STRESS-STRAIN AND STRENGTH CHARACTERISTICS OF CLAY DURING POST-CYCLIC MONOTONIC LOADING

By

HENDRA JITNO

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Department of **CIVIL ENGINEERING**

The University of British Columbia
Vancouver, Canada

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ABSTRACT

An important consideration in the design of clay foundation for seismic or wave loading is the undrained response of clay during and after cyclic loading. Cyclic loading of clays causes, in general, a reduction in both stiffness and undrained strength on subsequent static loading. No systematic study has been carried out to assess this loss in stiffness, and there are conflicting conclusions as to the magnitude of strength reduction in studies reported in the literature.

This thesis presents a study of the influence of cyclic loading on the post-cyclic undrained stress-strain characteristics of a marine clay. The influence of factors, such as, cyclic stress level, number of cycles, amplitude of maximum axial strain during cyclic loading, residual pore pressure and residual strain at the conclusion of cyclic loading is systematically investigated. In addition, the influence of initiating cyclic loading with the type of loading pulse (compression and extension) and the sense of residual strain in relation to the sense of strain during post-cyclic monotonic loading is studied.

It is shown that the loss in undrained stiffness and undrained strength of the undisturbed clay as a consequence of cyclic loading are not uniquely related to the amplitude of strain during cyclic loading, as commonly assumed. Nor can they be explained in terms of overconsolidation induced as a result of pore pressure generated due to cyclic loading. A rational explanation and correlation of both the changes in post-cyclic stress-strain and strength of clay is provided in terms of hysteretic work absorbed by the clay during cyclic loading.
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LIST OF SYMBOLS

\( \gamma_{afst} \) = Shear strain at peak shear stress.

\( \gamma_{amax} \) = Maximum shear strain during cyclic loading.

\( \Delta u \) = Pore pressure generated during monotonic loading.

\( \Delta u_{eq} \) = Pore pressure generated during equalization after cyclic loading.

\( \Delta u_{res} \) = Residual pore pressure.

\( \epsilon_a \) = Axial strain during monotonic loading.

\( \epsilon_{afpc} \) = Axial strain at peak deviator stress during post-cyclic static loading.

\( \epsilon_{afst} \) = Axial strain at peak deviator stress during monotonic loading.

\( \epsilon_{amax} \) = Maximum axial strain during cyclic loading.

\( \epsilon_{ares} \) = Residual strain.

\( \epsilon_{pp} \) = Peak to peak axial strain during cyclic loading.

\( \sigma^{'}/\sigma^{'\prime}_3 \) = Stress ratio.

\( \sigma^{'c} \) = Effective confining stress.

\( \sigma^{'cm} \) = Maximum effective consolidation stress.

\( \sigma_a \) = \( \sigma_v \) = Axial stress.

\( \sigma_d \) = \( \sigma_a - \sigma_r \) = Deviator stress.

\( \sigma_{dmax} \) = Maximum deviator stress.

\( \sigma_r \) = \( \sigma_h \) = Radial stress.

\( \tau_{cyc}/S_{uc} \) = Cyclic stress level.
\( \phi' \) = Friction angle.

\( c' \) = Cohesion intercept.

\( E_{sec} \) = Secant modulus.

\( \text{ESP} \) = Effective stress paths.

\( \text{LL} \) = Liquid Limit.

\( N \) = Number of cycles

\( \text{NC} \) = Normally consolidated clay.

\( \text{OC} \) = Overconsolidated clay due to unloading.

\( \text{OC}_{\text{cyc}} \) = Overconsolidated clay due to cyclic loading history.

\( \text{OCR} \) = Overconsolidation ratio due to unloading.

\( \text{OCR}_{\text{cyc}} \) = Overconsolidation ratio due to cyclic loading.

\( \text{PI} \) = Plasticity Index.

\( \text{PL} \) = Plastic Limit.

\( S_u \) = Undrained strength of undisturbed clay (NC and OC).

\( S_{uc} \) = Pre-cyclic undrained strength of NC clay in compression.

\( S_{ue} \) = Pre-cyclic undrained strength of NC clay in extension.

\( S_{upc} \) = Post-cyclic undrained strength of NC clay.

\( w \) = Hysteretic work absorbed by soil specimens per unit volume within 1 cycle (kJ/m\(^3\)).

\( W \) = Cumulative hysteretic work absorbed by soil specimens per unit volume (kJ/m\(^3\)).

\( w_n \) = Natural water content.
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Due mainly to critical liquefaction phenomena, attention has mostly focussed on understanding the behavior of cohesionless soils under undrained cyclic loading. However, the construction of major structures, such as offshore gravity platforms in the North Sea and nuclear power plant in New Jersey coastal waters, which are founded on cohesive soils, has necessitated study of the behavior of clay under undrained cyclic loading (e.g. Andersen, 1975; Andersen et al., 1980; Fischer et al., 1976; Foss et al, 1978; Lee and Focht, 1976; Koutsoftas, 1978; Singh et al., 1978).

Undrained cyclic loading of foundation clays could cause two types of stability problems: (1) failure during cyclic loading and (2) failure under static loads following cyclic loading. The first case may occur during severe storm or earthquake loading due to pore pressure increase and large strain development in the foundation clays. In case no failure occurs during cyclic loading, the strain developed and the pore pressure increase due to cyclic loading may cause a decrease in stiffness and undrained strength of clays. This stiffness and strength degradation may lead to large movement under the initial weight of the structure. Several case histories of clay slope failures after cyclic loading have been reported (e.g. Conlon, 1966; Morimoto et al, 1967).

Considerable research on the behavior of clays during cyclic loading has been done during the last three decades. Clay behavior has been studied under constant-
stress and constant-strain amplitude cyclic loading, both one-way and two-way loading, under isotropic and anisotropic consolidation stresses, using triaxial and simple shear apparatus (e.g. Andersen, 1975, 1976; Azzouz et al, 1989; Sangrey, 1966). It has been shown that at cyclic stress levels above a Critical Level of Repeated Loading (CLRL), strain and pore pressures generated increase with increasing number of cycles. At cyclic stress levels below CLRL, however, non failure equilibrium is reached. Previous studies using the triaxial apparatus usually initiate cyclic loading with a compression pulse. Possible differences in clay behavior when starting with extension pulse have not been considered.

Post-cyclic behavior of clay is generally considered to depend on maximum strain developed during cyclic loading. Little systematic study of post-cyclic stress-strain response and its relationship to precyclic behavior has been done. Some conclusions from these studies are conflicting. For example, post-cyclic stiffness of clays undergoing small maximum axial strain during cyclic loading has been shown to increase or decrease when compared to pre-cyclic stiffness (Motherwell and Wright, 1978; Taylor and Bacchus, 1969). Moreover, there has been no recognition of the differences in post-cyclic stiffness depending on the sense of residual strain after cyclic loading in relation to the sense of strain during post-cyclic loading.

The ratio of post-cyclic and pre-cyclic undrained strength is generally considered to be related to the ratio of the maximum axial strain developed during cyclic loading and the axial strain at peak strength during pre-cyclic monotonic loading. Such relationships although found reasonable in constant-stress amplitude
cyclic loading are not found to be valid under constant-strain amplitude loading. A survey of the literature suggests that undrained strength ratio is related not only to the maximum axial strain during cyclic loading, but may also depend on other cyclic loading parameters, such as cyclic stress level, number of cycles, residual strain and pore pressure induced due to cyclic loading.

A systematic testing program aimed at investigating the fundamental behavior of clay during post-cyclic undrained monotonic loading and its relationship to pre-cyclic behavior was devised. The study is confined to isotropically normally consolidated clay in the triaxial apparatus. Both post-cyclic stress-strain and undrained strength characteristics are examined. Differences between post-cyclic and pre-cyclic behavior are related to cyclic loading parameters such as cyclic stress levels, maximum axial strain, residual pore pressure, residual strain and the nature of loading pulse used during cyclic loading. The concept of hysteretic work absorbed during cyclic loading is advanced to explain rationally some of the observations related to stiffness and strength degradation of clay during post-cyclic monotonic loading.

Important findings and conclusions from previous work on undrained behavior of clay during and after cyclic loading will be critically reviewed in Chapter 2. This is followed by a description of the testing apparatus, material tested and the test procedures adopted in this study in Chapter 3. In Chapter 4, the results of undrained behavior during and after cyclic loading are presented and discussed with emphasis on the elucidation of post-cyclic monotonic behavior. Primary findings of this investigation are then summarized and concluded in Chapter 5.
CHAPTER 2

LITERATURE REVIEW

2.1. Clay Behavior During Undrained Cyclic Loading

A large number of studies (e.g. Andersen, 1975; Azzouz et al., 1989; Sangrey, 1966; Seed and Chan, 1966) have been reported in literature regarding the behavior of clay during undrained cyclic loading. The studies were conducted in both triaxial and simple shear apparatus under constant-stress and constant-strain amplitude cyclic loading, one-way and two-way loading, on normally consolidated (NC) and overconsolidated clay (OC) and under isotropic and anisotropic consolidation stress. General aspects of clay behavior during undrained cyclic loading will be discussed herein.

2.1.1. Strain and Pore Pressure Development

There is a general agreement among the results of previous investigations regarding the effect of cyclic stress level \( \frac{\tau_{\text{cyc}}}{S_{\text{uc}}} \) on strain and pore pressure development. At cyclic stress levels below a certain magnitude called the critical level of repeated loading (CLRL) the clay will develop strain until a state of equilibrium is reached. At this stage, a closed hysteresis loop occurs with subsequent cycles. At cyclic stress levels above CLRL, the strain and the pore pressure developed increase as the number of cycles increases. The rate of strain development and pore pressure generation also increases with increasing cyclic stress levels (Figure 2.1.a & b). This
Figure 2.1. Strain and pore pressure development during cyclic loading at various cyclic stress levels.
general behavior has been found for normally consolidated and overconsolidated clays under one-way and two-way cyclic loading in both triaxial and simple shear tests.

Previous investigations on clay behavior under two-way cyclic loading using the triaxial apparatus generally initiate cyclic loading with a compression pulse. In this pulse type, axial strain development seems to be faster on extension than on compression side. This behavior was observed on both NC and OC clay (Andersen, 1980; Fischer et al., 1978). This is believed to be attributed to inherent anisotropy of clay. However, no data regarding clay behavior during two-way cyclic loading starting with extension pulse has been reported. It will be of interest to study possible differences in clay behavior due to these different cyclic loading pulses.

2.1.2. Hysteretic Work During Cyclic Loading

Several investigators have tried to correlate hysteretic work absorbed by the soil to pore pressure development during cyclic loading on sands (e.g. Finn and Bhatia, 1981; Kuerbis, 1989; Towhata and Ishihara, 1984). Others attempted to use it to assess liquefaction potential of sands (e.g. Law et al., 1990). In clay soils, attention has also been paid to determine hysteretic work and total strain energy to study the damping characteristics of soil at very low strain levels (e.g. Hardin and Drnevich, 1972; Seed and Idriss, 1970). However, limited information has been published regarding hysteretic work at high strain levels. Two of the published work on this topic will be reviewed herein.
Hysteretic work data from Taylor and Bacchus (1969), is replotted in Figure 2.2. This figure shows the hysteretic work absorbed by the soil per unit volume in each cycle \( (w) \) during constant-strain amplitude cyclic loading \( (f=0.2 \text{ Hertz}) \). The figure suggests that for a given number of cycles, the clay subjected to the largest strain amplitude accumulates the greatest \( w \). Moreover, at a given strain amplitude, \( w \) decreases with increasing number of cycles. The decrease is more substantial in the clay subjected to large strain amplitudes.

