure under cyclic stress generated by fast moving trains is becoming a major problem. Therefore it is necessary to investigate the loading rate on the performance of soft clays under cyclic loading. The rate dependent behaviour of soft soil under monotonic loading has been recognised very well, and the undrained strength of saturated clays can be significantly affected by the applied loading rate. The undrained strength generally increases with an increasing strain rate (Richardson and Whitman 1963; Lefebvre and LeBoeuf 1987; Sheahan et al. 1996). To quantify the relationship between an increased undrained strength and strain rate, a strain rate sensitivity (s_q) can be introduced that may be defined as a change in the undrained strength ($\Delta q_{u,s}$), based on (a) per tenfold increment in strain rate ($\dot{\epsilon}_{aL,s}^0$):

$$(1 + s_q)^\alpha = \frac{q_{u,s}^0 + \Delta q_{u,s}}{q_{u,s}^0} \quad (1)$$

where $\alpha = \log(\dot{\epsilon}_{aL,s} / \dot{\epsilon}_{aL,s}^0)$ and $q_{u,s}^0$ is the value of $q_{u,s}$ at the reference strain rate ($\dot{\epsilon}_{aL,s}^0$), or based on (b) per tenfold decrement in time to failure (t_f):

$$(1 + s_q)^\beta = \frac{q_{u,s}^0 + \Delta q_{u,s}}{q_{u,s}^0} \quad (2)$$

where $\beta = \log(t_f^0 / t_f)$ and t_f^0 is the reference time to failure corresponding to $q_{u,s}^0$.

The collective value of strain rate sensitivity from the literature varies from 0 to 20%, with an over consolidation ratio ranging from 1 to 16, depending on the types of soil (Richardson and Whitman

1963; Ladd et al. 1972; Crooks and Graham 1976; Vaid and Campanella 1977; Vaid et al. 1979; Baracos et al. 1980; Andersen and Stenhamar 1982; Graham et al. 1983; Adachi et al. 1985; Lefebvre and LeBoeuf 1987; Sheahan et al. 1996).

The effect of the strain rate has also been investigated using cyclic loading tests (Lefebvre and LeBoeuf 1987; Lefebvre and Pfendler 1996). The high strain rate in stress controlled cyclic tests could result in a higher cyclic shear strength compared to the undrained shear strength determined under monotonic conditions at standard strain rates between 0.5 and 1.0 %/h. For example, Lefebvre and Pfendler (1996) conducted direct simple shear tests and found that at an equivalent strain rate of 300 %/h corresponding to 0.1 Hz cyclic loading, the undrained shear strength was 40% higher than that determined under a monotonic test. This is equivalent to a 12% increase per log cycle of strain rate. Lefebvre and LeBoeuf (1987) showed that an equivalent strain rate corresponding to 0.1 Hz was 3,500 %/h, where the cyclic shear strength was 43% higher than that determined by a conventional monotonic test. In cyclic loading tests, due to the high strain rate, 12 cycles (Lefebvre and Pfendler 1996) and 300 cycles (Lefebvre and LeBoeuf 1987) could be applied before failure occurred at a level of cyclic stress equal to the undrained shear strength determined in monotonic tests at standard strain rates.

In addition, some researchers conducted stress controlled cyclic loading tests on soft soils with different loading frequencies (Matsui et al. 1980; Takahashi et al. 1980; Procter and Khaffaf 1984; Hyde et al. 1993; Zhou and Gong 2001; Liu and Xiao 2010). However, only limited study has been focussed on the strain rate dependent cyclic behaviour of soft soils under combinations of the cyclic stress ratio and loading frequency.

In this paper a series of undrained cyclic triaxial loading tests were carried out on specimens on soft Kaolin clay. The factors influencing strain rate, such as the cyclic stress ratio ($CSR = 0.4, 0.6$ and 0.8) and loading frequency ($f = 0.1, 1, 2$, to 5 Hz) were investigated and the strain rate dependent cyclic behaviour were analysed. The laboratory testing procedure and the discussion of experimental data are presented in the following.

2 CYCLIC TRIAXIAL TEST PROCEDURES

2.1 Soil properties

Specimens of reconstituted Kaolinite 38 mm in diameter by 76 mm high were used in this triaxial test. The soil had the following properties: specific gravity $G_s = 2.7$, liquid limit $w_L = 55\%$, plastic limit $w_p = 27\%$, compression index $C_c = 0.42$, and swelling index $C_s = 0.06$.

