MULTI-DIRECTIONAL CYCLIC SHEAR-INDUCED PORE PRESSURE AND SETTLEMENT OF UNDISTURBED CLAY

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Background

The clayey soils have been considered relatively stable for earthquake induced liquefaction...

In the clayey soils, the pore water pressure may accumulate and due to the disturbance of the soil structure, the post-earthquake settlement would occur.

Before After

Clay particles

Earthquake Wave

Pore Water Pressure Accumulation

Post-Earthquake Settlement

During

Clay particles

2
Effects of sample disturbance on the following 3 points:

1. Effects of disturbance on the pore water pressure accumulation during cyclic shear
2. Effects of disturbance on post-cyclic settlement
3. Effects of cyclic shear on $e - \log\rho$ relations
Sample and Specimens

◆ Soil Profile

◆ Sampling Position

◆ Index Properties of Tohoku Clay

<table>
<thead>
<tr>
<th>$\rho_s$ (g/cm$^3$)</th>
<th>$W_L$ (%)</th>
<th>$W_P$ (%)</th>
<th>$I_p$</th>
<th>$C_c$</th>
<th>$C_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.607</td>
<td>124.7</td>
<td>40.5</td>
<td>84.2</td>
<td>1.29</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Test Apparatus

【The Multi-directional Cyclic Simple Shear Test Apparatus】

【Outline of the Apparatus】

【Deformation of Specimen during Cyclic Shear】

Specimens

 Drainage
 Specimen
Φ: 75mm, h: 20mm
 Pore pressure transducer
 Fastener
 Acrylic rings
 Membrane
 Linear bearing
 Load cells
 LVDT
 Air pressure regulator
 Bellofram cylinder

 h (mm)

 Multi-direction

 h(mm)
# Experiments

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cyclic Shear Strain</th>
<th>Shear Strain Amplitude $\gamma_{\text{dyn}}$ (%)</th>
<th>$\sigma'_{v0}$ (kPa)</th>
<th>Period $T$ (sec)</th>
<th>Number of Cycles $n$</th>
<th>Phase Difference $\theta$ (°)</th>
<th>Step Load After Cyclic Shear $\sigma'_{v0}$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undisturbed</td>
<td>Uniform</td>
<td>0.12, 0.45, 0.90, 2.86</td>
<td>0.12</td>
<td>157</td>
<td>2.0</td>
<td>200</td>
<td>90</td>
</tr>
<tr>
<td>Disturbed</td>
<td>Uniform</td>
<td>0.57, 1.21, 1.87, 2.47</td>
<td>0.57</td>
<td>157</td>
<td>2.0</td>
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</tr>
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**Uniform Waves**

- $\gamma = 1.0\%$, $\theta = 90°$  
- Shear strain (%)
  - X direction
  - Y direction

- $\gamma = 1.0\%$
  - X shear strain $\gamma_X$ (%)  
  - Y shear strain $\gamma_Y$ (%)  

- $\theta = 20°$, $\theta = 45°$, $\theta = 70°$, $\theta = 90°$
Test Procedure

1. Pre-Consolidation by $\sigma'_v = 157\text{kPa}$
   ($\text{①} \rightarrow \text{②}$)

2. Cyclic Shear Test under Undrained Condition
   ($\text{②} \rightarrow \text{③}$)
   - Pore Water Pressure Measurement

3. Recompression by $\sigma'_v$ under Drainage Condition
   ($\text{③} \rightarrow \text{④}$)
   - Settlement Measurement

4. Consolidation under $\sigma'_v = 294, 392\text{kPa}$
   ($\text{④} \rightarrow \text{⑤} \rightarrow \text{⑥}$)
   - Settlement Measurement

5. Settlement Measurement during cyclic shearing

(Specimen in the Shear Box)

(During Cyclic Shearing)
Pore Water Pressure during Cyclic Shearing

- **Cumulative Shear Strain**
  \[ G^* = \sum \Delta G^* = \sum \sqrt{\Delta \gamma_x^2 + \Delta \gamma_y^2} \]
  \[ G^* = n(5.995\gamma_{dy} + 0.3510) \]

- \( U_{dy}/\sigma_{v0} \) of the disturbed specimens are larger than those of the undisturbed ones.

