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Effect of OCR on Cyclic Shear Strength Degradation of Marine Clay

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Abstract: **Cyclic loading in marine clay may lead to gradual loss of its shear strength and it is a major cause for increasing pore water pressure. This paper presents the strain-controlled cyclic direct simple shear test results to describe the cyclic undrained shear strength of Malaysia marine clay under different overconsolidation ratios (OCR) and strain amplitudes ranging from ±1% to ±5%. It is reported herein that the degradation of shear strength and pore water pressure increment are significant when cyclic strain amplitude applied on clay specimen increases. On the other hand, overconsolidated clay specimens tend to develop negative pore pressure at low strain level (±1%) as soon as cyclic tests began. However, normally consolidated clay specimens generate positive pore pressure at all strain amplitudes applied in the present study.**

Keywords: **Clay, strain-controlled, strain amplitudes, pore pressure, simple shear, overconsolidation ratio.**

I. INTRODUCTION

Offshore structures with marine clay foundation may be subjected to undrained cyclic loads due to earthquakes, ocean waves and pile driving [1]. Therefore, soft marine clay presents critical problems for the design of stable offshore structures against the cyclic loading [2]. Cyclic strain-controlled tests have been extensively investigated to study the effects of OCR by many researchers [3, 4, 5, 6].

The undrained cyclic loading may lead to failure of clay due to the development of pore pressure and cyclic induced shear strain [7, 8, 9, 10]. Clay soil exhibits pronounced non-linear and hysteretic behaviour under cyclic loading [11]. Kagawa [2] reported that the hysteresis loop produced in marine clay under cyclic loading is small at small strain amplitudes. However, at large strain amplitude, both the area of hysteresis loop and excess pore water pressure increase. Thus, the strength and stiffness of clay decrease. Mortezaie and Vucetic [5] also found that the cyclic degradation and pore water pressure changes corresponding to number of cycles are larger if the cyclic strain amplitudes are larger. The result revealed that the cyclic strain amplitude and number of cycles, *N*, are the determining factors which influence the degradation.

In the present study, the cyclic behaviour of Malaysia marine clay was tested in the cyclic strain-controlled simple shear tests. The objective of this investigation is to examine the influences of OCR and the strain amplitudes on Malaysia marine clay which govern the shear strength of marine clay subjected to undrained cyclic loading. Studies conducted on cyclic loading of Malaysia marine clay are scarce despite the vast exploration of oil and gas industry in Malaysia. Hence, the results of the present work can give valuable insights for the offshore geotechnical constructions.

II. TESTING PROGRAMME

The results presented herein have been derived from constant volume simple shear (CDSS) device conducted in the laboratory. The tests were performed on reconstituted marine clay specimens which were recovered from offshore Terengganu, Malaysia. The index properties of Terengganu offshore clay (TOC) are listed in Table I. A detailed geotechnical properties of clay specimens are further discussed by Thian and Lee [12].

TABLE.I: GEOTECHNICAL PROPERTIES OF TOC SPECIMEN

Liquid limit	54%
Plastic limit	27%
Plasticity index	27%
Clay fraction (d < 0.002 mm)	43%
Specific gravity	2.58

The saturated TOC specimen was prepared with moisture content of 40 % and initial dry density of about 1.25 g/cm^3. CDSS tests were conducted on cylindrical specimen of 70 mm diameter and 25 mm height. The specimen was consolidated under normal load within a stack of thin rings that provided lateral confinement, but allowed the specimen to be deformed vertically. During consolidation, stacked rings were clamped to prevent lateral strain. All the TOC specimens were subjected to K_o consolidation. Overconsolidated TOC specimens were consolidated at 400 kPa vertical stress before being unloaded to achieve the desired overconsolidation ratio prior to shearing. The specimens were tested at various OCR (OCR = 1, 4 and 10) with standard loading rate of 1.2 mm/min on all normally and overconsolidated specimens.