The specimens were subjected to an effective vertical stress of 40 kPa to represent the in situ stress and consolidated under anisotropic condition with a consolidation stress ratio of $k_0 = 0.6$, which may be defined as the ratio of effective lateral stress to vertical stress.

2.2 Test schedule

The undrained cyclic loading tests were carried out using triaxial cyclic loading apparatus, as shown in Figure 1. The apparatus mainly comprises an axial loading unit, an air pressure and water control unit, a pore pressure measurement system and a volumetric change measurement device. Excess pore pressure was measured through the drainage valve at the base.

A series of conventional monotonic triaxial tests were conducted to obtain the maximum deviator stress at failure q_f during static loading. Then the cyclic stress ratio was defined as the ratio of cyclic stress to the maximum deviator stress at failure ($CSR = q_{cyc} / q_f$). All the test conditions for the triaxial cyclic loading tests are given in Table 1. The patterns of cyclic stress for different loading frequencies are provided in Figure 2.



Figure 1. Triaxial cyclic loading equipment GDS

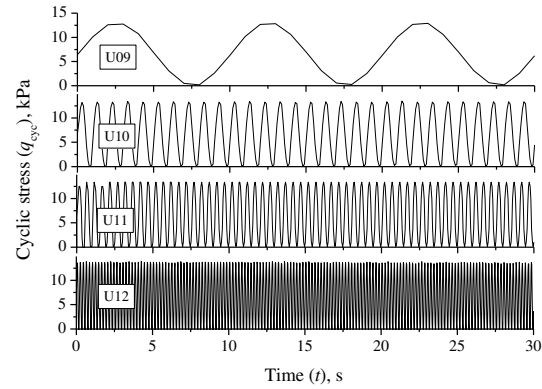


Figure 2. Patterns of applied cyclic stress

Table 1: Test conditions and results

Sample	Cyclic stress ratio (CSR)	Cyclic loading frequency (f), Hz	Loading cycles (N)	Time (t), min	Failure or not
U01	0.4	0.1	6,000	1,000	No
U02	0.4	1	34,466	574	No
U03	0.4	2	34,466	287	No
U04	0.4	5	33,000	115	No
U05	0.6	0.1	6,000	1,000	No
U06	0.6	1	34,466	574	No
U07	0.6	2	34,466	287	No
U08	0.6	5	34,466	115	No
U09	0.8	0.1	1,793	299	Yes
U10	0.8	1	10,419	174	Yes
U11	0.8	2	18,590	160	Yes
U12	0.8	5	33,964	113	Yes

3 TEST RESULTS AND ANALYSIS

3.1 Generation of excess pore pressure and axial strain

The results of the cyclic triaxial loading tests are given in Table 1. Failure occurred after a number of cycles for specimens tested under CSR of 0.8. The number of cycles at failure increased from 1,793 to 33,964 after the loading frequency was increased from 0.1 Hz to 5 Hz. This observation was consistent with the studies by Andersen (2009) and Takahashi et al. (1980) where more cycles were needed to bring the specimen to failure at a higher frequency. The time to failure could be calculated by $t_f = N_f(1/f)$, where N_f is the number of cycles at failure. In this current study t_f decreased from 299 to 113 min when the loading frequency was increased from 0.1 to 5 Hz.

The effects of frequency on normalised excess pore pressure and axial strains against time are illustrated in Figures 3 to 5. Figures 3 and 4 indicate that for CSR of 0.4 and 0.6, the excess pore pressure and axial strains do not deviate significantly from each other, although the frequency varied from 0.1 to 5 Hz. This verifies that for CSR in the range of 0.4 to 0.6, an increase in frequency has a negligible effect on the excess pore pressure and strains. However, as the CSR increased to 0.8 (see Figure 5) and the excess pore pressure trends remained similar, the axial strains showed a slight difference when the frequency increased from 0.1 to 5 Hz. A rapid upward trajectory of strains representing failure could be observed. As expected, at the highest frequency of 5 Hz, failure usually began at a smaller time scale (i.e. $t < 100$ minutes), while at the smallest frequency of 0.1 Hz, failure still occurred at a delayed time scale ($t > 250$ minutes).

To summarise, Figure 5 suggests that for any failure to occur, the CSR must exceed a critical value (i.e. CSR > 0.6 for this soil) irrespective of the frequency. On the other hand, at a given critical CSR where failure is inevitable, the higher the frequency the less time required for failure to occur. For CSR

of 0.4 and 0.6, the normalised excess pore pressure after about 200 minutes approached 0.2 and 0.4 respectively. Not surprisingly, a significantly higher excess pore pressure exceeding 0.6 was observed for the four failed specimens (U09-U12) having a CSR of 0.8 (see Figure 5).