- **Estimation Equation (Matsuda et al. (2011))**

\[ \frac{U_{dy}}{\sigma_{v0}} = \frac{G^*}{\alpha + \beta \cdot G^*} \]

\[ \alpha = A \gamma^m \]
\[ \beta = B \gamma \]

○: Experimental Constants
Post-Cyclic Settlement

- Post-cyclic settlement increases with the shear strain amplitude.
- Consolidation of the undisturbed specimens are faster than those of the disturbed ones.
Estimation of Post-Cyclic Settlement

- $\Delta e - SRR$ Relations

Tohoku clay, $\sigma'_{v0}=157$ kPa
$\gamma \approx 0.1\% \sim 3.0\%$
$n = 200$, $\theta = 90^\circ$

- Estimation Equation (Ohara et al. (1988))

$$
\varepsilon_v = \frac{\Delta H}{H_0} = \frac{\Delta e}{1 + e_0} = \frac{C_{dyn}}{1 + e_0} \log SRR
$$

$SRR$: Stress Reduction Ratio
$C_{dyn}$: Cyclic shear-induced recompression index

- $C_{dyn}$ of the undisturbed specimen is larger than the disturbed one.
Calculated Results of Post-Cyclic Settlement

- The observed and the calculated results agree well.
- Post-cyclic settlement of the disturbed specimens are slightly larger than those of the undisturbed ones.

<table>
<thead>
<tr>
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<th>Disturbed</th>
<th>Undisturbed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calculated</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

Tohoku clay, \( \sigma'_{v0} = 157 \text{ kPa} \)
\( \gamma \approx 0.1\% \sim 3.0\% \)
\( n = 200, \theta = 90^\circ \)
e-logp relations after cyclic shear does not contact with the normal consolidation line.
Conclusions

• The pore water pressure accumulation and post-cyclic settlement of the disturbed specimens are larger than those of the undisturbed ones.

• The $e$-log$p$ relations on the undisturbed specimen obtained after cyclic shear does not contact with the virgin compression line even at 2.5 times of pre-consolidation stress.
Thank you for your kind attention!
The Contents of Today’s Presentation

1. Background and Objective
2. Experimental Method
3. Results and Discussions
   - Pore water pressure
   - Settlement
   - $e - \log p$ relations
   - Multi-directional cyclic shear
4. Conclusions
## Experiments

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<td>200</td>
<td>90</td>
<td>294, 392</td>
</tr>
<tr>
<td>Irregular</td>
<td>0.13, 0.55, 1.12, 3.05</td>
<td></td>
<td></td>
<td>157</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>–</td>
</tr>
</tbody>
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### Uniform Cyclic Shear Strain

- $\gamma = 1.0\%$, $\theta = 90^\circ$

### Irregular Cyclic Shear Strain

- Hyogo-ken Nanbu earthquake, 1995
Pore Water Pressure During Cyclic Shear

**Undisturbed specimen**

Tohoku clay: Undisturbed specimen

$\sigma'_{v0} = 157$ kPa; $\theta = 90^\circ$

$\gamma = 3.05\%$

$\gamma = 1.12\%$

$\gamma = 0.55\%$

$\gamma = 0.13\%$

$U_{dyr}/\sigma'_{v0}$ increases with the number of cycles, the shear strain amplitude.

**Disturbed specimen**

Tohoku clay: Disturbed specimen

$\sigma'_{v0} = 157$ kPa; $\theta = 90^\circ$

$\gamma = 2.86\%$

$\gamma = 0.90\%$

$\gamma = 0.45\%$

$\gamma = 0.12\%$

$U_{dyr}/\sigma'_{v0}$ of the disturbed specimens are higher than those of the undisturbed ones.
**Estimation of the Cyclic Shear-Induced Pore Water Pressure**

\[
\frac{U_{\text{dyn}}}{\sigma_{v0}} = \frac{G^*}{\alpha + \beta \cdot G^*}
\]

\[\begin{aligned}
\alpha &= (A \cdot \gamma^m) \\
\beta &= \frac{\gamma}{(B+C) \cdot \gamma}
\end{aligned}\]

(Matsuda et al. (2011))

- **\(G^*\):** Cumulative shear strain (%)

\[
G^* = \sum \Delta G^* = \sum \sqrt{\Delta \gamma_x^2 + \Delta \gamma_y^2}
\]

\[
G^* = n(5.995 \gamma_{dyn} + 0.3510)
\]

- **\(\gamma\):** Shear strain amplitude
- **\(\alpha, \beta\):** Experimental parameters
- **A, B, C, m:** Experimental constants

