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Pseudo-Elastic Response and Performance of Micropiles

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Presentation Outline

- Introduction
- Stress-Strain Behavior and Composite Modulus
- Cyclic Load-Deformation Behavior

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Introduction

- Modulus of elasticity and spring stiffness of micropile foundations is necessary for structure performance predictions
- Modulus of elasticity E_p and spring stiffness k_c for deep foundations is not a constant
- 13 monotonic and cyclic load tests
  - 6 tests employed strain gauges, both embedment and spot-weldable types

Introduction

Case No.	Project Name	Location	Pile Design Load DL (kN)	Max. Test Load TL (kN)	Test Type	Load Cycling
1	Dublin Road Pump Station (DRPS)	Jackson, NJ	534	933	ML	N
2A	Wheel Truing Facility	Harrison, NJ	534	1512	ML	N
2B	Wheel Truing Facility	Harrison, NJ	356	1068	ML	N
3A	Johnson St.	Brooklyn, NY	1112	2669	ML	Y
3B	Johnson St.	Brooklyn, NY	1112	2224	ML	Y
4	NBME	Philadelphia, PA	2002	4000	QL	N
5	Xanadu	Secaucus, NJ	623	1245	ML	Y
6A	Wards Island	Manhattan, NY	845	1690	ML/QL	Y
6B	Wards Island	Manhattan, NY	445	890	ML/QL	Y
7A	Reed Street Br.	Norwalk, CT	712	1779	QL	Y
7B	Reed Street Br.	Norwalk, CT	712	1779	QL	Y
8A	Birmingham Br.	Pittsburgh, PA	890	1780	QL	Y
8B	Birmingham Br.	Pittsburgh, PA	1281	3180	QL	Y

NOTE: ML=Maintained Load Test, QL=Quick Load Test

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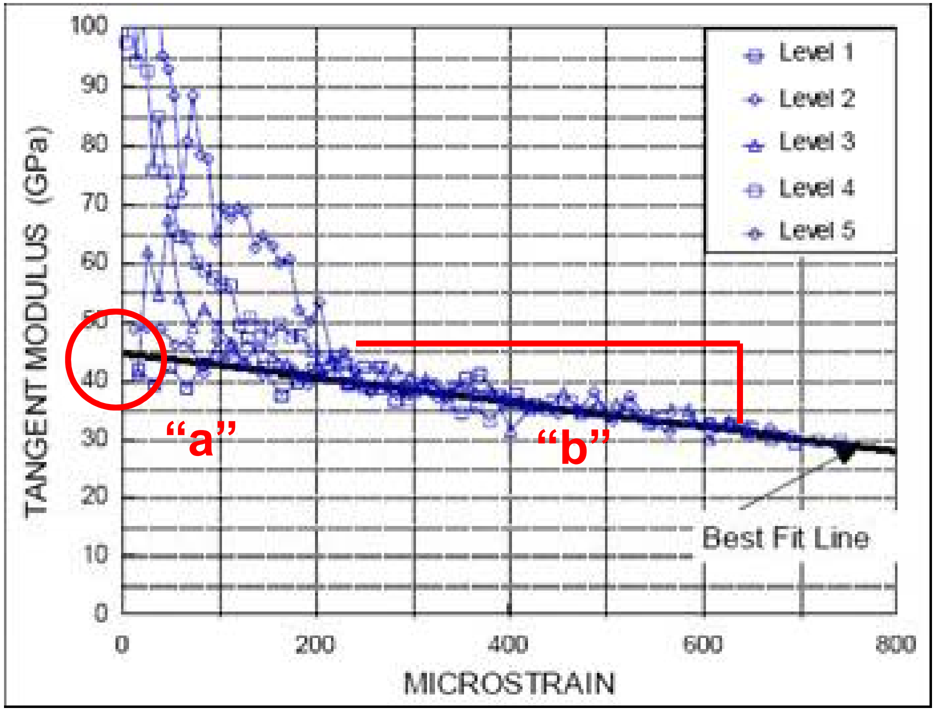
Case No.	Pile Casing Dia. (mm)	Total Pile Length (m)	Cased Length (m)	Bond/ Socket Length (m)	Bond/Socket Material	Reinf. Cross Sect. Area (mm^2)	Depth of Strain Gauge Levels (m)
1	194	21.3	13.7	7.6	Glauconitic F/M Sand	1452	13.6, 16.8, 20.3
2A	244	23.8	6.1	17.7	Sand and Silt	1452	0.2, 6.6, 22.4
2B	244	16.8	6.1	10.7	Sand and Silt	1452	0.2, 6.6, 16.3
3A	273	18.3	9.2	9.1	Gravelly Sand	2581	0, 6.1, 9.1, 13.7, 17.7
3B	273	15.2	9.2	6.1	Gravelly Sand	2581	0, 6.1, 9.1, 12.2, 14.8
4	244	15.3	9.2	6.1	Weath. to Sound Schist	2581/3813	2.1, 7.3, 9.1, 10.4, 11.9, 14.3
5	244	11.5	8.5	3.0	Mudstone	1452	0.9, 7.9, 8.8, 10.1, 11.6
6A	194	11.3	7.6	3.7	Gneiss	2581	-
6B	194	9.7	7.6	2.1	Gneiss	1452	-
7A	244	21.3	9.1	12.2	Gravelly Sand	1452	-
7B	244	21.3	9.1	12.2	Gravelly Sand	1452	0.6, 1.5, 7.9, 9.4, 11.3, 13.1
8A	194	26.2	24.4	4.9	Claystone/ Sandstone	3168	-
8B	194	26.2	24.4	4.9	Claystone/ Sandstone	3168	-