Devenny (1975) studied the differences between hysteretic work absorbed during constant-strain and constant-stress amplitude cyclic loading tests on Leda clay, leached Leda clay and grundite. He computed the cumulative hysteretic work \( (W) \) and plotted it as a function of number of cycles. The development of \( W \) during cyclic loading is plotted schematically in Figure 2.3. In constant-strain amplitude cyclic test \( \text{(curve B)} \), \( W \) develops very rapidly at lower number of cycles but the increase in \( W \) slows down as the number of cycles increases. This agrees with the data from Taylor and Bacchus (1969) in Figure 2.2. On the other hand, under constant-stress amplitude cyclic loading \( \text{(curve B)} \), \( W \) gradually increases with number of cycle and the slope of \( W \) curve increases as the number of cycles increases. As a consequence, at a lower number of cycles, constant-strain amplitude cyclic tests tend to yield higher value of \( W \) than constant-stress amplitude cyclic tests. Such difference in \( W \) absorbed between the two methods of loading (constant-strain or constant-stress amplitude) could explain some of the contradictory conclusions in the literature regarding some aspects of clay behavior during cyclic and post-cyclic monotonic loading.
Figure 2.2. Hysteretic work absorbed per unit volume in each number of cycle (After Taylor and Bacchus, 1969).
Figure 2.3. Schematic diagram of cumulative hysteretic work absorbed during cyclic loading for different method of loading.
2.2. Post-cyclic Undrained Monotonic Behavior

2.2.1. Stress-Strain Characteristics

Little attention has been paid to the study of post-cyclic stress-strain characteristics of clay. Previous investigators generally found that the stress-strain response of NC clay during post-cyclic monotonic loading is softer than that of clay without cyclic loading. This finding was reported by several researchers including Andersen (1975, 1988), Castro and Christian (1976), Koutsoftas (1978), Matsui et al. (1980), Matsui and Abe (1981), and Singh et al. (1978).

Maximum axial strain ($\varepsilon_{amax}$) during cyclic loading has been considered to influence post-cyclic behavior in a major way. The stiffness degradation increases as $\varepsilon_{amax}$ increases (Figure 2.4.a). This behavior has been observed by Taylor and Bacchus (1969) in constant-strain amplitude cyclic tests on Halloysite clay (LL=62, PL=36). Koutsoftas (1978) reported similar behavior in constant-stress amplitude cyclic loading on two marine clays (Figure 2.4.b). For similar levels of $\varepsilon_{amax}$ (e.g. at $\varepsilon_{amax}=0.80\%$), stiffness degradation is found to be much more severe in constant strain than constant stress amplitude loading.

Despite a general agreement among the data reported regarding soil stiffness degradation due to cyclic loading, Motherwell and Wright (1978) found that clays that reached an equilibrium condition during constant stress amplitude one-way cyclic loading, demonstrate somewhat stiffer stress-strain response on subsequent static loading (Figure 2.4.c). Such a tendency may also be noticed in the data reported by Andersen (1975) in similar tests on Drammen clay. Cyclic loading with stress levels
Figure 2.4. Stress-strain characteristics during post-cyclic monotonic loading.
below the critical level of repeated loading may contribute to stiffening instead of softening of post-cyclic response. The maximum axial strain due to cyclic loading was less than 1% (Motherwell and Wright, 1978) and less than 0.6% for Drammen clay (Andersen, 1975). It is interesting to note that this behavior does not emerge in Taylor and Bacchus's results (Figure 2.4.a) at similar small maximum axial strain levels, and even for $\epsilon_{\text{amax}}$ as low as 0.14 %. These differences in behavior may lie in the nature of stress-controlled versus strain-controlled cyclic loading.

2.2.2. Effective Stress Paths and Failure

Several researchers have reported the similarity in undrained effective stress paths (ESP) of overconsolidated clay and that of normally consolidated clay after cyclic loading (OC$_{\text{cyc}}$) (Andersen, 1975; Hyde and Ward, 1986; Matsui and Abe, 1981; Singh et al., 1978). Increase in pore pressure due to cyclic loading of normally consolidated clays has been considered to impart to it an effect similar to overconsolidation.

Andersen (1975) observed an increase in cohesion intercept $c'$ in NC clay that was monotonically loaded following cyclic loading, whereas the friction angle $\phi'$ remained essentially equal to the pre-cyclic $\phi'$ (Figure 2.5.a). Hyde and Ward (1986) also show that an increase in $c'$ is observed for NC and lightly OC clay during post-cyclic monotonic loading (Figure 2.5.b). It must be noted, however, that neither Andersen (1975) nor Hyde and Ward (1986) allowed the pore pressure generated during cyclic loading to equalize prior to post-cyclic monotonic loading. This could
Figure 2.5. Effective stress paths during post-cyclic monotonic loading.
result in erroneous pore pressure measurements and hence influence inferred strength parameters.

The increase of $c'$ in NC clay as a result of cyclic loading does not appear in the data of Singh et al. (1978), Figure 2.5.c. The data represents the behavior of a Holocene clay ($w_a=37-48\%$; $LL=33-40\%$, $LL=18-20\%$) subjected to constant strain amplitude cyclic loading and then sheared monotonically after allowing 24 hours pore pressure equalization. This different ESP response from Figure 2.5.a and b may be attributed to different characteristics of pre-cyclic NC and OC of Holocene clay.

2.2.3. Post-cyclic Undrained Strength

Two different approaches have been used to explain the relationship between pre and post-cyclic undrained strength of clays. Both recognize the dependency of post cyclic strength of soil on residual pore pressures due to cyclic loading. Despite this awareness, proponents of the first approach (Thiers and Seed, 1969; Lee and Focht, 1976, Ling, 1977; Sangrey and France, 1980) believe that the post cyclic undrained strength can be estimated by only looking at the maximum strain developed during cyclic loading. They reasoned that since the excess pore pressure is fundamentally a strain dependent rather than a stress dependent process, the post cyclic undrained strength is also a strain dependent process. Proponents of the second approach such as Azzouz et al.(1989), Koutsoftas (1978), Matsui et al.(1980), Matsui and Abe (1981), Singh et al. (1978), and Yasuhara (1985) attempted to relate the post-cyclic undrained strength to overconsolidation ratio, $OCR_{cyc}$, induced by cyclic loading. They argued
that the post-cyclic undrained strength of clay is more closely related to the OCR$_{cyc}$ than the maximum axial strain developed during cyclic loading. Some of the published work is summarized in Table 2.1.

2.2.3.a. Strain Approach

Results from Constant-Strain Amplitude Cyclic Loading

Figure 2.6 shows results of Thiers and Seed (1969) on San Francisco Bay Mud and Anchorage silty clay. Additional data from Taylor and Bacchus (1969) and Ling (1977) are also included. All data shown were obtained from the samples previously subjected to constant-strain amplitude cyclic loading and were subsequently sheared monotonically.

Based on the data shown in Figure 2.6 (curve A), Thiers and Seed (1969) concluded that as long as the maximum axial strain ($\epsilon_{amax}$) remains below one half of the peak strain at failure during pre-cyclic undrained monotonic test ($\epsilon_{afst}$), the loss of undrained strength will not be significant. However, at $\epsilon_{amax}$ in excess of this value, a dramatic reduction in undrained strength occurs. The data obtained on a Halloysite clay (curve B) by Taylor and Bacchus (1969), however, does not appear to support conclusions of Thiers and Seed. Curve B in Figure 2.6 clearly shows that even at $\epsilon_{amax}/\epsilon_{afst}$ about 0.2, the undrained strength reduction is as high as 25% which increase to 40% at $\epsilon_{amax}/\epsilon_{afst}$ of about 0.4. Similar deviation from Thiers and Seed's hypothesis is more dramatically observed in the data of Ling (1977), curve C Figure 2.6. The post-cyclic data was obtained from NE Pacific clay loaded under constant-strain
### Table 2.1. Summary of Some Published Work on Post-Cyclic Undrained Strength of Clay

<table>
<thead>
<tr>
<th>Type of clay</th>
<th>$w_n$ (%)</th>
<th>LL (%)</th>
<th>PL (%)</th>
<th>$%&lt;\mu$</th>
<th>Loading</th>
<th>Freq. (Hz)</th>
<th>N</th>
<th>Pp equal.</th>
<th>Strength Loss at $\frac{\varepsilon_{\text{max}}}{\varepsilon_{\text{afst}}} = 1.0$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Drammen Clay (NC)</td>
<td>52</td>
<td>55</td>
<td>28</td>
<td>45-55</td>
<td>A,C,D,S,Tz</td>
<td>0.1</td>
<td>&gt;2655 No</td>
<td>&lt;10%</td>
<td>&lt;20%</td>
<td>Andersen (1975)</td>
</tr>
<tr>
<td>2. Drammen Clay (OC)</td>
<td>52</td>
<td>55</td>
<td>28</td>
<td>45-55</td>
<td>A,C,D,S,Tz</td>
<td>0.1</td>
<td>≤5000 No</td>
<td>&lt;20%</td>
<td>&lt;40%</td>
<td>Andersen (1975)</td>
</tr>
<tr>
<td>3. SF Bay Mud &amp; Anchorage Silty clay</td>
<td>85-96</td>
<td>88</td>
<td>43</td>
<td>?</td>
<td>B,D,S</td>
<td>1.0</td>
<td>200 No</td>
<td>&lt;10%</td>
<td>=60%</td>
<td>Thiers and Seed (1969)</td>
</tr>
<tr>
<td>4. Halloysite</td>
<td>37-42</td>
<td>62</td>
<td>36</td>
<td>100</td>
<td>B,D,S</td>
<td>0.2</td>
<td>100 ?</td>
<td>&lt;55%</td>
<td>=60%</td>
<td>Taylor and Bacchus (1969)</td>
</tr>
<tr>
<td>5. Holocene Clay</td>
<td>50-60</td>
<td>60-90</td>
<td>30-40</td>
<td>?</td>
<td>A,D,S</td>
<td>1.0</td>
<td>&lt;5000 Yes</td>
<td>&lt;10%</td>
<td>&lt;20%</td>
<td>Koutsofas (1978)</td>
</tr>
<tr>
<td>- Plastic</td>
<td>30-40</td>
<td>30-50</td>
<td>15-20</td>
<td>70</td>
<td>A,D,S</td>
<td>1.0</td>
<td>&lt;5000 Yes</td>
<td>&lt;10%</td>
<td>&lt;20%</td>
<td>Koutsofas (1978)</td>
</tr>
<tr>
<td>- Silty</td>
<td>50-60</td>
<td>60-90</td>
<td>30-40</td>
<td>?</td>
<td>A,D,S</td>
<td>1.0</td>
<td>&lt;5000 Yes</td>
<td>&lt;10%</td>
<td>&lt;20%</td>
<td>Koutsofas (1978)</td>
</tr>
<tr>
<td>6. NE Pacific clay</td>
<td>95</td>
<td>40</td>
<td>75</td>
<td>?</td>
<td>B,D,S</td>
<td>0.025</td>
<td>50-6500 ?</td>
<td>0-33%</td>
<td>?</td>
<td>Ling (1977)</td>
</tr>
<tr>
<td>8. Kaolinite</td>
<td>73-75</td>
<td>82</td>
<td>42</td>
<td>100</td>
<td>A,C</td>
<td>0.1</td>
<td>≤500 No</td>
<td>None</td>
<td>?</td>
<td>Motherwell and Wright (1978)</td>
</tr>
</tbody>
</table>

**Note:**
- A = Constant-stress amplitude cyclic loading test
- B = Constant-strain amplitude cyclic loading test
- C = One-way cyclic loading
- D = Two-way cyclic loading
- S = Sinusoidal Pulse
- Tz = Trapezoidal Pulse
Figure 2.6. Change in undrained strength after a constant-strain amplitude cyclic loading.
amplitude cyclic loading in Torsional Simple Shear Device (TSSD). Test samples were subjected to a given strain amplitude but number of cycles (N) ranging from 50 to 6500 (Ling, 1977). The highest point on curve C represents the sample with N=50, and the lowest point with N=6500. For the selected $\gamma_{amax}/\gamma_{afst}$ of about 0.1, the loss in undrained strength varies from 0 to 33 %. Ling's data clearly shows that the undrained strength loss due to constant-strain amplitude cyclic loading depends not only on maximum axial strain but also on the number of loading cycles.

Results from Constant-Stress Amplitude Cyclic Loading

While Thiers and Seed (1969), Taylor and Bacchus (1969), and Ling (1977) found a substantial loss in undrained strength due to cyclic straining at $\varepsilon_{amax} = 0.5 \varepsilon_{afst}$ or less, other investigators who used constant-stress amplitude cyclic loading reported only small or even no significant strength reduction at similar $\varepsilon_{amax}$ levels.