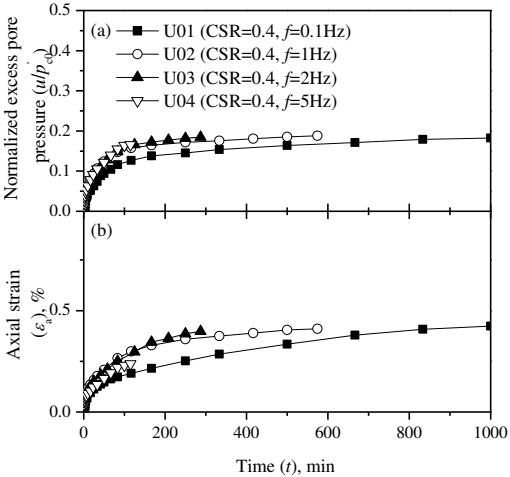


Figure 3. Normalised excess pore pressure and axial strain (CSR = 0.4)

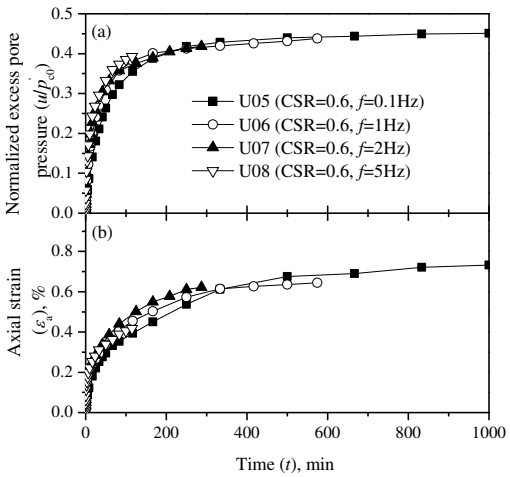


Figure 4. Normalised excess pore pressure and axial strain (CSR = 0.6)

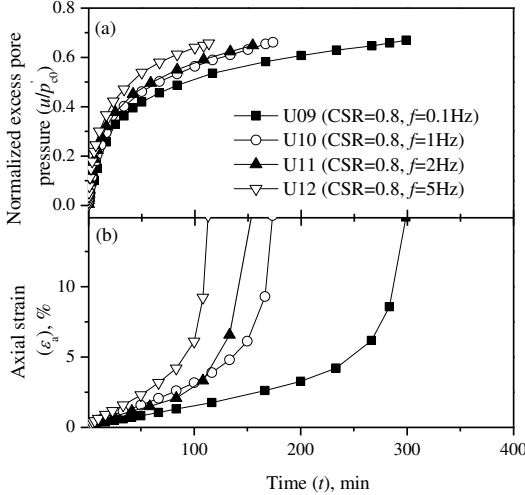


Figure 5. Normalised excess pore pressure and axial strain (CSR = 0.8)

3.2 Effects of Strain rate

With stress controlled cyclic loading tests, the strain rate was much larger than conventional monotonic loading (usually at 0.5-1.0 %/h). Assuming that a constant strain rate applies during the whole cycle, then the strain rate of axial strain for stress controlled cyclic loading can be given by:

$$\dot{\epsilon}_{a,c} = 2 \times \epsilon_{a,cycle} \times f \tag{3}$$

where $\epsilon_{a,cycle}$ is the axial strain for a half cycle and f is the frequency of cyclic loading.

Table 2 shows the strain rate for each cyclic loading condition, with an increasing number of cycles. The strain rate for each value of CSR seemed to be constant during the whole process of cyclic loading for each condition. The average value of strain rate was calculated and then tabulated in Table 2. The relationship between the equivalent strain rate and cyclic stress ratio is shown in Figure 6. The strain rate increased with an increasing cyclic stress ratio for all frequency values. When the cyclic stress ratio increased from 0.6 to 0.8, the axial strain rate increased rapidly, further confirming previous observations that failure would occur at CSR=0.8, irrespective of the frequency. It should be

noted that all the four plots for $f = 0.1$ to 5 Hz were close together, indicating that the strain rate did not depend on the frequency.