Micropile σ-ε Behavior and Composite Modulus

- Micropile responds nonlinearly under load
- Analysis of load tests with assumed constant E_p can introduce significant errors
- Tangent modulus method used to assess E_{tan} and linear degradation according to Fellenius method (1989, 2001)



Plot of tangent modulus dσ/dε vs. ε for thin-walled steel pipe pile (Monotube) from Fellenius (2001)

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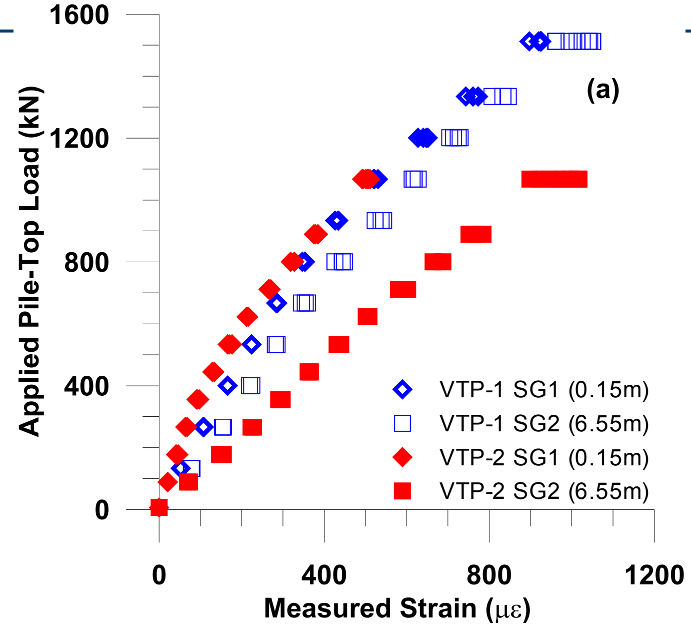
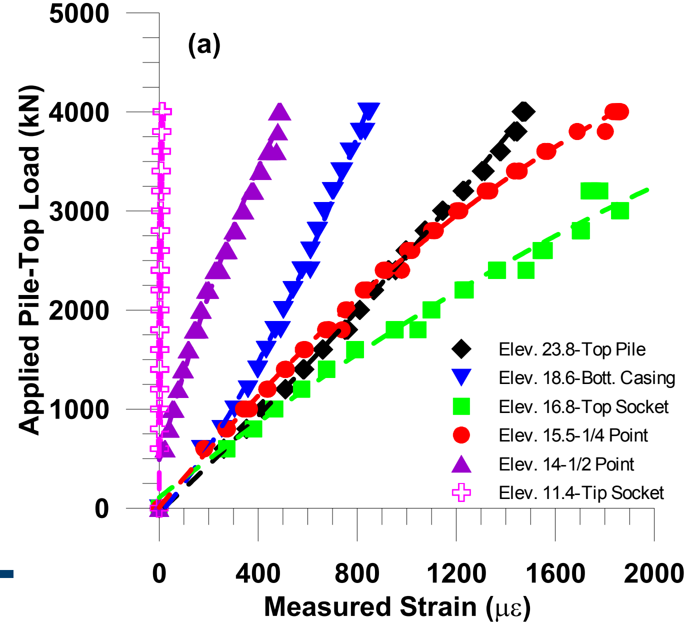
Observed σ-ε Behaviors