Koutsoftas (1978) presented a study of the effect of cyclic loading on two marine clays. He summarized his results on a plot similar to that used by Thiers and Seed (1969), as shown in Figure 2.7. Although Koutsoftas noticed that the post-cyclic undrained strength is a function of $\varepsilon_{amax}/\varepsilon_{afst}$, the post-cyclic undrained strength never dropped below 80 % of precyclic value even at $\varepsilon_{amax}/\varepsilon_{afst} = 1.0$. His findings are in agreement with the results presented by Castro and Christian (1976) who show that there is a maximum of 20% reduction in undrained strength of silty clay even after 14.6% double amplitude axial strain ($\varepsilon_{amax}/\varepsilon_{afst}$ about 1.8).

Andersen (1975) was the first who expressed the opinion that the post-cyclic
Figure 2.7. Change in undrained strength after constant-stress amplitude cyclic loading. (Koutsofas, 1978).
undrained strength seems to be dependent not only on $\epsilon_{\text{amax}}$ but also on number of cycles during cyclic loading. Based on a comprehensive study on Drammen clay, he concluded that provided the maximum shear strains are less than 3% (for triaxial test: $\epsilon_{\text{amax}} < 2\%$) and the number of cycles do not exceed 1000, the strength loss will be less than 25% (Figure 2.8).

Two possible reasons for the difference between the results reported by Thiers and Seed (1969), Taylor and Bacchus (1969), Ling (1977) and Koutsoftas (1978), Castro and Christian (1976), Andersen (1975) can be advanced: (1) different soil types and (2) different methods of loading. Different soil plasticity may lead to different behavior during monotonic or cyclic loading. Different method of loading (constant-strain and constant-stress amplitude) may result in different hysteretic work absorbed by the soil specimens at any given $\epsilon_{\text{amax}}$, as discussed in Section 2.1.2. These differences are likely to give rise to different characteristic behavior during post-cyclic monotonic loading.

2.2.3.b. OCR Approach

An alternative point of view advanced by other researchers such as Azzouz et al. (1989), Koutsoftas (1978), Matsui et al. (1980), Matsui and Abe (1981), Singh et al. (1978), and Yasuhara (1985) is that the post-cyclic undrained strength depends on $\text{OCR}_{\text{cyj}}$. They concluded that the post-cyclic monotonic undrained strength is very close to the undrained strength of undisturbed OC at OCR equal to $\text{OCR}_{\text{cyj}}$. This is
Figure 2.8. Change in undrained strength during post-cyclic monotonic loading on Drammen clay: a. Simple shear test (OCR=4) b. Triaxial test (NC). (Andersen, 1975).
shown in the plot of $S_{upc}/\sigma'_c$ versus OCR$_{cyc}$ in Figure 2.9. The relationship between post-cyclic strength and OCR$_{cyc}$ may be seen to be similar to the plot of $S_{uc}/\sigma'_c$ versus OCR for stress overconsolidated clay. Thus, post-cyclic undrained strength can be predicted provided OCR$_{cyc}$ is known.

Figure 2.9 suggests that despite the similarity of shape, the $S_u$ - OCR relationship for OCR$_{cyc}$ clay (curve B) lies above the relationship for OC undisturbed clay (curve A). Singh et al. (1978) reported similar trend between OC undisturbed and OC$_{cyc}$ clay in their triaxial test data. This implies that at a given OCR, OC$_{cyc}$ clay is stronger than OC undisturbed and the strength difference increases with increasing OCR. This OCR approach seems to be suitable only for low OCR$_{cyc}$ values. It will yield values of post-cyclic undrained strength that are too conservative in case of high OCR$_{cyc}$ values.

2.2.4. Summary

The review of published work on the behavior of clay during and after cyclic loading suggests that there is no general consensus among researches regarding the effect of cyclic loading parameters on stiffness degradation and undrained strength loss during post-cyclic monotonic loading.

Different stiffness degradation experienced by samples having similar $\varepsilon_{amax}$ but different methods of loading, as discussed in Section 2.2.1, suggests that $\varepsilon_{amax}$ may not be the only parameter governing the post-cyclic stress-strain characteristics. This emphasizes the need for studying effect of $\varepsilon_{amax}$ on stress strain characteristics after
Figure 2.9. Comparison between undrained strength of OC clay due to cyclic loading history and OC clay due to unloading history.
cyclic loading. Conflicting conclusions regarding the effect of cyclic loading on $c'$ increase in NC clay, as discussed in Section 2.2.2, also need further clarifications. Comparison of stress-strain characteristics among samples having similar $OCR_{cyc}$ but different $\epsilon_{amax}$, and among samples having $OCR_{cyc}$ equal stress OCR are also of interest. In addition, the influence of initiating cyclic loading with type of loading pulse (E/C or C/E) and the sense of residual strain on the post-cyclic stress-strain characteristics needs to be clarified. These studies would allow possible factor(s) that influence stress-strain characteristics during post-cyclic monotonic loading to be identified.

The post-cyclic undrained strength of clay seems to be dependent on $\epsilon_{amax}$, number of cycles and method of loading. This dependency complicates the prediction of undrained strength reduction. Post-cyclic undrained strength prediction based on only one of these parameters would not yield reliable values.

The post-cyclic undrained strength is often correlated to $OCR_{cyc}$. This relationship is considered similar to that for OC undisturbed clay. The indication that the actual strength at a given $OCR_{cyc}$ seems to be higher than that of OC undisturbed clays at OCR equal $OCR_{cyc}$ needs further confirmation. Furthermore, since the $OCR_{cyc}$ is a function of residual pore pressure after cyclic loading ($\Delta u_{res}$), it would be interesting to examine the effect of different $\epsilon_{amax}$ levels for a given $\Delta u_{res}$ on post-cyclic undrained strength.

The study in this thesis is intended to clarify the effect of cyclic loading parameters on the post-cyclic stress-strain characteristics and post-cyclic undrained
strength. In particular, the effect of maximum axial strain, residual strain, residual pore pressure or OCRcyc, and cumulative hysteretic work absorbed by soil specimens (W) is investigated. The hypothesis that post-cyclic monotonic behavior is governed by the amount of cumulative energy dissipated during cyclic loading will be examined. Furthermore, the effects of cyclic stress level, $\epsilon_{amax}$, and different sense of loading pulse on pore pressure generation during cyclic loading and after equalization will be examined.
CHAPTER 3
EXPERIMENTATION

In this chapter, the details of experimental aspects are discussed. The test equipment including measurement devices and data acquisition system are described first, followed by discussion of material tested and test procedures. The testing program is then described and finally the repeatability of test results is discussed.

3.1. Test Equipment

3.1.1. Triaxial Apparatus

All tests were carried out using the triaxial apparatus. The top cap of triaxial apparatus is threaded to the loading ram to facilitate monotonic compression and extension loading, as well as cyclic loading tests. Triaxial specimens were 35 mm diameter x 81 mm high. Conventional frictional end plattens were used in this testing program for the following reasons: (1) Marginal effectiveness of frictionless end plattens due to long testing times (Duncan and Dunlop, 1968). (2) Length to diameter in excess of 2 gives no significant error in the strength measurement (Bishop and Henkel, 1957; Lacasse and Berre, 1988).

A low-friction continuously air-leaking hydrostatic seal was employed (Figure 3.1). This enabled confident measurements of axial load outside the cell. In utilizing this hydrostatic seal, air pressure equal to the cell pressure is applied through the loading ram housing to counteract the cell pressure. This results in a thin film of air
Figure 3.1. Components of the hydrostatic seal system for low friction triaxial cell. (After Zergoun, 1982).
continuously bleeding past the low clearance between the fixed ring and the loading ram.

3.1.2. Loading System

The loading system consists of two parts, monotonic loading system and cyclic loading system. In general, the system is similar to that described by Vaid et al. (1987). However, a small modification in the loading piston for cyclic tests was done to enable faster constant stress amplitude cyclic loading.

3.1.2.1. Consolidation

Consolidation can be performed using either monotonic or cyclic loading system. Isotropic consolidation was achieved by applying compensating load in vertical direction to counter the uplift force on the triaxial loading ram. Complete features of monotonic and cyclic loading system will be discussed in the following section.

3.1.2.2. Monotonic Loading System

The monotonic loading system allows tests under load or strain controlled conditions. It consists of a double-acting water saturated piston, a strain drive, and a displacement plunger (Figure 3.2). Each side of the piston is connected to the displacement plunger and a reservoir fed by regulated pressure. Stress-controlled loading can be carried out by adjusting pressures in the reservoirs. For performing strain-controlled monotonic tests, the strain drive feeds water at a constant rate from
Figure 3.2: Schematic layout of monotonic loading apparatus.
the displacement plunger to the loading piston. Depending on the feed chamber of the loading piston, either compression test or extension test can be carried out.

3.1.2.3. Cyclic Loading System

The cyclic loading system consists of a double-acting loading piston, a function generator driving an electropneumatic transducers and a ratio relay (Figure 3.3). Instead of water-piston, a double-acting air piston was utilized to apply cyclic loads to the specimens. The air pressure in the bottom chamber of the piston was controlled by the pressure regulator whereas the pressure in the top chamber was controlled by the DC Offset from the function generator. Sinusoidal voltage signals produced by the function generator are converted to cyclic pressure by the electro-pneumatic transducer which are fed to the top chamber of the piston. Since the output of the electropneumatic transducer was too small to generate the cyclic stress levels needed, a ratio relay was employed to amplify the output pressures.

3.2. Measurement Devices

Electronic transducers were used to measure all variables. The transducers were selected with consideration as to their stability and repeatability. A stable transducer is required for testing over long periods of time, whereas high-repeatability transducer is important for cyclic loading tests (Germaine and Ladd, 1988).

Each loading system has four transducers. Two pressure transducers, with resolution of 0.05 kpa and 0.1 kpa, respectively were utilized to monitor pore water
Figure 3.3: Schematic layout of cyclic loading apparatus.
pressure and cell pressure. The axial load was measured by a 50 kg capacity load cell capable of measuring deviator stress as low as 0.02 kpa. The volume change during consolidation was recorded using a pipette and the change in axial deformation was monitored using a Linear Variable Displacement Transducer (LVDT). Axial strains could be measured with a resolution of 0.01%. All transducers, except load cells, were exited by 6 volts D.C. D.C. power supplies set at 9.5 volts were used to excite the load cells.

3.3. Data Acquisition

A computer interfaced data acquisition system (HP 3497A) was used to automatically record test data. During monotonic loadings, data at discrete time intervals was directly stored in floppy disks. During cyclic loadings, however, the data was stored in a 200 kilo byte ram-disk to enable fast reading and storing. As many as 11 readings per second could be obtained using this system. The data were then transferred to a floppy disk after the cyclic test was completed. In addition, test data was also continuously monitored in parallel by means of a three-pen strip chart recorder (Figure 3.3).

3.4. Material Tested

A local undisturbed marine clay called Cloverdale clay was used in this study. Cloverdale clay is grey, sensitive, silty clay of soft consistency. Sensitivity is attributed to leaching due to surface infiltration following marine deposition. The clay was block
sampled from an open excavation. Some physical properties of the clay are given in Table 3.1.

3.5. Test Procedure

In undrained tests, one should be aware of the several factors causing errors in the pore pressure measurements. Membrane leakage, saturation of the membrane and the measuring system and air diffusion into the sample can be potential sources of these errors.

Leakage out of the specimen tends to decrease the measured pore pressure, while leakage into the specimen causes increase in pore pressure. These leakages were minimized by using swagelok fittings in the measurement system, and by sealing the samples to the end caps with two rubber O-rings.