---

**Diagram:**
- Hyperbolic curve formula
- Estimation of \(U_{\text{dyn}}/\sigma_{v0}\)
- \(1/\beta\)
- \(1/\alpha\)
- \(G^*\)
The calculated results agree well with the observed ones.
Estimation of Post-Cyclic Settlement

\[
\varepsilon_v = \frac{\Delta H}{H_0} = \frac{\Delta e}{1 + e_0} = \frac{C_{dyn}}{1 + e_0} \log SRR
\]

\[
SRR = \frac{1}{1 - \frac{U_{dyn}}{\sigma_{v0}}}
\]

(Oharaら(1988))

\[
\frac{U_{dyn}}{\sigma_{v0}} = \frac{G^*}{\alpha + \beta \cdot G^*}
\]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta H)</td>
<td>Settlement of specimen</td>
</tr>
<tr>
<td>(H_0)</td>
<td>Height at the start of cyclic shear</td>
</tr>
<tr>
<td>(\Delta e)</td>
<td>Change of void ratio</td>
</tr>
<tr>
<td>(e_0)</td>
<td>Void ratio at the start of cyclic shear</td>
</tr>
<tr>
<td>(C_{dyn})</td>
<td>Cyclic shear-induced recompression index</td>
</tr>
<tr>
<td>(SRR)</td>
<td>Stress Reduction Ratio</td>
</tr>
</tbody>
</table>

- \(C_{dyn}\) can be obtained by the relations between \(\Delta e\) and \(SRR\).
Effects of Irregular Cyclic Shear

- **Pore water pressure**

Tohoku clay, \( \sigma'_v = 157 \text{ kPa} \)

Irregular cyclic shear

- **\( \gamma_{\text{max}} \) values**
  - \( \gamma_{\text{max}} = 2.47\% \)
  - \( \gamma_{\text{max}} = 1.87\% \)
  - \( \gamma_{\text{max}} = 1.21\% \)
  - \( \gamma_{\text{max}} = 0.57\% \)

- **Pore water pressure**

The post-cyclic settlement

- **\( e - \log p \) relations**

\( N_c \) of the Hyogo-ken Nanbu earthquake is 8.9th < Uni=200th.

- **\( e - \log p \) relations after cyclic shear does not contact with virgin compression line.**
The Change of $C_{dyn}$, $C_{cdyn}$, $C_{sdyn}$ due to Cyclic Shear

- $C_{dyn}$ and $C_{sdyn}$ are constant regardless of $\gamma_{dyn}$.
- $C_{cdyn}$ tends to decrease with $\gamma_{dyn}$.

Specimens without cyclic shearing history.

<table>
<thead>
<tr>
<th></th>
<th>Irregular</th>
<th>Uniform</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{cdyn}$</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>$C_{dyn}$</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>$C_{sdyn}$</td>
<td>△</td>
<td>△</td>
</tr>
</tbody>
</table>
How to Calculate Experimental Constants \((A,B,C,m)\)

**Step 1**

Calculate \(\alpha\) and \(\beta\) for each experiment case

\[
G^*/(U_{dyn}/\sigma'_{v0}) = \beta \cdot G^* + \alpha
\]

**Estimation Equation**

(Matsuda et al. (2011))

\[
\frac{U_{dyn}}{\sigma'_{v0}} = \frac{G^*}{\alpha + \beta \cdot G^*}
\]

\[
\begin{align*}
\alpha &= A \cdot \gamma^m \\
\beta &= \frac{\gamma}{B+C \cdot \gamma}
\end{align*}
\]

O: Experimental Constants
How to Calculate Experimental Constants ($A, B, C, m$)

**Step 2**

Calculate $A, B, C$ and $m$ from relationship with $\gamma$

- **Equation Conversion**
  \[
  \frac{\gamma_{\text{dyn}}}{\beta} = B + C \cdot \gamma_{\text{dyn}}
  \]

- **Step 2**
  \[
  y = 428.06x^{-1.091} \quad R^2 = 0.9595
  \]
  \[
  y = 179.45x^{-1.393} \quad R^2 = 0.9907
  \]
  \[
  y = 0.8177x - 0.253 \quad R^2 = 0.9822
  \]
  \[
  y = 0.8882x - 0.2776 \quad R^2 = 0.9817
  \]

- **Tohoku clay**
  \[
  \sigma'_{v_0} = 157 \text{ kPa};
  n = 200; \theta = 90^\circ
  \]

