Long-Term Performance Assessment of Micropiles
Subject to Cyclic Axial Loading

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Summary

1. Introduction to Axial Cyclic Behavior of Micropiles
2. Assessment of Current Design & Testing Practice
3. Research Objectives
4. Scope of Research
   • Modeling the long-term behavior of strain-rate and frequency-dependent materials
   • Development of strain-rate controlled testing procedure to assess long-term strain under:
     • Monotonic axial loading
     • Cyclic axial loading
   • Experimental model evaluation
     • Monotonic & cyclic axial loading tests on plastic samples
     • Monotonic & cyclic calibration chamber micropile model testing
5. Conclusions & Research Needs
Axial Cyclic Behavior of Piles: Applications

Examples of Cyclically Loaded Pile Foundations (Schwarz, 2002)
Axial Cyclic Behavior of Micropiles: Testing Practice

Unique applications (Courtesy of United States Navy)

Machine foundations (Cadden et al., 1998)

Full-scale field testing (USN, 2000)

Full-scale field testing (Fujita Corp.)

Catenary towers (Cavey et al., 2000)
Axial Creep Load Testing: Design & Testing Practice

Anchor tension test for determination of critical creep load (Bureau Securitas, 1977)
Axial Cyclic Load Testing of Ground Anchors: Field Observations

The effect of number of load cycles on anchor displacement for a range of load amplitudes (After Al-Mosawe, 1979)

The effect of load cycles on the rate of anchor displacement (After Al-Mosawe, 1979)
Limitations of Practice

- **Ground anchors, micropiles, piles, & drilled shafts**
  - **Creep** – Extrapolating short-term, load-control test results for prediction of long-term strain.
  
  - **Cyclic loading** – Extrapolating results of load-control tests with limited number of cycles to predict long-term cyclic strain OR long-term load-control cyclic testing leading to costly, time-consuming & impractical testing procedures.
1. Develop for strain-rate dependent or frequency dependent materials a strain-rate controlled testing procedure and interpretation model for using short-term test results to:
   - Predict long-term strain under monotonic and cyclic axial loading
   - Establish a Critical Creep Load and Critical Cyclic Load under monotonic and cyclic axial loading, respectively.

2. Experimentally evaluate the testing procedure and the interpretation model through the performance of monotonic and cyclic strain-rate controlled and load-controlled tests including:
   - * Axial loading tests on plastic samples
   - Calibration chamber tests on model micropiles.
Strain-Rate Controlled Axial Compression Tests

Load Control:
\[ \varepsilon = f(t, \sigma) \]

Strain Rate Control:
\[ \varepsilon = g(\varepsilon_t, \sigma) \]

Strain rate controlled monotonic axial compression tests results
Strain-Rate Controlled Cyclic Testing Procedure

**Load Control:**

\[ \varepsilon = f (\sigma, \omega, t) \]

**Strain Rate Control:**

\[ \varepsilon = g (\varepsilon_t, \varepsilon_n, \sigma) \]

Conceptual strain-rate controlled cyclic loading function

1. **Constant Applied Strain Rate** (cyclic strain rate constant)
2. **Constant Cyclic Strain Rate** (applied strain rate constant)

\[ \omega_1 = \frac{1}{2} (\varepsilon_t / \varepsilon_n) \]
\[ \omega_n = \frac{1}{n} (\omega_1) \]
Model for Cyclic Loading: Applied Strain-Rate Control

Conceptual applied strain-rate controlled cyclic loading response for a series of cyclic loading tests (cyclic envelope shown for clarity)
Model for Strain-Rate Controlled Cyclic Loading

The procedure charts including (a) stress, $\sigma$, vs. strain, $\varepsilon$, at constant applied strain rate (b) strain rate vs. strain, $\dot{\varepsilon}$, at constant stress (c) residual strain rate vs. stress, $\dot{\varepsilon}_{res}$ and (d) strain, $\varepsilon$, vs. cycle number, $n$ at constant stress.

\[
\frac{d\varepsilon}{dt} = \varepsilon = \varepsilon_0 * \varepsilon^{-\beta} + \varepsilon_{res}
\]

\[
\varepsilon(t) = \left[ \varepsilon_0 (\beta +1) \right]^{1/ (\beta+1)} * t^{1/ (\beta+1)}
\]
Polytechnic Institute of NYU

Urban Infrastructure Institute
Experimental Research Program: Phase 1

Instron 8800 servo-hydraulic fatigue testing system

Low-density polyethylene plastic rod
Ecole Nationale des Ponts et Chaussées

CERMES
Centre d’Enseignement et de Recherche en Mécanique des Sols
Experimental Research Program : Phase 2