Unsaturated membrane could significantly decrease the measured pore pressures during the tests. Baldi et al. (1988) reported that in triaxial tests on Lower Cromer Till (LL=25%, PI=13%), unsoaked membranes caused an increase in effective stress as high as 50% when the specimens were left undrained for 8 hours under zero deviator stress. On the other hand, pre-soaked membranes decreased the effective stress as low as 3% during the first 2 hours, but subsequently increased it back to the initial effective stress after about 4 hours. Although the pore pressure increase due to arrest of secondary consolidation was not taken into account, the effect of pre-soaked and unsoaked on changes in effective stress was evident. Therefore, to minimize the errors caused by water exchange between the membrane
Table 3.1. Physical properties of Cloverdale clay

(After Zergoun, 1990)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural water content</td>
<td>51 % ± 3 %</td>
</tr>
<tr>
<td>Liquid limit</td>
<td>51 % ± 3 %</td>
</tr>
<tr>
<td>Plastic limit</td>
<td>24 % ± 3 %</td>
</tr>
<tr>
<td>Plasticity Index</td>
<td>27 % ± 3 %</td>
</tr>
<tr>
<td>Liquidity Index</td>
<td>1.0</td>
</tr>
<tr>
<td>Degree of saturation</td>
<td>100 %</td>
</tr>
<tr>
<td>Specific gravity at 20° C</td>
<td>2.79</td>
</tr>
<tr>
<td>Clay fraction (d &lt; 0.002 mm)</td>
<td>49 %</td>
</tr>
<tr>
<td>Silt fraction (0.002 mm &lt; d &lt; 0.06 mm)</td>
<td>45 %</td>
</tr>
<tr>
<td>Activity</td>
<td>0.55</td>
</tr>
<tr>
<td>Sensitivity (Lab. vane)</td>
<td>16</td>
</tr>
<tr>
<td>Past maximum consolidation pressure</td>
<td>95 kpa</td>
</tr>
<tr>
<td>Undrained strength (Lab. vane)</td>
<td>15 kpa</td>
</tr>
<tr>
<td>Salt content of pore fluid</td>
<td>5 g/l</td>
</tr>
</tbody>
</table>
and the specimen, the membranes were soaked for at least 4 hours prior to their used in the test.

The measured pore pressures will be lower than the actual if the measuring system is not fully saturated. The pore pressure measuring system was fully saturated by flushing all lines in the system with de-air water and using a back pressure to dissolve air bubbles, if any. Moreover, to increase the rigidity of the system, a stiff diaphragm pressure transducer was used and the 0.3 cm outside diameter saran tube drainage lines between the cell and the transducers were kept as short as possible.

The air diffusion through the membrane was minimized by utilizing de-aired water for the cell fluid. The saran tube diffusion loops of about 1 meter long between the specimen or the cell and the air-water interfaces in the back-pressure pipette or the cell pressure reservoir prevented air diffusion into both the cell fluid and pore water.

3.5.1. Sample Preparation

Triaxial specimen were trimmed from the undisturbed blocks taken from the same horizon. This ensured minimum variability among individual specimens. Porous stones were boiled for at least 15 minutes and cooled to room temperature prior to trimming the specimens. The height, circumference and the weight of the samples were then measured.

A water presoaked latex membrane of 0.3 mm thick was installed onto the samples using dummy end caps and a membrane stretcher (Figure 3.4.a). The air trapped between the membrane and the samples, if any, was worked out using gentle
finger pressure. The membrane was then folded over at the specimen ends in preparation for installation on the triaxial base pedestal. The saturated porous stones were inserted in the recesses of the triaxial base pedestal and the top cap. The sample was then carefully placed on the triaxial pedestal and the membrane unrolled onto the pedestal. Care was taken not to trap any air in this process. After sealing the membrane to the pedestal with two rubber O-rings, the triaxial top cap with its drainage spiral was carefully placed on the sample. The membrane was unrolled and sealed with two O-rings that awaited on expanders threaded onto the top drainage spiral (Figure 3.4.b). Immediately, a vacuum of about 5-7 cm Hg was applied to Reservoir 1 and the drainage lines opened for about 30 seconds to draw out any excess water (Figure 3.4.b). This eliminates the possibility of water exchange between porous stones the specimens. The triaxial cell was then assembled and filled with de-aired water.

3.5.2. Sample Set Up

Extreme care was taken to avoid disturbance during cell assembly and sample set up. The LVDT bracket was clamped to the loading ram and was adjusted so that it had a suitable clearance from the top of the triaxial cell. After positioning triaxial apparatus in the loading frame, the cell pressure lines from the triaxial chamber was connected to cell pressure source. The cell pressure was transmitted through Reservoir 2 and 3 (Figure 3.4.c). Before zero readings were taken, the water level in the pipette was adjusted to correspond to the middle of the sample. Zero readings for
Figure 3.4: A schematic diagram of testing procedures.
LVDT, cell pressure, pore pressure and load cell were now taken. Atmospheric pressure was taken as zero reference for pressure transducers, whereas the load cell output when freely suspended from the loading piston was taken as zero reference load.

Reservoir 2 is connected to the triaxial cell by a large bore tube to enable fast pressure response in the cell during increasing confining pressure. A small confining pressure (about 30 kpa) was applied through Reservoir 2. When water slowly came out from the top bushing housing, the counter pressure was then applied through pressure port in the top bushing housing (Figure 3.4.c).

The confining pressure was then increased to about 50 kpa so as to develop some positive pore water pressure in the sample. This enables air-free connection of drainage lines when they are disconnected from the set up reservoir 1 for reconnection to the volume change and pore pressure measuring devices.

Skempton B-value was measured before starting consolidation. B-value equal to one was usually achieved in each test, which ensured saturation of the specimen. Back pressure technique was used to increase saturation in case the B-value obtained was less than 0.94. In that case, a back pressure of 100 kpa was found to be sufficient to achieve B-value of 0.97.

3.5.3. Consolidation

The specimens were normally consolidated to an all round effective stress ($\sigma'_c$) of 200 kpa. This stress is about twice as high as the pre-consolidation stress of the
clay. A back pressure of 100 kpa was used in all tests. The uplift force on the loading ram was compensated by loading with the air piston so that isotropic consolidation stress condition was achieved. During consolidation, double drainage was permitted for 36 hours. The drainage was then terminated and the sample left undrained under zero deviator-stress for 12 hours. This was intended to allow pore pressure equalization throughout the sample and development of pore water pressure due to the arrest of secondary consolidation. It was recognized that a small increase in pore pressure would occur during this period. Although Holzer and Hoeg (1973) and Holzer et al. (1973) reported that the excess pore pressures caused by creep under zero deviator stress are insignificant, about 5% to 11% decrease in effective stress was observed due to excess pore pressure generated during this period for the clay tested.

3.5.4. Monotonic Loading

Undrained monotonic compression and extension tests were done under strain-controlled condition at a strain rate of 1% per hour. This rate was slow enough to enable reliable pore pressure measurements (Bishop and Henkel, 1957). The same rate of strain was used for both pre-cyclic and post-cyclic monotonic loading to eliminate the differences in stress strain response due to rate effect. Both compression and extension tests were carried out by varying the axial load while the cell pressure was held constant.
3.5.5. Cyclic Loading

Undrained cyclic tests were conducted using constant stress amplitude cyclic loading. Since two-way cyclic loading is more damaging than one way cyclic loading, it was decided to study clay behavior under two-way cyclic loadings. Cyclic deviator stresses were imposed by changes in axial load under constant confining pressure. All tests were carried out in a temperature controlled environment.

3.6. Testing Program

This testing program was aimed at a systematic study of the following:

1. Effect of cyclic stress level, maximum axial strain amplitude, residual strain, cyclic loading sequence and strain reversal on stress-strain and undrained strength characteristics of clay during post-cyclic monotonic loading.

2. Possible relationship between both residual pore pressure (after equalization) and maximum axial strain during cyclic loading and cumulative hysteretic work absorbed by soil specimens at various cyclic stress levels.

3. Verify the concept of equivalence between stress overconsolidation and overconsolidation induced by pore pressure increase due to cyclic loading of NC clay.

4. Correlation between cumulative hysteretic work absorbed and the loss in undrained strength due to cyclic loading.
3.6.1. Pre-cyclic Monotonic Loading

Monotonic undrained tests were performed on normally consolidated clay at effective stress levels of $\sigma'_c = 200, 225, 300$ and $400$ kpa. Both compression and extension loading tests were performed. Extension tests were done at effective consolidation stress of $200$ kpa only. Compression tests on OC clay were carried out using maximum past pressure $\sigma'_cm = 200$ kpa and OCR value of $2, 3, 4$ and $5$. The results of these monotonic tests constituted reference data for control of undrained cyclic tests and comparison of behavior with post-cyclic monotonic response.

3.6.2. Undrained Cyclic Loading

In cyclic loading test, the term cyclic stress level ($\tau_{cyc}/S_{uc}$) is defined herein as cyclic shear stress divided by the peak shear stress in an undrained static compression test run at axial strain rate of $1\%$ per hour. The maximum axial strain ($\epsilon_{a max}$) is the largest single-amplitude axial strain at the end of cyclic loading either in compression or extension (Figure 3.5.a).

In preliminary tests, it was found that cyclic stress level of $0.50$ resulted in only a small increase of pore pressure and developed a maximum axial strain of $0.24\%$ in $N = 300$. An equilibrium condition seemed to be reached after about $500$ cycles. However, later tests at this stress level carried out over large number of cycles ($1424$) showed maximum axial strain of up to $3\%$ and still increasing. Thus, according to the concept of Critical Level of Repeated Loading (CLRL) (Sangrey et al. 1969), this stress level is still above the CLRL.
Figure 3.5. Definition of maximum axial strain ($\varepsilon_{\text{amax}}$) and strain reversal.
(a) Maximum axial strain (b) Post-cyclic monotonic loading with strain reversal.
(c) Post-cyclic monotonic loading without strain reversal.
Constant stress amplitude undrained cyclic loading tests were performed at cyclic stress levels of 0.50, 0.60, 0.70 and 0.80 using a loading frequency = 0.1 Hz. Only a limited number of tests were done at cyclic stress level of 0.50. Sinusoidal loading pulse was utilized and two different sequences of loading, namely compression/extension (C/E) pulse and extension/compression (E/C) pulse were used. C/E represents cyclic test which initiates with the compression loading pulse. E/C, on the other hand, represents cyclic test that initiates with extension pulse. Different sense of the loading pulse was intended to check the effect of residual strain on the stress strain behavior of clay during post-cyclic monotonic loading.

At each cyclic stress level, loading was continued until a specified maximum axial strain was developed. Several levels of this fixed strain development: 0.5%, 2%, 3% and 5% were considered. Only a limited number of tests were performed for the maximum axial strain of 1%. Cyclic test were terminated at the specified maximum axial strain, by two mechanical contact stops (see Figure 3.2).

3.6.3. Post-cyclic Monotonic Loading

Following cyclic loading, the excess pore pressure was allowed to equalize under zero deviator stress for 12 hours. Monotonic compression or extension test at constant rate of strain of 1% per hour was then carried out. One of the objective of this study was to investigate possible differences in post cyclic behavior as affected by the sense of residual strain in relation to the sense of strain during post cyclic monotonic loading. Samples previously subjected to C/E cyclic
loading develop residual strain in the extension mode, whereas those subjected to E/C cyclic loading develop residual strain in the compression mode. During post-cyclic loading, the samples with residual strain in extension will experience strain reversal during subsequent monotonic compression loadings. No such strain reversal would occur during post-cyclic extension loadings (Figures 3.4.b and 4.3.c).

3.7. Repeatability of Test Results

To enhance confidence level of experimental data, one should first examine the repeatability of test results. Repeatability of test results using identical samples depends on natural variability among individual samples and the extent to which identical test routine is followed. Typical results of repeated tests on essentially identical samples (taken from the same horizon) are shown in Figures 3.6 and 3.7. The figures show excellent repeatability of test results, both under monotonic loadings and cyclic loadings.
Figure 3.6. Repeatability of test results. Undrained monotonic loading on undisturbed NC samples.
Figure 3.7. Repeatability of cyclic loading tests.
CHAPTER 4
TEST RESULTS

In this chapter, firstly the undrained behavior of isotropically consolidated clay during pre-cyclic monotonic loading, both in compression and extension modes, is discussed. Then, results of cyclic loading tests under several cyclic stress levels ($\tau_{\text{cyc}}/S_{\text{uc}} = 0.50$ to 0.81) are presented. Clay resistance to cyclic loading under E/C or C/E loading pulses is discussed by examining the development of axial and residual strain and residual pore pressure with cyclic loading. Data on time required for equalization of residual pore pressure following cyclic loading, as a function of maximum axial strain, are also presented. Finally, result of post-cyclic monotonic loading of samples having been subjected to different cyclic stress levels, loading sequences and maximum axial strain are discussed. This constitutes comparison of both post-cyclic stress-strain response and undrained strength with pre-cyclic static behavior.