- Strain “hardening”
  - Observed for rock-socketed piles
  - High degree of confinement for grout and reinforcement
- Strain “softening”
  - Pile stiffness>soil stiffness→lower confinement effect
  - Composite behavior of bond zone is dominated by softening of grout
    - Same for rock sockets after exceeding dilatant response and accumulation of shear and volumetric strains

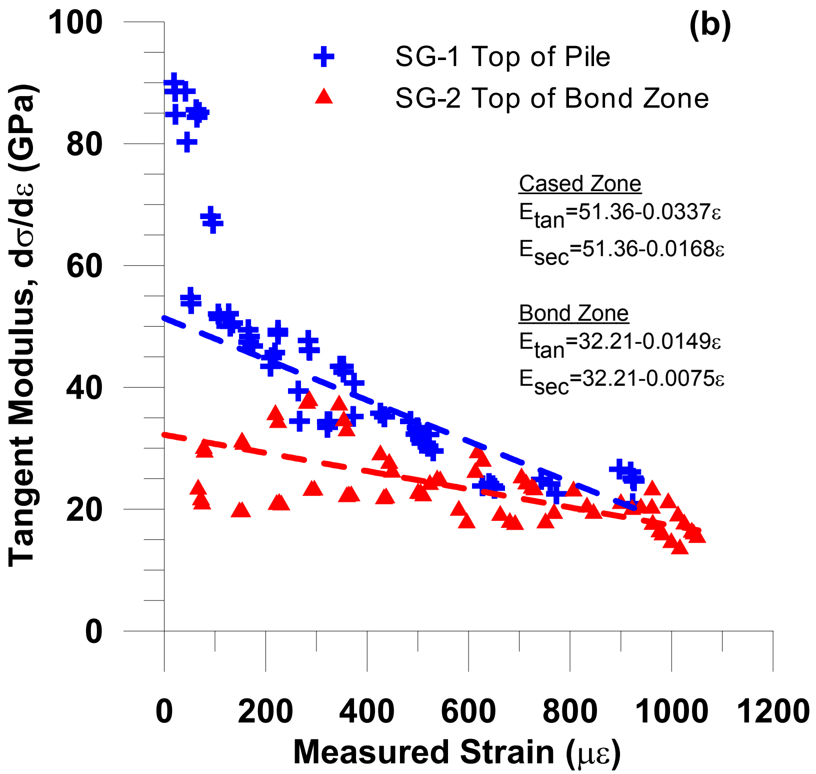


Case No. 2
Bond Zone in Soil



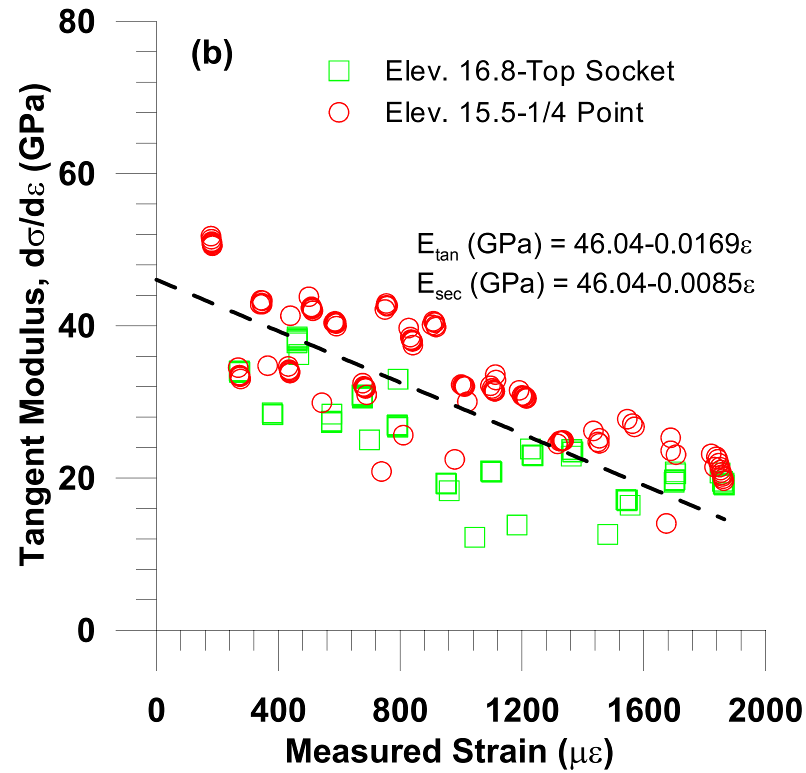
Case No. 4
Bond Zone in Rock

Strain-Dependency of E_{tan}



Case No. 2

Bond Zone in Soil



Case No. 4

Bond Zone in Rock

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Summary of E_{tan} and Degradation Data

	Cased Zone				Bond Zone/Rock Socket			
Case No.	E_{tan} (GPa)	Rate of Modulus Degradation (GPa/$\mu\varepsilon$)	Ratio of Steel/Grout (%)	Calc. Initial Grout Modulus E_{gi} (GPa)	E_{tan} (GPa)	Rate of Modulus Degradation (GPa/$\mu\varepsilon$)	Ratio of Steel/Grout (%)	Calc. Initial Grout Modulus E_{gi} (GPa)
1	-	-	-	-	41.9	-0.033	2.9	37.2
2A, 2B	51.4	-0.034	27.8	34.0	32.2	-0.015	2.6	27.8
3	76.4	-0.055	28.4	41.3	64.2	-0.038	3.1	47.5
4	49.7	0.011	31.8	26.4	46.0	-0.017	13.3	32.7
5	-	-	-	-	79.6	-0.070	3.9	74.9
Mean	59.2	-0.026	29.3	33.9	52.8	-0.035	5.2	44.0