CERMES Calibration Chamber

Data Acquisition & Command Control Center

Principle Schematic of the CERMES Calibration Chamber
Experimental Equipment

Schematic of the jacking and loading system

Model micropile
Jacking & Loading

Hydraulic jack
Single stroke
(force transducer)

Loading jack
(Displacement & force transducer at head)

Loading of micropile

Jacking of micropile
Experimental Equipment

Section through pluviation device (Dupla, 1995)

Pluviation system
Applied Stresses

Boundary conditions
(after Balachowski, 1995)
Fontainebleau Sand: Material Parameters

Grain-size distribution curve

Test massif characteristics

<table>
<thead>
<tr>
<th>Test</th>
<th>Designation</th>
<th>$M_t$ (Kg)</th>
<th>$I(g/cm^3/s)$</th>
<th>$I_D$</th>
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Characteristics of Fontainebleau sand

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<thead>
<tr>
<th>Sand</th>
<th>$D_{50}$ (mm)</th>
<th>$e_{max}$</th>
<th>$e_{min}$</th>
<th>$\rho_d (g/cm^3)$</th>
<th>$\rho_d (g/cm^3)$</th>
<th>$\rho_{d_{max}} (g/cm^3)$</th>
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<td>0.94</td>
<td>0.54</td>
<td>2.65</td>
<td>1.37</td>
<td>1.72</td>
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Experimental Research Program: Phase 2

Bishop & Wesley triaxial cell and Fontainebleau soil specimen after test (TCD6, $\sigma_c = 100$ kPa)

Drained triaxial compression tests on Fontainebleau sand:
Effect of axial strain rate
## Experimental Research Program: Phase 2

<table>
<thead>
<tr>
<th>Test</th>
<th>Massif</th>
<th>$I_D$</th>
<th>$K_0$</th>
<th>$\delta t$ (mm/min)</th>
<th>$\delta n$ (mm/cycle)</th>
<th>$\omega_n$ (cycle/min)</th>
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<td>FDRC-5</td>
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<td>0.414</td>
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<td>0.001</td>
<td>1000</td>
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<td>1</td>
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</table>

**Testing Schedule** – Monotonic & cyclic displacement-rate and load controlled tests
Experimental Testing Results
(Construction & Jacking): Repeatability

Influence of deposition intensity, I on density index, $I_D$
(Fontainebleau sand)

Force versus displacement: Repeatability of jacking phase
Experimental Testing Results
(Monotonic Loading): Repeatability

Sleeve friction - displacement curves for two loading rates

Tip resistance - displacement curves for two loading rates
Experimental Testing Results (Monotonic Loading): Repeatability & Influence of Monotonic Displacement Rate

<table>
<thead>
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<th>Monotonic Displacement Rate</th>
<th>Force (kN)</th>
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<tr>
<td>3</td>
<td>0</td>
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<tr>
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<td>1</td>
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<tr>
<td>4.5</td>
<td>1.5</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
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ADR = 1mm/min (MDRC-1)
ADR = 0.02mm/min (MDRC-3)
ADR = 1mm/min (MDRC-1c)
ADR = 0.02mm/min (MDRC-3b)

Load-displacement curves for two loading rates (4 tests)
Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading:
(Cyclic Displacement Rate)

<table>
<thead>
<tr>
<th>Test Designation</th>
<th>Applied Displacement Rate (mm/min)</th>
<th>Cyclic Displacement Rate (mm/cycle)</th>
<th>Frequency (N = 1) (cycle/min)</th>
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<tbody>
<tr>
<td>FDRC-1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
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<td>0.1</td>
<td>10</td>
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<td>FDRC-3</td>
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<td>FDRC-5</td>
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<td>n.a.</td>
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Testing Schedule – Cyclic displacement-rate and load controlled tests
Experimental Testing Results (Cyclic Loading): Influence of Cyclic Displacement Rate

**Force vs. displacement**

![Graph showing force vs. displacement](image)

**Force vs. displacement – region of initial displacement**

- **MDRC-1c (ADR = 1 mm/min)**
- **FDRC-1 (ADR = 1 mm/min; CDR = 1 mm/cycle; F = 1 cpm; N = 11 cycles)**
- **FDRC-2 (ADR = 1 mm/min; CDR = 0.1 mm/cycle; F = 10 cpm; N = 100 cycles)**
- **FDRC-3 (ADR = 1 mm/min; CDR = 0.02 mm/cycle; F = 50 cpm N = 58 cycles)**
Experimental Testing Results (Cyclic Loading): Influence of Cyclic Displacement Rate