4.1. Pre-cyclic Monotonic Behavior

Two series of static triaxial tests were conducted to establish reference data for cyclic loading and post-cyclic monotonic loading tests. The first series consisted of undrained compression and extension tests on isotropically normally consolidated (NC) clay at effective consolidation stresses varying between 200 and 400 kpa. This series was intended to verify the existence of normalized behavior for the clay tested.
The second test series was conducted on undisturbed clay with various over-consolidation ratio (OCR) ranging from 2 to 5. All specimens in this series were consolidated to the same maximum consolidation stress $\sigma''_c = 200$ kpa. Results of this series were intended for comparison with post-cyclic behavior with equivalent OCR induced in NC clay as a result of increase in pore pressures.

In order to facilitate proper distinction between compression and extension modes of loading, compressive strains are considered positive, and the deviator stress $\sigma_d$ is defined as $\sigma_a - \sigma_r$, where $\sigma_a =$ axial stress, $\sigma_r =$ radial stress. Thus $\sigma_d$ is positive in compression loading and negative in extension loading.

A summary of test results is given in Table 4.1.

4.1.1. Stress-strain Characteristics

Figures 4.1 shows normalized deviator stress and pore pressure response - axial strain response in compression tests for isotropically NC samples. It may be noted that normalized behavior exists for the clay tested as the data from all tests collapses into essentially a single line.

Stress-strain response of NC specimens during undrained compression and extension is compared in Figure 4.2. To provide a better comparison of the stress-strain response, the secant moduli are also plotted versus absolute values of the axial strain. It may be noted that the stress-strain response is softer in extension than compression. Moreover, undrained strength in compression loading ($S_{uc}$) is higher than that in extension ($S_{ue}$). This phenomenon is attributed to inherent anisotropy of
Table 4.1. Results of Pre-cyclic Monotonic Tests

<table>
<thead>
<tr>
<th>Test No</th>
<th>(\sigma'_c) kpa</th>
<th>At (\sigma_{d\ max})</th>
<th>At (\sigma'<em>1/\sigma'3</em>{\ max})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\epsilon'_a) (%)</td>
<td>(S_u/\sigma'_c)</td>
<td>(\sigma'_1/\sigma'3)</td>
</tr>
<tr>
<td>Undisturbed NC clay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. Compression Test :</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>225</td>
<td>6.06</td>
<td>0.300</td>
</tr>
<tr>
<td>A2</td>
<td>300</td>
<td>7.14</td>
<td>0.270</td>
</tr>
<tr>
<td>A3</td>
<td>300</td>
<td>5.15</td>
<td>0.270</td>
</tr>
<tr>
<td>A4</td>
<td>400</td>
<td>5.47</td>
<td>0.260</td>
</tr>
<tr>
<td>A5</td>
<td>200</td>
<td>4.58</td>
<td>0.280</td>
</tr>
<tr>
<td>B. Extension Test :</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>200</td>
<td>-7.56</td>
<td>-0.235</td>
</tr>
<tr>
<td>B2</td>
<td>200</td>
<td>-7.39</td>
<td>-0.240</td>
</tr>
<tr>
<td>Undisturbed OC clay ((\sigma'_m = 200) kpa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test No</td>
<td>OCR</td>
<td>At (\sigma_{d\ max})</td>
<td>At (\sigma'<em>1/\sigma'3</em>{\ max})</td>
</tr>
<tr>
<td>---------</td>
<td>-----</td>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td></td>
<td>(\epsilon'_a) (%)</td>
<td>(S_u/\sigma'_{c\ m})</td>
<td>(\sigma'_1/\sigma'3)</td>
</tr>
<tr>
<td>C1</td>
<td>2</td>
<td>4.85</td>
<td>0.255</td>
</tr>
<tr>
<td>C2</td>
<td>3</td>
<td>7.68</td>
<td>0.223</td>
</tr>
<tr>
<td>C3</td>
<td>4</td>
<td>8.11</td>
<td>0.243</td>
</tr>
<tr>
<td>C4</td>
<td>5</td>
<td>8.36</td>
<td>0.205</td>
</tr>
</tbody>
</table>
Figure 4.1. Normalized stress-strain and pore pressure response of undisturbed normally consolidated clay during monotonic loading.
Figure 4.2. Comparison of stress-strain response of NC clay during undrained compression and extension loading.
undrained strength in natural clays (Duncan and Seed, 1966a; Ladd et al, 1977). The ratio of \( S_{ue}/S_{uc} = 0.88 \) for the clay tested. These differences in compression and extension static behavior will directly influence symmetry of strain development during cyclic loading.

The results of undrained compression test on OC samples are given in Figure 4.3. The stress-strain response becomes softer and undrained strength decreases with increasing OCR. Consequently, the failure strain increases as the OCR increases, as indicated by the arrows in Figure 4.3.a. This would be expected since all specimens were preconsolidated to a common maximum stress and samples with the highest OCR were unloaded to the lowest consolidation stresses. This behavior is similar to that of other overconsolidated clays (e.g. Andersen, 1975).

The development of pore pressure with strain on OC undisturbed samples is shown in Figure 4.3.b. It is seen that the pore pressure generated decreases with increasing overconsolidation ratio. However, no negative pore pressure was developed even at OCR=5. Andersen (1975) showed similar trend on OC undisturbed Drammen clay and negative pore pressure only developed in heavily OC clay (OCR>10).

**4.1.2. Effective Stress Paths and Failure Envelope**

Figure 4.4 shows effective stress paths (ESP) for both NC and OC states. All stresses are normalized with respect to the maximum effective consolidation stress \( (\sigma'_{cm}) \). Stress paths are shown for compression and extension loading. For compression
Figure 4.3. Normalized stress-strain and pore pressure response with respect to maximum effective consolidation stress.
Figure 4.4. Normalized stress paths with respect to maximum effective consolidation stress.
loading, data are shown for specimens with different OCRs. The figure clearly shows that the failure envelope is best represented by straight line with zero cohesion intercept. The average angle of friction in compression loading for both NC and OC is 32.1° and in extension it equals to 30.6°.

Andersen (1975) reported different compression failure envelope for NC and OC Drammen clay. OC Drammen clay has cohesion intercept $c' = 14$ kpa but $\phi'$ angle is the same which is equal to 30.7°. The range of OCR considered was however larger (4 to 50). These different characteristics of Drammen and Cloverdale clays will influence the result of post-cyclic monotonic loading differently. Different change in $c'$ and $\phi'$ of NC sample on post-cyclic monotonic loading between Drammen and Cloverdale clays could be expected.

4.1.3. Undrained Shear Strength

Figure 4.5 presents the normalized undrained strength, $S_{uc}/\sigma'_c$ OC and $S_{uc}/\sigma'_c$ NC as a function of overconsolidation ratio (OCR). The relationship between normalized strength and OCR may be described by an equation of the form,

$$ (S_{uc}/\sigma'_c)_{OC} = (S_{uc}/\sigma'_c)_{NC} \cdot OCR^m \quad (4.1) $$

where $m$ is a dimensionless coefficient which depends on the mode of shearing and plasticity of clay (Ladd et al.,1977). For the data shown in Figure 4.5 the value of $m$ is 0.77.
Figure 4.5. Effect of overconsolidation ratio on undrained strength of undisturbed clay.
It is interesting to note that Koutsoftas (1981) reported m-values ranging from 0.80 to 0.85 under $K_o$ consolidated triaxial compression and extension, and $K_o$ Simple Shear tests. Ladd et al. (1977) reported m-values ranging between 0.75 and 0.85 for five different clays under Direct Simple Shear loading.

4.2. Cyclic Loading Behavior

Post-cyclic behavior of clay is intimately linked to the parameters of cyclic loading. These parameters govern conditions at the end of cyclic loading which significantly affect the behavior during subsequent static loading. In this section, effect of cyclic stress level, $\tau_{cyc}/S_{uc}$, and loading pulse type (C/E or E/C) during cyclic loading will be examined in relation to strain and pore pressure development. Time required and pore pressure generated during equalization will also be discussed as they are affected by $\tau_{cyc}/S_{uc}$, maximum axial strain and loading pulse type. Finally, the degree of soil damage due to various cyclic stress levels will be highlighted by comparing the strain energy or hysteretic work absorbed by soil samples at each cyclic stress level.

4.2.1. Strain and Pore Pressure Development

The development of maximum and residual axial strain and residual pore pressure with cycles of loading is shown in Figure 4.6 for E/C and Figure 4.7 for C/E pulse under $\tau_{cyc}/S_{uc}$ ranging from 0.50 to 0.81. Residual pore pressure has been normalized by the effective stress at the end of consolidation. This normalized form provides a general picture of pore pressure response under any confining stress.
Figure 4.6. Development of maximum axial strain, residual strain and residual pore pressure during cyclic loading at various cyclic stress levels. E/C loading pulse.
Figure 4.7. Development of maximum axial strain, residual strain and residual pore pressure during cyclic loading at various cyclic stress levels. C/E loading pulse.
At any given $\tau_{cyc}/S_{uc}$, maximum and residual strains gradually increase with increasing number of cycles. The number of cycles required to reach any given maximum or residual axial strain decreases as $\tau_{cyc}/S_{uc}$ increases. Strain development seems to be faster on the extension side. As explained earlier, this non-symmetrical strain response is partly caused by the inherent anisotropy in undisturbed clay and partly due to the fact that the samples were subjected to constant amplitude cyclic load. During extension phase of cyclic loading, especially at large strains, the net area of the samples decreases whereas it increases in compression. This causes cyclic stress amplitude in extension larger than that in compression resulting in larger axial strain in extension. Similar behavior was also observed by previous investigators including Andersen (1975), Azzouz et al. (1989); Fischer et al. (1976), and Takahashi and Hight (1980).

Similar to the development of maximum and residual axial strain, at any given $\tau_{cyc}/S_{uc}$, normalized residual pore pressure gradually increases as number of cycle increases. Moreover, the increase in pore pressure with cycles of loading is faster with increasing $\tau_{cyc}/S_{uc}$.

Despite the trend for larger strain amplitude on the extension side for both type of loading pulses, strain development due to C/E loading pulse appears to be more symmetrical than E/C loading (Figure 4.6.a and 4.7.a). Moreover, at any given number of cycles and $\tau_{cyc}/S_{uc}$, maximum axial strain developed due to C/E loading seems to be larger than that due to E/C loading pulse.

The development of residual strain during C/E and E/C loading is quite
different. As can be seen in Figure 4.6.b and 4.7.b, positive (compressive) residual strain developed during E/C loading, whereas in C/E loading, residual strain accumulated on the extension side. This would be expected since E/C loading ends with compression pulse and the strain rebound on unloading is small. On the contrary, C/E loading ends with extension pulse and thus in negative residual strain. This sense of residual strain will affect the behavior during post-cyclic monotonic loading, as will be discussed later.

A careful examination of Figures 4.6.c and 4.7.c suggests that at any given number of cycle and $\tau_{\text{cyc}}/S_{\text{uc}}$, residual pore pressure during E/C loading appears to be higher than under C/E loading pulse. However, the total residual pore pressure after equalization following a rest period after termination of cyclic loading seems to be independent of the type of loading pulse. This feature is clearly seen in Figure 4.8.a, b & c, which show residual pore pressure versus number of cycles for C/E and E/C loading pulses under similar $\tau_{\text{cyc}}/S_{\text{uc}}$. The lack of correspondence during cyclic loading is believed to be due to unequalized pore pressures in the sample due to fast cyclic loading, together with frictional restrain at the ends.

4.2.2. Pore Pressure Response During and After Equalization

Typical pore pressure changes during equalization after the end of cyclic loading are shown in Figure 4.9. Effect of cyclic stress level during equalization is presented in Figure 4.9.a, whereas the effect of maximum axial strain at a given $\tau_{\text{cyc}}/S_{\text{uc}}$ is illustrated in Figure 4.9.b.
Figure 4.8. Effect of loading phase on residual pore pressures during cyclic loading. C/E loading pulse versus E/C loading pulse.
There is a tendency in the specimens having similar maximum axial strain that the one subjected to the lowest \( \tau_{\text{cy}}/S_{\text{uc}} \) exhibits the longest time for equalization (indicated by the arrows), Figure 4.9.a. Figure 4.9.b shows that for a given \( \tau_{\text{cy}}/S_{\text{uc}} \) the specimen that undergoes the largest maximum axial strain exhibits the longest time for equalization. Thus, it is clear from this observation of unequalized pore pressures that post-cyclic monotonic test performed without allowing pore pressure to equalize will not reveal the true behavior of clay during post-cyclic static loading.