Std. Dev.	14.9	0.034	2.2	7.4	19.0	0.022	4.6	18.7
COV	25%	130%	7%	22%	36%	64%	89%	43%

- E_{tan} has a significant range for cased and bond lengths
  - Little influence of steel/ grout ratio?
- Degradation rate falls within 0.1<b<0.01 GPa/$\mu\varepsilon$
  - Directly responsible for nonconstant E_{tan}
  - Controlled by grout

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Initial Grout Modulus E_{gi}

- Calculate assuming very small strain levels and elastic compatibility

$$E_{gi} = \frac{E_{\tan} A_p - E_s A_s}{A_g}$$

- Wide range of E_{gi} for bond zones
  - Mean=44 GPa (83% of Ave. E_{tan})
  - Still twice E_u for grout calculated by ACI methods for concrete

$$E_u = 6.895x10^{-6}(33\gamma^{1.5}\sqrt{f'_c})$$

  - Grout provides bulk of mechanical response in bond zone/rock socket→small diff. in E_{gi} and E_{tan}

Tangent Modulus Method-Issues for Analysis

- Strain levels must be adequate to exercise as many strain gauge levels as possible
  - Overdesign of “test” piles is problematic in this regard
  - Low strain levels lead to convergence
  - Strain levels over 1000 $\mu\varepsilon$ and approaching 2000 $\mu\varepsilon$ are desirable
- Many of these issues may not exist for typical driven or drilled deep fdns.