Sleeve friction vs. displacement

Sleeve friction vs. displacement – region of initial displacement
Experimental Testing Results (Cyclic Loading): Influence of Cyclic Displacement Rate

Tip resistance vs. displacement

Tip resistance vs. displacement – region of initial displacement
Model for Cyclic Loading: Cyclic Strain-Rate Control (Frequency-Dependent Material)

Load Control:

\[ \varepsilon = f (\sigma, \omega, t) \]

Strain Rate Control:

\[ \varepsilon = g (\dot{\varepsilon}_t, \dot{\varepsilon}_n, \sigma) \]

Conceptual cyclic strain-rate controlled cyclic loading function

* **Constant Cyclic Strain Rate** (applied strain rate constant)
Interpretation Model for Cyclic Loading: Cyclic Strain-Rate Control

Conceptual cyclic strain-rate controlled cyclic loading response for a series of cyclic loading tests (cyclic envelope shown for clarity)
Model for Cyclic Loading: Cyclic Strain-Rate Control

Conceptual cyclic strain-rate controlled cyclic loading response for a series of cyclic loading tests (cyclic envelope shown for clarity)

Conceptual cyclic strain rate-strain curves (constant stress levels)
Model Application to Establish the Critical Cyclic Load and Design Load for Allowable Displacement

$Q_{CCyL} = \text{Critical Cyclic Load}$

$\varepsilon_{n,\text{res}}$
Experimental Evaluation of Testing Procedure & Interpretation
Model for Cyclic Loading: (Cyclic Displacement Rate)

Force vs. displacement

Force vs. displacement (region of initial displacement)
Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading: (Cyclic Displacement Rate)

Force vs. displacement rate (region of initial displacement)

Cyclic displacement rate vs. displacement (constant levels of force)
Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading: (Cyclic Displacement Rate)

Cyclic displacement rate vs. displacement – effect of frequency

Cyclic displacement rate vs. displacement – regions of cyclic softening/stiffening
Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading (Cyclic Displacement Rate): Critical Cyclic Load

Residual cyclic displacement rate vs. load
Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading: Load-Controlled Cyclic Loading Tests

Displacement vs. Cycle Number
Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading: Load-Controlled Cyclic Loading Tests

**Total displacement rate vs. number of cycles**

**Rate of displacement vs. number of cycles (100's of cycles)**
Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading (Cyclic Displacement Rate): Prediction of Displacement

Displacement vs. number of cycles for load level $Q \approx Q_{\text{CCyL}}$
Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading (Cyclic Displacement Rate): Critical Cyclic Load

Limit cyclic displacement vs. load
Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading (Cyclic Displacement Rate)

Cyclic displacement rate versus displacement (constant levels of load) for load-controlled and displacement-rate controlled tests (Q = 3.15 kN)

Cyclic displacement rate versus displacement (constant levels of load) for load-controlled and displacement-rate controlled tests (Q = 1.80 kN)
Conclusions

• Experimental Model Evaluation illustrates that long-term behavior of strain-rate dependent and frequency dependent materials and mechanisms such as soil-pile interaction can be predicted using the short-term strain rate controlled cyclic model pile test results.

• For design practice, the proposed short-term testing procedure and interpretation model provide reliable methodology to establish for both strain-rate and frequency-dependent materials:
  – Critical creep load
  – Critical cyclic load
  – Long-term cyclic strains or displacement under any loading level and frequencies
  – Design load for allowable long-term cyclic strain or displacement.

• For research purposes, the proposed short-term testing procedure provides a most efficient methodology to parametrically investigate the effect of material properties and loading characteristics on the long-term performance of geosystems, such as micropiles, piles and ground anchors, soil nails, etc. and their soil-inclusion interaction mechanisms under long-term cyclic loading.

• Further Research and Impact on Engineering Practice. Existing pile load testing equipment could be modified to conduct full-scale field loading tests using the suggested testing protocol. If successful, testing standards could be developed which could lead to adopting the proposed cyclic strain testing procedure and strain rate controlled cyclic strain model as a base line for industry pile testing and design standards.
Research Program Support

Urban Utility Center (Polytechnic Institute of NYU)
Schnabel Engineering
International Association of Foundation Drilling (ADSC)
Ecole Nationale des Ponts et Chaussées (CERMES)

Applied Geotechnical Engineering (AGE)
Branlow Piling Solutions
CAT Construction/Traylor Group
Con-Tech Systems LTD.
DBM Construction
Geosystems LP
Hayward Baker, Inc.
Ischebeck
Isherwood Associates
Layne GeoConstruction
Moretrench American Corp.
Nicholson Construction
TEI Rock Drills