A modified computer-controlled CDSS device incorporated with a data logging system was used. CDSS tests on soils has been studied extensively for half a century and is described in the standard ASTM D 6528 [13]. The specimen height was continuously maintained during shearing test to ensure constant volume. Rather than measuring pore pressures, which would require complete saturation of specimen, the pore pressure response was inferred from the change in vertical stress. The change in soil sample vertical stress is assumed to be equal to the changes in pore pressure that would have taken place in a truly undrained test condition [14, 15, 16, 17]. In such tests, the vertical stresses applied via top specimen cap, and the horizontal stresses developed by the confinement of rubber membrane with stacked rings, are always effective stresses. Figure I illustrates the test specimen assembly for CDSS used in the present study.

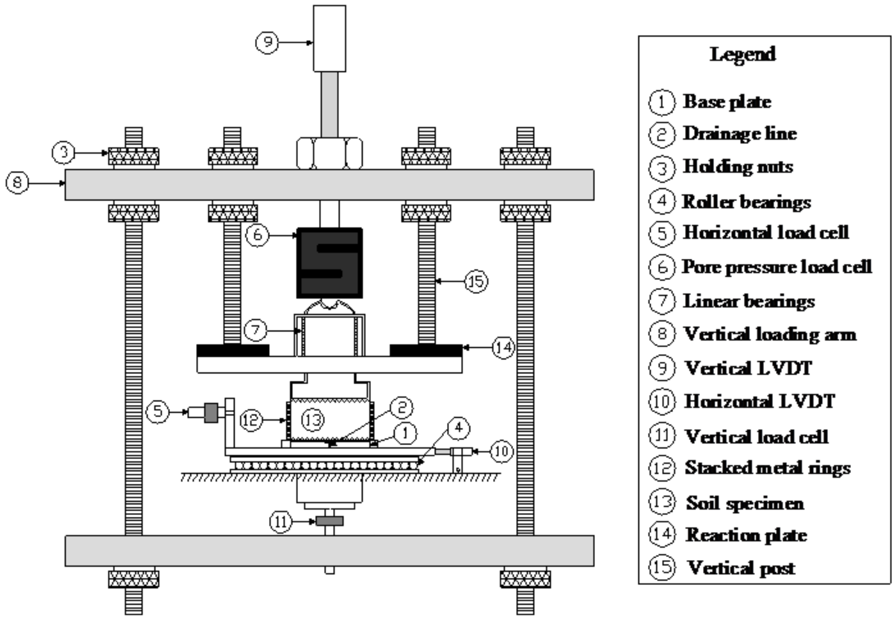


FIGURE.I: PLAN VIEW OF TEST SPECIMEN ASSEMBLY OF CDSS

In this study, undrained symmetrical (two-way) strain-controlled quasi-static tests were conducted on TOC specimens. Cyclic strain, γ_{cy} (single amplitude; $\gamma_{cy} = 0.5\cdot[\gamma_{max} - \gamma_{min}]$), ranging from ±1 to ±5% were kept constant during the test and cyclic stress, τ_{cy}, required to maintain the cyclic strain was measured. All cyclic tests were limited to maximum 500 cycles due to the limitation of the device. Details of the tests are given in Table II.