- **Tohoku clay**
  \[
  \sigma'_{v_0} = 157 \text{ kPa};
  n = 200; \theta = 90^\circ
  \]
実験定数 $A, B, C, m$ と塑性指数 $I_P$ の関係

過剰間隙水圧比の収束値に関わる実験定数 $B, C$ は、他の撹乱試料と概ね類似の傾向を示し、$I_P$ から推定可能である。

過剰間隙水圧比の立上り勾配に関わる実験定数 $A, m$ は、他の撹乱試料と異なる傾向を示した。
実験定数 $C_{dyn}$ と $I_p$ の関係

- 不撹乱試料で $C_{dyn} = 0.23$、撹乱試料で $C_{dyn} = 0.17$ となる
- $C_{dyn}$ は他の撹乱試料と概ね類似の傾向を示す
繰返しほん断後の沈下ひずみの推移（γ=2.0%, n=200）

- IPが小さい粘土ほど沈下ひずみは大きい
- 一方向よりも多方向せん断の方が沈下ひずみは大きい
- εvが大きい条件とU_{dyn}/σ'_{v0}が大きい条件は一致

<table>
<thead>
<tr>
<th></th>
<th>Uni (θ=0°)</th>
<th>Multi (θ=90°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolin</td>
<td>- □ -</td>
<td>- ■ -</td>
</tr>
<tr>
<td>Tokyo bay clay</td>
<td>- ▲ -</td>
<td>- ▲ -</td>
</tr>
<tr>
<td>Kitakyushu clay</td>
<td>- ◆ -</td>
<td>- ◆ -</td>
</tr>
</tbody>
</table>

γ=2.0%, n=200

東京湾粘土 (I_p=41.6)
北九州粘土 (I_p=63.8)
カオリン (I_p=25.5)

σ'_{v0}=49kPa
繰返しせん断後の沈下ひずみ

Step④→⑤

Tohoku clay(Undisturbed)
\( \sigma'_{v0} = 294 \text{ kPa} \)
\( n = 200 \)
\( \theta = 90^\circ \)

Step⑤→⑥

Tohoku clay(Undisturbed)
\( \sigma'_{v0} = 392 \text{ kPa} \)
\( n = 200 \)
\( \theta = 90^\circ \)

➤ Step②とは異なり、\( \gamma_{dyn} \)に依らずほぼ同じ沈下曲線となる
等価規則波への変換方法

不規則波

規則波

地震動の不規則性

過剰間隙水圧比は繰返し回数によって異なるため、等価繰返し回数$N_{cy}$を決定する必要がある

\[ G_r^* = n \left( 5.995 \gamma + 0.3510 \right) \]

\[ G_{r1}^* \quad G_{r2}^* \quad G_{r3}^* \]

\[ G_{i1}^* \quad G_{i2}^* \quad G_{i3}^* \]
等価繰返し回数$N_{cy}$の算定

等価繰返し回数$N_{cy}$の算定には、地震工学の分野で最も多く用いられている次式を用いた

\[ N_{cy} = \frac{1}{2} \sum_{i=1}^{2T_n} \left( \frac{u_i}{u_{max}} \right)^2 \]

ここに、
- $N_{cy}$: 等価繰返し回数
- $u_i$: $i$番目の半波の加速度振幅
- $u_{max}$: 加速度最大振幅
- $T_n$: 繰返し回数

本手法でポートアイランド波の有効繰返し回数を求めると、
$N_{cy}=8.9 (=4.7(EW)+4.2(NS))$となる

→ $n=10$の規則波の実験結果を用いて変換
二次圧密係数 $\varepsilon_\alpha$ （不撹乱と撹乱の比較）

Step②の $\varepsilon_\alpha$ はStep③、④の $\varepsilon_\alpha$ に比べて明らかに小さくなる。
2.2 粘土の撹乱の影響

背景
既往の地震後沈下推定法は、撹乱粘土の実験結果から導かれたものであり、不撹乱粘土への適用性については明らかになっていない。

目的
試料の乱れによる影響を明らかにするため
- 不撹乱試料と撹乱試料を用いて、多軸単純せん断試験を実施
- 過剰間隙水圧変化および沈下特性を把握
- 不撹乱試料への既往推定式の適用性を確認

【撹乱試料（東北粘土）】
【不撹乱試料（東北粘土）】