It is also interesting to note that type of loading pulse also seems to affect the change in pore pressure during equalization (\( \Delta u_{\text{eq}} \)). At low \( \tau_{\text{cy}}/S_{\text{uc}} \) (about 0.60), there is no clear difference between \( \Delta u_{\text{eq}} \) for C/E loading and E/C loading pulse (Figure 4.10.b). However, for higher stress level (\( \tau_{\text{cy}}/S_{\text{uc}} = 0.80 \)), a clear trend is observed that C/E loading pulse generates higher \( \Delta u_{\text{eq}} \) than E/C loading, as shown in Figure 4.10.a. Regardless of the type of loading pulse, \( \Delta u_{\text{eq}} \) nevertheless increases with increasing maximum axial strain.

The residual pore pressure after equalization is plotted as a function of number of cycles in Figure 4.11. Despite the scatter in the data, the regression lines drawn through the points at each \( \tau_{\text{cy}}/S_{\text{uc}} \) clearly show that at a given number of cycles, the residual pore pressure after equalization increases as the \( \tau_{\text{cy}}/S_{\text{uc}} \) increases.

4.2.3. Strain Contours

Strain contours are a very useful tool to predict strain development during cyclic loading. This strain prediction can be done not only for a constant amplitude
Figure 4.9. Typical pore pressure response during equalization after cyclic loading.
Figure 4.10. Effect of loading phase on pore pressure during equalization after cyclic loading.
Figure 4.11. Effect of number of cycles at various cyclic stress levels on residual pore pressure after equalization.
cyclic stress loading but also for random loading as actually occurs in the field. A method utilizing this contours has been proposed by Andersen (1975).

Strain contours for C/E and E/C loading pulses for the clay tested are given in Figure 4.12.a and b. Each contour represents a certain value of maximum axial strain \( (\varepsilon_{\text{amax}}) \) generated during cyclic loading. The contours for C/E loading pulse appear to be flatter than those of E/C loading pulse. This implies that at higher stress levels, C/E loading is likely to be more damaging than E/C loading. However, at low stress levels \( (\tau_{\text{cyc}}/S_{\text{uc}} < 0.60) \), the strain developed at any given number of cycle and \( \tau_{\text{cyc}}/S_{\text{uc}} \) is essentially independent of the pulse type.

Strain development in the form of contour of number of cycles is also a convenient way to present cyclic loading data, as shown in Figure 4.13.a and b. These contours could also be used to assess the strain developed in any given number of cycles under a specified \( \tau_{\text{cyc}}/S_{\text{uc}} \).

4.2.4. Hysteretic Work

Hysteretic work during cyclic loading is often correlated to the degree of damage brought about by cyclic loading on soils (Devenny, 1975). The hysteretic work per unit volume \( (w) \) absorbed by soil the specimen during a loading cycle equals the area of the hysteretic stress-strain loop. Cumulative hysteretic work \( (W) \) is then the total of the hysteretic work absorbed by soil specimen from the start of the test. In this section, the development of hysteretic work during cyclic loading in relation to number of cycles, cyclic stress levels and maximum axial strain will be discussed. This will be used to clarify some aspects of soil behavior during post-cyclic monotonic
Figure 4.12. Contours of maximum axial strain (in extension) for C/E and E/C loading pulses.
Figure 4.13. Contours of number of cycles for C/E and E/C loading pulses.
loading in a later section.

Figure 4.14 presents the hysteretic work absorbed by soil specimens during cyclic loading at three different $\tau_{\text{cycle}}/S_{\text{uc}}$. All tests were C/E type and were cycled until a specified level of maximum strain ($\approx 5\%$) was developed. The figure clearly shows that for a given number of cycles, hysteretic work increases as the $\tau_{\text{cycle}}/S_{\text{uc}}$ increases. This observation can also be used to explain the fact that higher pore pressure and maximum axial strain are developed with increasing $\tau_{\text{cycle}}/S_{\text{uc}}$ at a given number of cycles. Moreover, despite slightly different maximum axial strain developed among the specimens, there is a trend that for a given maximum axial strain, hysteretic work increases with decreasing $\tau_{\text{cycle}}/S_{\text{uc}}$. This tendency is better observed in Figure 4.15 which shows hysteretic work versus maximum axial strain during cyclic loading. This would be expected since the samples subjected to the lowest $\tau_{\text{cycle}}/S_{\text{uc}}$ require a greater number of cycles to reach a given maximum axial strain and thus, tend to absorb more strain energy than those subjected to higher $\tau_{\text{cycle}}/S_{\text{uc}}$.

The results presented in Figure 4.15 imply that even though the specimens undergo similar maximum axial strain, they do not necessarily absorb the same strain energy, and thus do not suffer the same degree of damage. But, at a given maximum axial strain, the specimen subjected to the lowest $\tau_{\text{cycle}}/S_{\text{uc}}$ always suffers the most severe damage, and thus can be expected to exhibit the weakest response during post-cyclic monotonic loading.

The correlation of cumulative hysteretic work per unit volume ($W$) with normalized residual pore pressure is presented in Figure 4.16. Despite some scatter
Figure 4.14. Relationship between cumulative hysteretic work absorbed by soil specimens and number of cycles at various cyclic stress levels.
Figure 4.15. Relationship between cumulative hysteretic work absorbed by soil specimens and maximum axial strain during cyclic loading.
Figure 4.16. Relationship between cumulative hysteretic work absorbed by soil specimens and normalized residual pore pressure after equalization, $\Delta u_{res}/\sigma'_c$. 
in data, the figure suggests that residual pore pressure increases as hysteretic work increases. However, for $W$ in excess of about 40 Kj/m³, the residual pore pressure appears to level off with further increase in cumulative hysteretic work.

In Figure 4.16 no clear trend is observed regarding the effect of $\tau_{cyc}/S_{uc}$ on $\Delta u_{res}$ - $W$ relationship. All data seem to collapse into a single narrow band. The figure suggests that residual pore pressure is directly related to hysteretic work, regardless of $\tau_{cyc}/S_{uc}$. In case of sand, Towhata and Ishihara (1985) have shown that there is also a correlation between hysteretic work and residual pore pressure, regardless of stress path and mode of loadings.

This residual pore pressure - hysteretic work relationship suggests that at $W > 40$ Kj/m³, the samples having different magnitude of hysteretic work (thus, different degree of damage) could possibly have the same residual pore pressure. Its effect on post cyclic undrained strength will be discussed in a later section.

Figure 4.17 shows contours of hysteretic work during cyclic loading for both C/E and E/C loading pulses. Similar to strain contours, these contours are a useful tool to predict cumulative hysteretic work absorbed by the soil specimen in a given number of cycles and $\tau_{cyc}/S_{uc}$. This information can alternatively be obtained by means of $N$ contours as shown in Figure 4.18. Information about hysteretic work is used to estimate the loss in undrained strength during post-cyclic monotonic loading. The relation between hysteretic work and the loss in undrained strength is discussed in a later section.
Figure 4.17. Contours of cumulative hysteretic work absorbed by soil specimens during cyclic loading or C/E and E/C loading pulses.
Figure 4.18. Contours of number of cycles to predict cumulative hysteretic work at a given number of cycles and cyclic stress level.
4.3. Post-Cyclic Monotonic Behavior

4.3.1. Stress-Strain Characteristics

4.3.1.1. Effect of Maximum Axial Strain

Typical results of post-cyclic monotonic tests on the samples previously subjected to cyclic loading at various $\tau_{cyclic}/S_{uc}$ are presented in Figure 4.19 through 4.24. Data are given for C/E and E/C loading pulses and maximum axial strain ($\varepsilon_{amax}$) during cyclic loading from about 0.5% to 5%. Test results on undisturbed NC sample are also included for comparison with post-cyclic behavior. Data are presented in normalized form with respect to effective consolidation stress ($\sigma'_c$) at the end of consolidation.

It may be seen from Fig. 4.19 that the clay with cyclic loading history generally exhibits softer stress-strain response when compared to the pre-cyclic behavior. This softening effect becomes more pronounced as the maximum axial strain increases. Excepting the samples with small maximum axial strain ($\leq 0.6\%$) which did not seem to suffer much stiffness degradation, this trend is consistently found in the post-cyclic monotonic behavior of samples previously subjected to other cyclic stress levels and loading sequences, as shown in Figure 4.20 through 4.24. Taylor and Bacchus (1969) and Matsui and Abe (1981) also reported similar behavior during post-cyclic monotonic tests.

In comparison to the response of undisturbed NC clay, less pore pressures were generated during post-cyclic monotonic tests. The pore pressure generated decreases as $\varepsilon_{amax}$ increases. The samples having the largest $\varepsilon_{amax}$ develop remarkably
Figure 4.19. Normalized stress-strain and pore pressure response of clay during post-cyclic monotonic loading. C/E loading. \( \tau_{\text{cyc}}/S_{\text{uc}} = 0.61 \pm 0.01 \).
Figure 4.20. Normalized stress-strain and pore pressure response of clay during post-cyclic monotonic loading. C/E loading. $\tau_{\text{cyc}}/S_{\text{uc}} = 0.70 \pm 0.01$. 

(a) Normalized Deviator Stress

(b) Normalized Pore Pressure
Figure 4.21. Normalized stress-strain and pore pressure response of clay during post-cyclic monotonic loading. C/E loading. $\tau_{\text{cyc}}/S_{\text{uc}} = 0.80 \pm 0.01$. 

80
Figure 4.22. Normalized stress-strain and pore pressure response of clay during post-cyclic monotonic loading. E/C loading. $\tau_{\text{cyc}}/S_{\text{uc}} = 0.61 \pm 0.01$. 

\[ \sigma_d/\sigma_c \]

\[ \Delta \mu/\sigma_c \]

AXIAL STRAIN, $\varepsilon_a(\%)$
Figure 4.23. Normalized stress-strain and pore pressure response of clay during post-cyclic monotonic loading. E/C loading. $\tau_{cy} / S_{uc} = 0.70 \pm 0.01$. 

\[ E/C \text{ loading pulse} \]

\[ \tau_{cy} / S_{uc} = 0.70 \pm 0.01 \]

(a) Normalized Deviator Stress

\[ \frac{\sigma_d}{\sigma_c} \]

(b) Normalized Pore Pressure

\[ \frac{\Delta u}{\sigma_c} \]

AXIAL STRAIN, $\varepsilon_a(\%)$

Without cyclic loading

$\varepsilon_a$ max = 0.64%

$\varepsilon_a$ max = 1.91%

$\varepsilon_a$ max = 2.97%

$\varepsilon_a$ max = 5.00%
Figure 4.24. Normalized stress-strain and pore pressure response of clay during post-cyclic monotonic loading. E/C loading. $\tau_{yc}/S_{uc} = 0.80 \pm 0.01$. 

\[ \sigma_d/\sigma_c \] 
\[ \Delta \mu/\sigma_c \] 
\[ \varepsilon_a (\%) \]
small pore pressures during post-cyclic monotonic loading. Such pore pressure response is similar to that of lightly to moderately OC undisturbed samples, as discussed in Section 4.1.1. This suggests that the cyclic loading of NC clay creates an effect similar to that of an overconsolidation process. Similar results have been reported for other clays (e.g. Andersen, 1975; Koutsoftas, 1978).

The stiffness degradation as a result of cyclic loading could be explained using the concept of hysteretic work absorbed by soil specimens. As demonstrated earlier (Figure 4.15), at any given $\tau_{\text{cyc}}/S_{\text{uc}}$, the cumulative hysteretic work increases with $\varepsilon_{\text{amax}}$. Since the hysteretic work is correlated to soil damage, the samples with greater hysteretic work would suffer greater damage in the soil structure, which contributes to decrease in strength and stiffness.