TABLE.II: CDSS TESTS FOR STRAIN-CONTROLLED TESTS

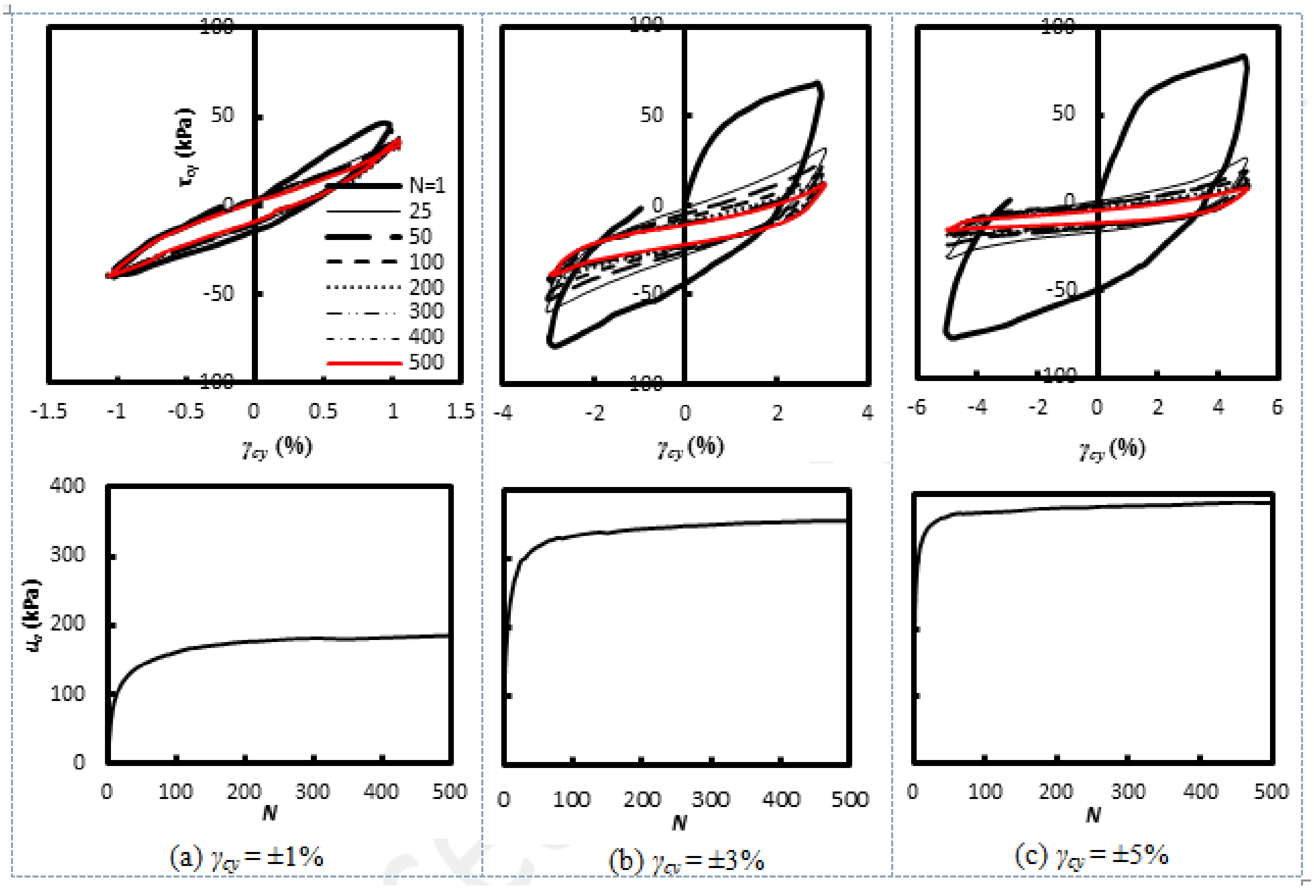
OCR	**Two-way strain-controlled tests; γ_{cy} (%)**
1	±1, ±3, ±5
4	±1, ±3, ±5
10	±1, ±3, ±5

III. RESULTS

Figure II presents the typical stress-strain hysteresis loops and average cyclic pore pressure, u_a, for normally consolidated TOC specimen subjected to strain-controlled tests at $\gamma_{cy} = \pm 1\%$, 3% and 5%. Generally, the amplitudes of γ_{cy} are constant, while the amplitudes of τ_{cy} degrade with the accumulation of u_a and N [5, 18]. The hysteresis loops for the first cycles gain high cyclic shear strength soon after the tests begin.

When TOC specimen is subjected to $\gamma_{cy} = \pm 1\%$ and $N > 25$, the shape of the hysteresis loops almost coincide with the previous ones. The specimen has reached equilibrium at this state where minimal degradation of cyclic strength is found. However, the τ_{cy} reduces significantly with N as the amplitude of γ_{cy} increases [19] especially when TOC specimen is subjected to $\gamma_{cy} = \pm 5\%$. The stress-strain hysteresis loops become more nonlinear and the hysteresis loops do not coincide with the previous ones. Instead, the hysteresis loops gradually tilt towards the horizontal axis and gradual softening of soil is noted. The area of the loops become fairly large with increasing γ_{cy} due to the larger damping at higher strain amplitudes [20]. The stress-strain loop clearly exhibits a reduction of the secant shear modulus with N [5].