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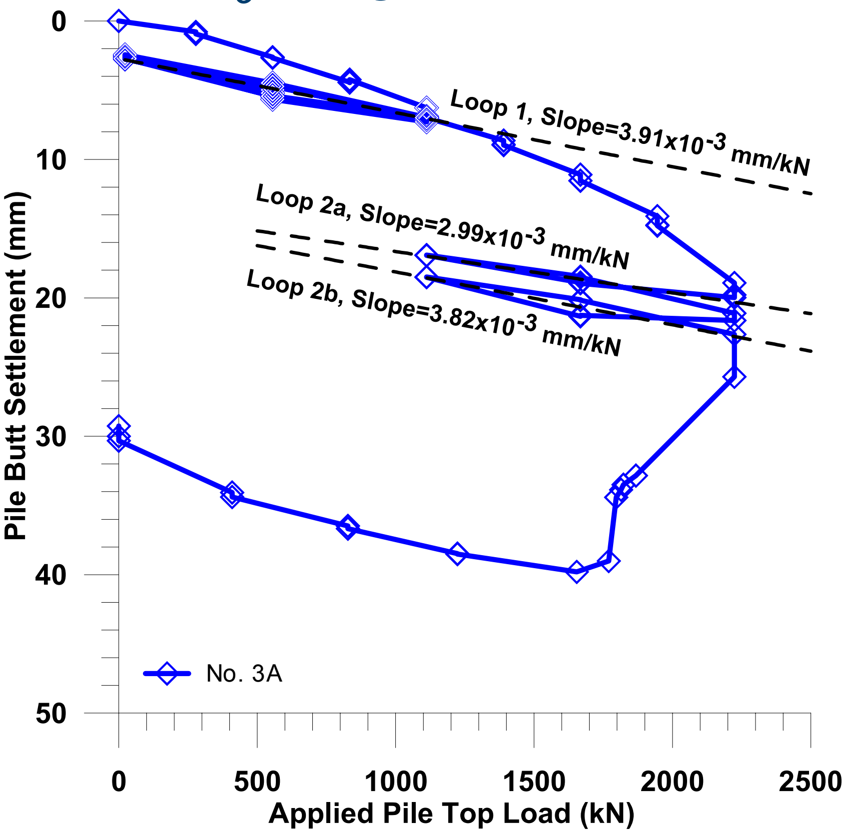
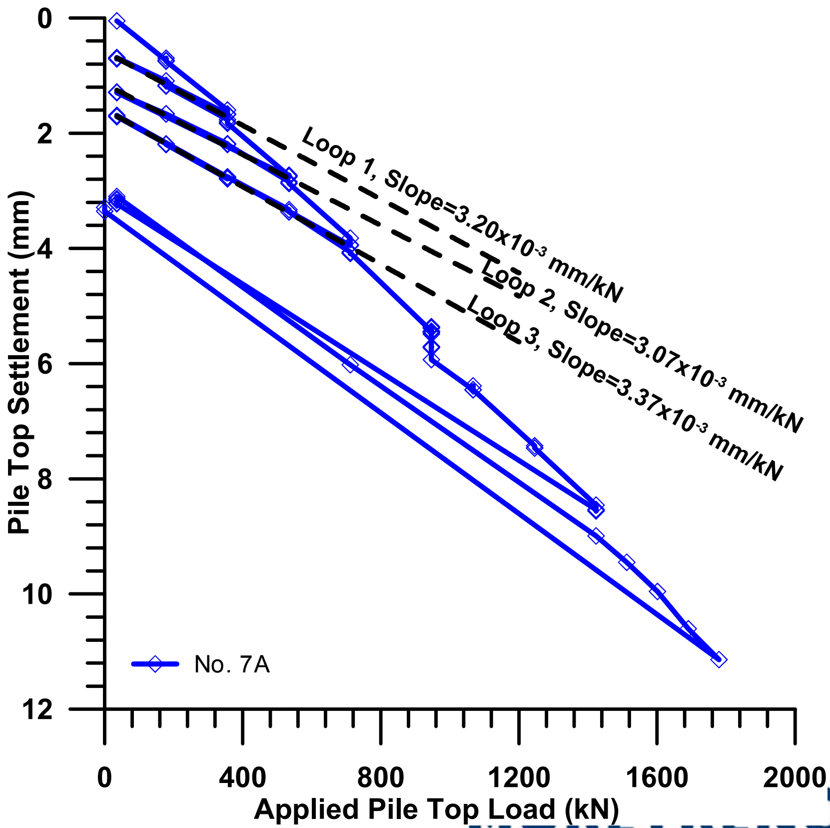
Cyclic Load-Deformation Behavior