However, in case of $\varepsilon_{\text{amax}}$ about 0.5% or less, this softening effect does not seem to emerge. Instead, the stress-strain response appears to be similar or somewhat stiffer than for the undisturbed clay, especially for specimens previously subjected to larger $\tau_{\text{cyc}}/S_{\text{uc}}$ (0.70 and 0.80). This is in agreement with the data reported by Motherwell and Wright (1978) and Andersen (1975). This phenomenon is probably partly due to the fact that such samples become only slightly overconsolidated due to cyclic loading and partly due to the fact that in this range of $\varepsilon_{\text{amax}}$ hysteretic work absorbed by soil specimens may be smaller than some threshold for inducing damage (Devenny, 1975).
4.3.1.2. Effect of Residual Strain

Figure 4.19 through 4.24 also show the effect of the sense of residual strain brought about by cyclic loading on post-cyclic behavior. The sample subjected to C/E loading sequence ended up on extension side or having negative residual strain, whereas E/C loading resulted in positive or compressive residual strain. Thus samples with C/E loading and hence negative residual strain will undergo "strain reversal" during subsequent monotonic compression loading. Strain reversal herein refers to compressing a specimen that is already in a state of extensional strain within respect to the end of consolidation configuration. In the discussion that follows the effect of residual strain will be considered as to whether strain reversal is induced or not. A casual examination of Figure 4.19 through 4.24 suggests that the samples undergoing strain reversal appear to be softer during post-cyclic monotonic loading than those which do not suffer strain reversal.

To get a better insight into the effect of strain reversal during post-cyclic compression loading, a direct comparison between test results of samples with and without strain reversal is presented in Figure 4.25. Data are given for identical cyclic stress level and maximum axial strain induced. Results from monotonic test on undisturbed NC sample are also included. As can be seen in Figure 4.25.a, the clay undergoing strain reversal exhibits softer stress-strain response than the clay with no strain reversal. However, no clear difference is noticed in the pore pressure developed, as shown in Figure 4.25.b. The undrained strength of both samples also
seems to be similar, although the strain at which it is mobilized is larger for the case of strain reversal.

It is often convenient to examine stress-strain response using hyperbolic stress-strain representation (Kondner, 1963; Sashitharan, 1989). This was attempted for post-cyclic stress-strain response of several specimens. The response was found to be not hyperbolic, as no straight lines emerged on the transformed hyperbolic plots. Therefore, in the following discussion, post and pre-cyclic stress-strain response is compared using normalized secant moduli $E_{sec}$.

Effect of strain reversal on stiffness during post-cyclic compression and extension loading is presented as plots between $E_{sec}/\sigma'_c$ versus absolute value of $\sigma_d/\sigma'_c$ in Figure 4.26. Two cyclically loaded samples having similar residual strain in compression were monotonically sheared without (compression) and with (extension) strain reversal (Figure 4.26.a). Similarly, Figure 4.26.b presents the result of two samples having residual strain in extension sheared without (extension) and with (compression) strain reversal. The results of compression and extension tests on undisturbed sample are included for comparison.

Figure 4.26. shows that cyclic loading causes very large loss in stiffness of the undisturbed clay. At any given $|\sigma_d/\sigma'_c|$, the sample undergoing strain reversal (in extension) is much softer than that without strain reversal (in compression), Figure 4.26.a. On the other hand, as shown in Figure 4.26.b, although the sample in compression loading undergoes strain reversal, it still exhibits slightly higher
Figure 4.25. Effect of strain reversal on normalized stress-strain and pore pressure response of clay during post-cyclic monotonic loading.
Figure 4.26. Effect of strain reversal caused by different loading direction on normalized secant moduli.
Figure 4.27. Effect of strain reversal on strain at peak deviator stress during post-cyclic monotonic loading.
normalized modulus compared to the one without strain reversal (in extension test). This is attributed to the inherent anisotropy in the clay which causes the stiffer behavior in compression loading to persist even after strain reversal during post-cyclic loading.

Since strain reversal affects the secant modulus during post-cyclic monotonic loading, it also influences the strain at peak stress, as shown in Figure 4.27. A general trend observed from the figure suggests that the strain at peak stress \( (\varepsilon_{afpc}) \) for the samples undergoing strain reversal is about 25% larger than when no strain reversal occurs. This difference increases as maximum axial strain induced during cyclic loading increases.

### 4.3.1.3. Effect of Cyclic Stress Level

Figure 4.28.a shows typical results of post-cyclic monotonic loading on the samples previously subjected to different \( \tau_{cyc}/S_{uc} \) but developed almost the same \( \varepsilon_{amax} \). The figure indicates that the stiffness degradation increases with decreasing \( \tau_{cyc}/S_{uc} \). Pore pressure developed on the other hand are not dependent \( \tau_{cyc}/S_{uc} \), as shown in Figure 4.28.b. This might be related to the fact that despite different amount of hysteretic work absorbed by each sample, they represent overconsolidation to almost similar OCR\(_{cyc}\). This will be discussed further in the next section.

As discussed previously, at any given \( \varepsilon_{amax} \), cumulative hysteretic work increases as \( \tau_{cyc}/S_{uc} \) decreases. Thus, at a given \( \varepsilon_{amax} \) the sample with the lowest \( \tau_{cyc}/S_{uc} \).
Figure 4.28. Effect of cyclic stress level on stress-strain and pore pressure response during post-cyclic monotonic loading.
absorbed the largest cumulative strain energy during cyclic loading, and therefore is likely to suffer the most damage in stiffness.

4.3.1.4. Overconsolidation Due to Cyclic Loading

The pore pressure generated during cyclic loading results in effective stress reduction. This has often be regarded as equivalent to an overconsolidation effect in the clay similar to that induced by real unloading history (Andersen, 1975; Koutsofas, 1978). In the following discussion, the OCR induced by cyclic loading history is called $\text{OCR}_{\text{cyc}}$ in order to differentiate it from OCR due to real unloading history.

Little information is available regarding cyclic loading induced OCR effects on stress-strain response (Matsui and Abe, 1981; Singh et al., 1978). To study this, the stress strain data in Figure 4.28.a is presented again in Figure 4.29 in the form of normalized secant modulus versus normalized deviator stress. The corresponding $\text{OCR}_{\text{cyc}}$ for each sample is also given. The normalized secant modulus - deviator stress relation of undisturbed OC sample with similar OCR ($\approx 5$) is also added in the plots for comparison.

Substantial differences in stiffness among samples previously subjected to different cyclic stress levels but similar OCR are more clearly observed in this figure. This suggests that although the OCR is similar, the secant modulus at any given deviator stress is not. This is attributed to different amounts of hysteretic work
Figure 4.29. Normalized secant moduli as a function of applied shear stress, $\sigma_d/2S_{uc}$ at the sample having OCR of about 5.
absorbed by the soil specimens. As discussed in Section 4.2.4, for $W \geq 40$ kJ/m$^3$ (for the clay tested), residual pore pressure and hence $OCR_{\text{cyc}}$, does not seem to be dependent on hysteretic work.

At low shear stress levels, the OC sample due to cyclic loading appears to be softer than OC undisturbed clay, but it becomes stiffer at higher shear stress levels. However, this feature does not appear in the sample tested with lower $\tau_{\text{cyc}}/S_{\text{uc}}$ (0.62). Thus, the assumption that the stress-strain characteristics of $OC_{\text{cyc}}$ clay is similar to OC clay of unloading history is likely to be incorrect for moderately to highly $OCR_{\text{cyc}}$. However, this assumption may be appropriate for lightly $OC_{\text{cyc}}$ clay experiencing maximum axial strain of about 0.5% or less.

Figure 4.30 and 4.31 show typical effective stress paths (ESP) during post-cyclic monotonic loading. Results of undisturbed clay with various OCR are also included for comparison. The figure shows that ESP of $OC_{\text{cyc}}$ samples are similar to ESP of OC undisturbed clay. All ESP appear to reach the same static failure line, i.e. undisturbed static failure line. Thus, no change in undisturbed $\phi'$ and $c'$ is observed during post-cyclic monotonic compression loading.

Andersen (1975) reported an increase in $c'$ of NC Drammen clay previously subjected to cyclic loading, but $\phi'$ remained essentially the same. Hyde and Ward (1978) and Matsui and Abe (1980) also showed similar results. In their case, the failure envelope for undisturbed OC clay was higher than that of NC clay. Therefore, when the NC clay previously subjected to cyclic loading was sheared monotonically,
Figure 4.30. Normalized stress paths during post-cyclic monotonic compression loading on the samples having various maximum axial strain at $\tau_{\text{cyc}}/S_{\text{uc}} = 0.61 \pm 0.01$. 

$\tau_{\text{cyc}}/S_{\text{uc}} = 0.61 \pm 0.01$

C/E loading pulse

- $\varepsilon_{\text{max}} = -0.57\%$
- $\varepsilon_{\text{max}} = -2.09\%$
- $\varepsilon_{\text{max}} = -3.28\%$
- $\varepsilon_{\text{max}} = -4.79\%$
- Without cyclic loading
Figure 4.31. Normalized stress paths during post-cyclic monotonic extension loading on the samples having various maximum axial strain at $\tau_{\text{vec}}/S_{uc} = 0.61 \pm 0.01$. 
its ESP travelled beyond the static failure envelope following the ESP of clay with OC induced by unloading history.

The ESP during post-cyclic monotonic extension loading for the clay tested are quite different from those during compression, as shown in Figure 4.30. Post-cyclic failure in extension indicates some development of $c'$, but $\phi'$ stays essentially equal to that of the undisturbed clay.

4.3.2. Post-Cyclic Undrained Strength

Many studies regarding relationship of post-cyclic undrained strength to pre-cyclic strength have been done by previous researchers. However, the results are often conflicting. In this thesis, a systematic study is attempted concerning the relationship of maximum axial strain during cyclic loading, residual strain, $\tau_{\text{cyc}}/S_{\text{uc}}$, and soil damage measured by the amount of energy absorbed by the soil specimens to the post-cyclic undrained strength ($S_{\text{upc}}$).

4.3.2.1. Effect of Maximum Axial Strain, Residual Strain and Cyclic Stress Level

The plot between normalized post-cyclic static undrained strength with respect to the pre-cyclic strength, $S_{\text{uc}}$, is given in Figure 4.32. The post-cyclic undrained strength decreases with increasing maximum axial strain ($\epsilon_{s\text{ max}}$) at all $\tau_{\text{cyc}}/S_{\text{uc}}$. Similar trend has also been reported for other clays (e.g. Andersen, 1975; Castro and Christian, 1978; Koutsoftas, 1978; Matsui et al., 1980; Thiers and Seed, 1969; Singh et al., 1978). Despite some scatter, the lines drawn through the data points for each
Figure 4.32. Effect of maximum axial strain at various cyclic stress levels on the loss in undrained strength.
τ_{cyc}/S_{uc} suggest that the loss in undrained strength depends not only on \( \varepsilon_{amax} \), as generally believed, but also on \( \tau_{cyc}/S_{uc} \). For a given \( \varepsilon_{amax} \) samples previously subjected to the lowest \( \tau_{cyc}/S_{uc} \) show the greatest loss in undrained strength. Again, this appears to be associated with the largest hysteretic work absorbed by the soil specimen during cyclic loading.

The concept of hysteretic work during cyclic loading seems to be able to explain the conflicting results in the current literature regarding the post-cyclic undrained strength. The results presented by Thiers and Seed which show a great loss at \( \varepsilon_{amax} > 0.5 \varepsilon_{afst} \), were based on constant strain and not stress amplitude cyclic loading. At such high strain levels and N=200 cycles, the hysteretic work absorbed by soil specimens would be very high, causing a serious loss in post-cyclic strength. Similar explanation can also be given for the results by Taylor and Bacchus (1969) and Ling (1977). The work by Andersen (1975), Castro and Christian (1978); Koutsoftas (1978); Matsui et al. (1980); Meimon and Hicher (1980) which show small or negligible loss of strength at \( \varepsilon_{amax} \geq 0.5 \varepsilon_{afst} \), were obtained using constant-stress amplitude cyclic loading. As discussed earlier, the hysteretic work in constant-stress amplitude cyclic loading depends on the cyclic stress level and number of cycles (Figure 4.14). The sample subjected to high cyclic stress level would develop maximum axial strain of about one half of \( \varepsilon_{afst} \) within only a few cycles. Thus much smaller hysteretic work would be absorbed by the soil specimen during cyclic loading (Figure 4.15), hence causing small loss in post-cyclic strength.