FIGURE.II: SHEAR-STRESS AND PORE PRESSURE RESPONSES UNDER STRAIN-CONTROLLED TEST WITH γ_{cy} = ±1, 3 AND 5% AT OCR 1



Figures III and IV illustrate the stress-strain loops and u_a development for overconsolidated TOC specimens at OCR = 4 and 10, respectively. When overconsolidated TOC specimens undergo strain-controlled tests at $\gamma_{cy} = \pm 1$, 3 and 5%, they show similar stress-strain loops as those of normally consolidated specimens. The deterioration of τ_{cy} becomes more apparent as γ_{cy} increases. However, the u_a development of overconsolidated TOC specimens differs from that of normally consolidated specimens. Negative u_a is generated due to dilatancy in overconsolidated TOC specimens especially if γ_{cy} is small and OCR is high. Similar observation is reported by Soralump and Prasomsri [6], Matasovic and Vucetic [21], Hsu and Vucetic [22], Javed [23] and Mortezaie [24]. In overconsolidated clay, negative u_a develops at initial cyclic loading, despite the fact that degradation of soil stiffness and strength occurs simultaneously [21]. It is an interesting phenomenon in cyclic clay behaviour, because soil degradation occurs despite the evident increase in effective stress [25, 26]. In subsequent cycles, due to increase in number of cycles, the previous greater effective consolidation pressure diminishes and TOC specimen behaves as if it is normally consolidated [23, 27]. Hence, positive u_a is generated.