Table 2: Equivalent strain rate for cyclic tests

		Strain rate ($\dot{\epsilon}_{aL,c}$), %/h					
N	0.1Hz			N	1Hz		
	CSR=0.4	CSR=0.6	CSR=0.8		CSR=0.4	CSR=0.6	CSR=0.8
500	185	290	580	5,000	198	260	574
1,000	186	282	585	10,000	192	256	564
3,000	186	265		30,000	198	240	
6,000	170	270					
Average	182	277	583	Average	190	257	569
		2Hz			5Hz		
N	CSR=0.4	CSR=0.6	CSR=0.8	N	CSR=0.4	CSR=0.6	CSR=0.8
	5,000	167	255		548	5,000	210
10,000	163	296	527	10,000	207	288	572
30,000	165	290		30,000	208	289	580
Average	167	278	538	Average	208	290	576

The relationships of the excess pore pressure ratio-strain rate and axial strain-strain rate are shown in Figures 7 and 8, respectively. It shows that the combined effect of the cyclic stress ratio and loading frequency can be represented by an equivalent strain rate. The higher the equivalent strain rate, the greater the excess pore pressure and axial strain generated during cyclic loading.

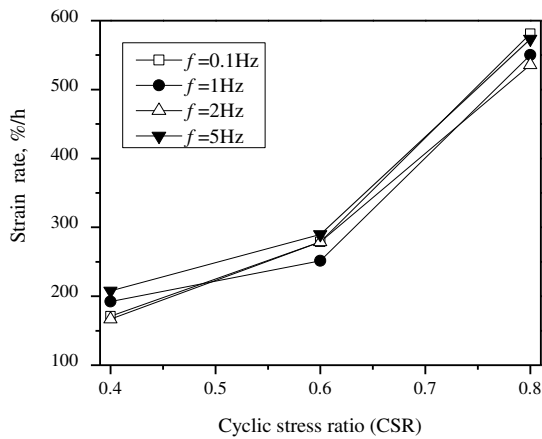


Figure 6. Equivalent strain rate for cyclic tests

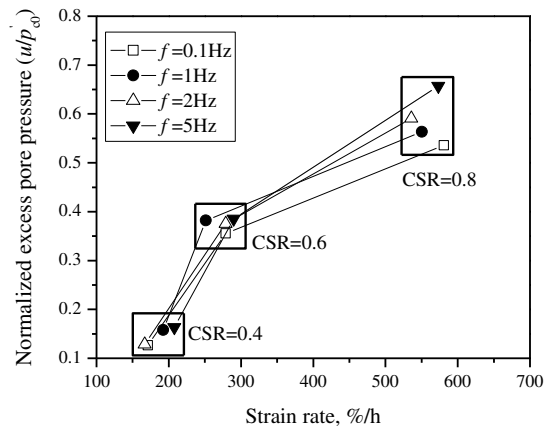


Figure 7. Relationship between normalised excess pore pressure and strain rate

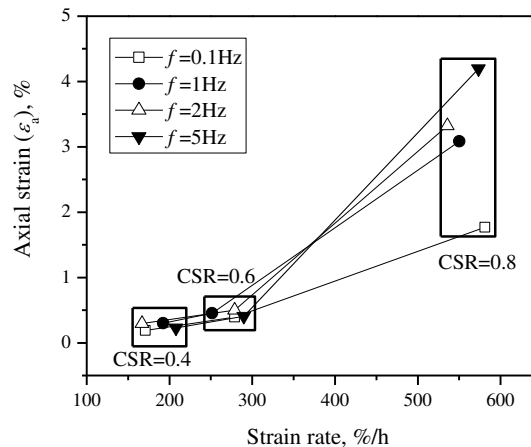


Figure 8. Relationship between axial strain and strain rate

4 CONCLUSION

Based on a series of cyclic triaxial loading test conducted at cyclic stress ratios ranging from 0.4 to 0.8 and cyclic loading frequencies from 0.1 to 5Hz, the following conclusions can be drawn:

- (1) Where $CSR = 0.4$ and 0.6 , the axial strains and excess pore pressure were very similar regardless of the frequency;
- (2) Where $CSR = 0.8$, while the excess pore pressure trends still remained similar to those conducted at a lower CSR , the axial strains showed a slight difference when the frequency was increased from 0.1 to 5 Hz, where a rapid upward trajectory of strains represents failure;
- (3) Strain rate depends on the cyclic stress ratio, and it does not depend on a loading frequency from 0.1 to 5 Hz and;
- (4) The higher the strain rate, the greater the excess pore pressure and axial strain generated during cyclic loading.

5 ACKNOWLEDGEMENTS

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