The effect of strain reversal on post-cyclic undrained strength is shown in
Figure 4.33. Data are given only for the samples previously subjected to cyclic loading at $\tau_{cyc}/S_{uc}$ of about 0.60. Although strain reversal does affect the stress-strain response during post cyclic monotonic loading, it does not seem to have any significant effect on post-cyclic undrained strength. Similar consistent trend was also found for the clay subjected to other cyclic stress levels.

4.3.2.2. Effect of Residual Pore Pressure

Figure 4.34 presents the relationship between normalized pore pressure after equalization ($\Delta u_{res}$) and post-cyclic undrained strength ratio. To get a better insight into the effect of $\Delta u_{res}$, the magnitude of maximum axial strain, for each test is included in the figure.

It can be seen in Figure 4.34 that there is a consistent decrease in post-cyclic undrained strength ($S_{upc}$) as the residual pore pressure increases. At residual pore pressure less than or equal to about one half of initial effective consolidation stress, the undrained strength is essentially unaltered. However, at $\Delta u_{res}/\sigma'_c$ greater than about 0.5, post-cyclic undrained strength suffers a substantial decrease. The decrease seems to be a function of both the residual pore pressure and maximum axial strain. At a given $\Delta u_{res}/\sigma'_c$, the sample with the largest $\epsilon_{max}$ appears to undergo the largest loss in strength. This is probably associated with different magnitude of cumulative hysteretic work absorbed by the soil specimens. Such a trend is similar to the observation of Andersen (1975), although he related the loss in undrained strength to the maximum axial strain and the number of cycles during cyclic loading. Andersen
Figure 4.33. Effect of strain reversal on post-cyclic undrained strength.
Figure 4.34. Effect of residual pore pressure after equalization and maximum axial strain on post-cyclic undrained strength.
(1975) observed that in Drammen clay, the largest loss in undrained strength occurs when maximum axial strain > 2% and N ≥ 1000.

4.3.2.3. Effect of Overconsolidation Ratio due to Cyclic Loading

Despite the similarity in increasing OCR, overconsolidation process due to cyclic loading history occurs at the same void ratio, whereas in real unloading history, it results in increasing void ratio. Therefore, even though the two samples with different OC histories possess the same degree of OCR, void ratio of the OC samples with cyclic loading history would be lower. This void ratio difference increases with increasing OCR. Figure 4.35 schematically plots the relationship between void ratio and effective consolidation stress for both types of overconsolidation histories. OCR can be computed by the equation:

\[
\text{OCR, } \text{OCR}_{\text{cyc}} = \frac{\sigma'_{\text{cm}}}{(\sigma'_{\text{cm}} - \Delta u_{\text{res}})} = \frac{\sigma'_{\text{cm}}}{\sigma'_{\text{e}}} \quad (4.3.1.)
\]

where

\[\sigma'_{\text{cm}}\] = maximum effective consolidation stress.

\[\Delta u_{\text{res}}\] = residual pore pressure due to cyclic loading, or effect stress reduction due to unloading.

\[\text{OCR}\] = Overconsolidation ratio due to unloading history.

\[\text{OCR}_{\text{cyc}}\] = OCR due to cyclic loading history.

In order to relate the effect of \(\text{OCR}_{\text{cyc}}\) on post-cyclic undrained strength, the
Figure 4.35. Schematic diagram of relationship between void ratio and effective consolidation stress (Modified from Matsui et al., 1980)
normalized undrained strength, is plotted versus the corresponding OCR$_{\text{cyc}}$ or OCR, in Figure 4.36. The curves can be represented by equation:

\[
(S_{\text{upc}}/\sigma'_c)_{\text{OCR}} = (S_{\text{uc}}/\sigma'_c)_{\text{NC}}(\text{OCR})^m \quad (4.3.2.)
\]

The $m$ values for each curve are as follow:

- Undisturbed samples: $m = 0.77$
- Samples with cyclic loading history: $m = 0.87$

All data points from various cyclic stress levels seem to fall inside a narrow band. The average value of the relationship can be represented by line A in Figure 4.36. The figure suggests that the increase in normalized undrained strength for OCR$_{\text{cyc}}$ clay is similar to OC clay with unloading history. For a given OCR, the undrained strength of the clay with cyclic history appear to be larger than that for stress overconsolidated clay. This trend is also found in the results reported by Koutsoftas (1978) and Singh et al. (1978). This may be attributed to different void ratios of samples at a given OCR due to different overconsolidation processes (Figure 4.35).

4.3.2.4. Effect of Hysteretic Work During Cyclic Loading

In order to see whether or not the hysteretic work absorbed during cyclic loading governs the post-cyclic undrained strength, undrained strength ratio is plotted
Figure 4.36. Effect of overconsolidation ratio (OCR, OCR_{cyc}) and cyclic stress levels on post-cyclic undrained strength.
as a function of hysteretic work in Figure 4.37. Despite some scatter, data at various $\tau_{cyc}/S_{uc}$ appear to collapse into a narrow band. It may thus be assumed that a unique relationship between undrained strength ratio and hysteretic work exists. This confirms the working hypothesis that the energy absorbed during cyclic loading controls the post-cyclic behavior of clay.

The work dependent hypothesis could explain different $S_{upc}$ for samples having the same maximum axial strain but previously subjected to different $\tau_{cyc}/S_{uc}$. It can also be used to clarify different strength reduction for samples having the same residual pore pressure, or $OCR_{cyc}$, but subjected to different cyclic loading history. The fact that the lowest $\tau_{cyc}/S_{uc}$ causes the most severe damage on the samples at a given $e_{amax}$ or $\Delta u_{rest}$, is reflected by the highest hysteretic work absorbed by soil specimens. Different work absorbed by soil samples, and thus different degree of soil damage, is mainly responsible for the different reduction in undrained strength.

It has long been known that stress-strain response of clay is a rate-dependent process (e.g. Robertson et al., 1978; Vaid and Campanella, 1977). This rate-effect increases with soil plasticity. Thus, different clays with different plasticity will have different response during cyclic loading, even though they are subjected to a given $\tau_{cyc}/S_{uc}$. Moreover, since the hysteretic work absorbed by soil specimens depends on the stress-strain response, different soils would absorb different amount of energy. Therefore, it can be expected that when soil specimens with different plasticity and subjected to a given $\tau_{cyc}/S_u$ reach a given maximum axial strain, different reduction in post-cyclic undrained strength would occur.
Figure 4.37. Effect of hysteretic work absorbed by soil specimens on post-cyclic undrained strength.
CHAPTER 5
CONCLUSIONS

Constant stress amplitude cyclic loading undrained tests were performed on isotropically NC clay at cyclic stress levels varying from 0.50 to 0.81 of static undrained strength. Two types of loading pulses (C/E and E/C) were utilized to study their effect on strain and pore pressure development during cyclic loading. Cyclic loading was terminated when specified levels of strain developed. After allowing pore pressure generated during cyclic loading to equalize, post-cyclic monotonic undrained behavior was studied using constant rate of strain. This was intended to assess cyclic loading effects on post-cyclic monotonic behavior. Based on the test results in this study, the following conclusion may be drawn.

1. Cyclic loading pulse (C/E or E/C) does not seem to have a significant effect on strain development during cyclic loading at $\tau_{cye}/S_{uc}$ below about 0.60. However, at $\tau_{cye}/S_{uc}$ greater than about 0.60, especially at $\tau_{cye}/S_{uc} \approx 0.80$, strain development seemed to be faster under C/E loading than under E/C loading. Residual pore pressure ($\Delta u_{res}$) was higher under E/C loading pulse than under C/E loading, regardless of cyclic stress level.

2. Residual pore pressure during equalization ($\Delta u_{eq}$) depends on $\epsilon_{amax}$ and the type of cyclic loading pulse. At high $\tau_{cye}/S_{uc}$ (about 0.80), $\Delta u_{eq}$ increases with increasing
\(\epsilon_{\text{amax}}\). Also, \(\Delta u_{\text{eq}}\) in C/E loading was found to be greater than \(\Delta u_{\text{eq}}\) in E/C loading pulse. At low \(\tau_{\text{cyc}}/S_{\text{uc}}\) however, no clear trend was observed.

Residual pore pressure after equalization does not seem to be affected by cyclic loading pulse. Both C/E and E/C loading pulses generate similar residual pore pressure provided \(\epsilon_{\text{amax}}\) and \(\tau_{\text{cyc}}/S_{\text{uc}}\) are similar.

Time for pore pressure equalization (\(t_{eq}\)) depends on \(\tau_{\text{cyc}}/S_{\text{uc}}\) and \(\epsilon_{\text{amax}}\). It was found that at a given \(\tau_{\text{cyc}}/S_{\text{uc}}\), \(t_{eq}\) increases with increasing \(\epsilon_{\text{amax}}\). On the other hand, at a given \(\epsilon_{\text{amax}}\), \(t_{eq}\) increases as \(\tau_{\text{cyc}}/S_{\text{uc}}\) decreases.

3. At a given \(\epsilon_{\text{amax}}\), hysteretic work absorbed by soil specimen increases with decreasing \(\tau_{\text{cyc}}/S_{\text{uc}}\).

4. For hysteretic work less than a specific value, about 40 kJ/m^3 for the clay tested, \(\Delta u_{\text{res}}\) after equalization is directly correlated to hysteretic work, regardless of \(\tau_{\text{cyc}}/S_{\text{uc}}\). Above this value, however, \(\Delta u_{\text{res}}\) seems to be independent of both hysteretic work and cyclic stress levels.

5. The stress-strain response of the clay during post-cyclic monotonic loading becomes increasingly softer as maximum axial strain due to cyclic loading, \(\epsilon_{\text{amax}}\), increases.

6. It was found that despite similar \(\epsilon_{\text{amax}}\) and \(\tau_{\text{cyc}}/S_{\text{uc}}\) during cyclic loading, the clay undergoing strain reversal during post-cyclic monotonic loading shows much softer stress-strain response than without strain reversal. This strain reversal also causes strain at peak deviator stress (\(\epsilon_{a\text{fpc}}\)) to be larger than that without strain reversal.
7. The clay subjected to different $\tau_{cyc}/S_{uc}$ but similar $\epsilon_{amax}$, the lowest cyclic stress level results in the softest stress-strain response.

8. The clay overconsolidation due to cyclic loading history (OCR$_{cyc}$) results in similar ESP, but different stress-strain response when compared to OCR induced by unloading history on undisturbed OC samples. In general, the overconsolidated clay due to cyclic loading OC$_{cyc}$ exhibited softer stress-strain response. For lightly overconsolidated OC$_{cyc}$ samples, however, the stress-strain response of OC$_{cyc}$ clay is almost similar to that of clay overconsolidated by unloading history.

9. Post-cyclic monotonic behavior of the clay depends not only on the maximum axial strain developed during cyclic loading, but also on the residual pore pressure after equalization. Prediction of post-cyclic undrained strength ($S_{upc}$) based only on one of these factors may lead to underestimate the loss in undrained strength.

10. Although the stress-strain response of OC$_{cyc}$ clay is softer than that of the clay overconsolidated by unloading history, $S_{upc}$ is generally larger. In the plot between normalized undrained strength ($S_{upc}/\sigma'_c$ or $S_{uc}/\sigma'_c$) versus overconsolidation ratio, the OC$_{cyc}$ line falls above that for unloading OC curve. Consequently, $S_{upc}$ prediction based on OC unloading data may be suitable for lightly to moderately OC$_{cyc}$. However, for highly OC$_{cyc}$ the discrepancy may be too large for economical design.

11. The post-cyclic undrained strength was found to be directly correlated to hysteretic work absorbed by the clay during cyclic loading. Based on this relation, post-cyclic undrained strength could be predicted directly without knowing $\epsilon_{amax}$, $\Delta u_{res}$ or
OCR_{cyc}. The hysteretic work contours can be utilized to obtain hysteretic work during cyclic loading at any given \( \tau_{cyc}/S_{uc} \) and number of cycles.

The conclusions drawn above are based on the test results on Cloverdale clay isotropically consolidated under initial effective consolidation stress of 200 kpa. However, these conclusion are believed to be applicable to other clays with similar plasticity at any given initial effective consolidation stress, provided the normalized behavior exists in those clays.


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