FIGURE.III: SHEAR-STRESS AND PORE PRESSURE RESPONSES UNDER STRAIN-CONTROLLED TEST WITH γ_{cy} = ±1.3, 3 AND 5% AT OCR 4

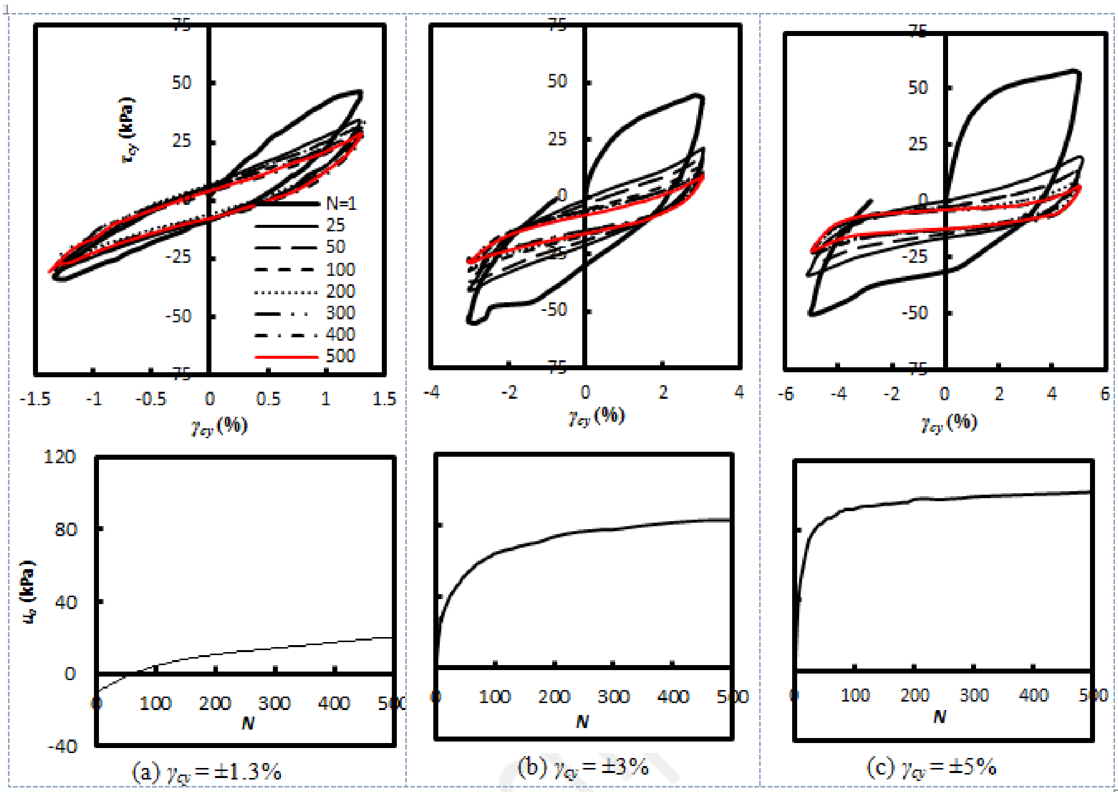
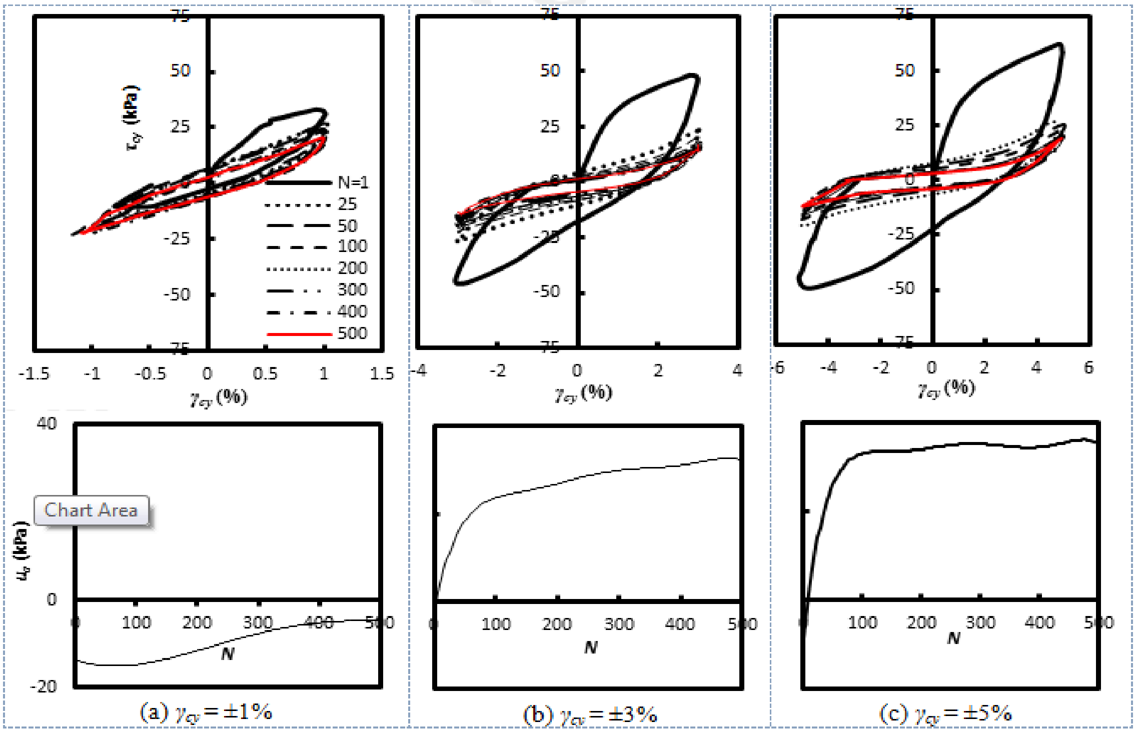


FIGURE.IV: SHEAR-STRESS AND PORE PRESSURE RESPONSES UNDER STRAIN-CONTROLLED TEST WITH γ_{cy} = ±1, 3 AND 5% AT OCR 10



IV. CONCLUSIONS

A series of two-way strain-controlled undrained cyclic simple shear tests was carried out to investigate the effect of OCR and strain amplitudes on reconstituted TOC specimens. The amplitudes of τ_{cy} degrade with the accumulation of pore pressure in clay specimens as the number of cycles increases. The degradation of τ_{cy} and pore pressure accumulation become more significant as strain amplitude increases in both normally and overconsolidated specimens. However, negative pore pressure is developed in overconsolidated specimens particularly when strain amplitude is small and OCR is high which can be attributed to dilatant tendency of clay. The hysteresis loops gradually tilt towards the horizontal axis and gradual softening of soil is noted.

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