- Spring stiffness *k* of a micropile can be assessed from static or cyclic compression load test
- Misconception→There is one single elastic spring constant
  - Inelastic micropile spring stiffness from unload-reload loops
  - Elastic spring stiffness from cyclic compression tests

Inelastic k_c from Unload-Reload

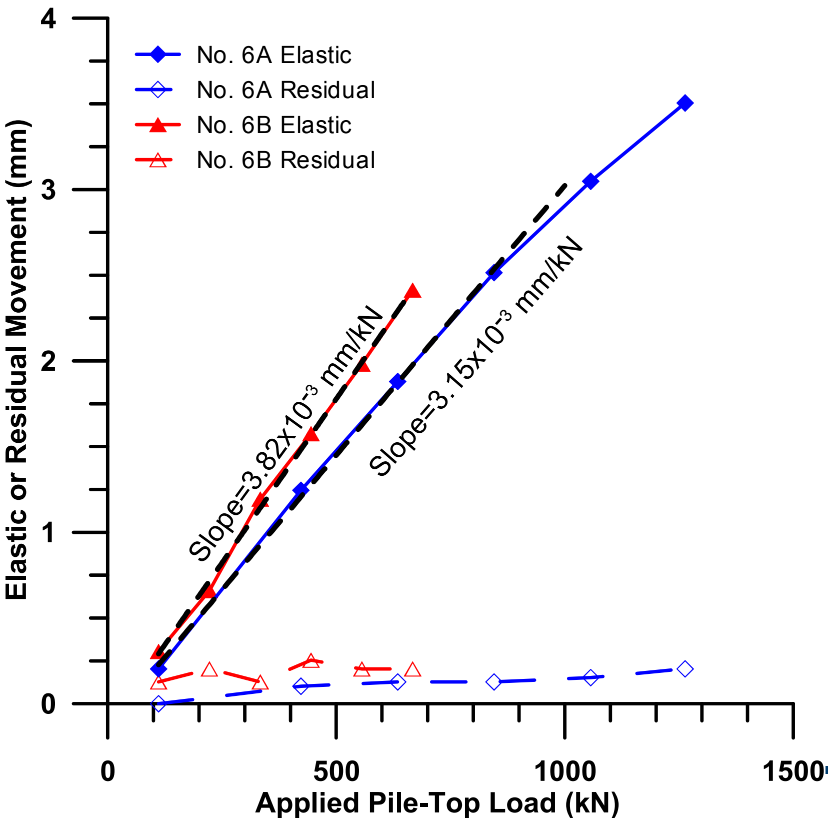
- Compression spring stiffness k_c from UR loops
  - Function of loop length, state of initial loading, no. of cycles
  - k_c ranges from 2.5-3.91x10^{-3} mm/kN

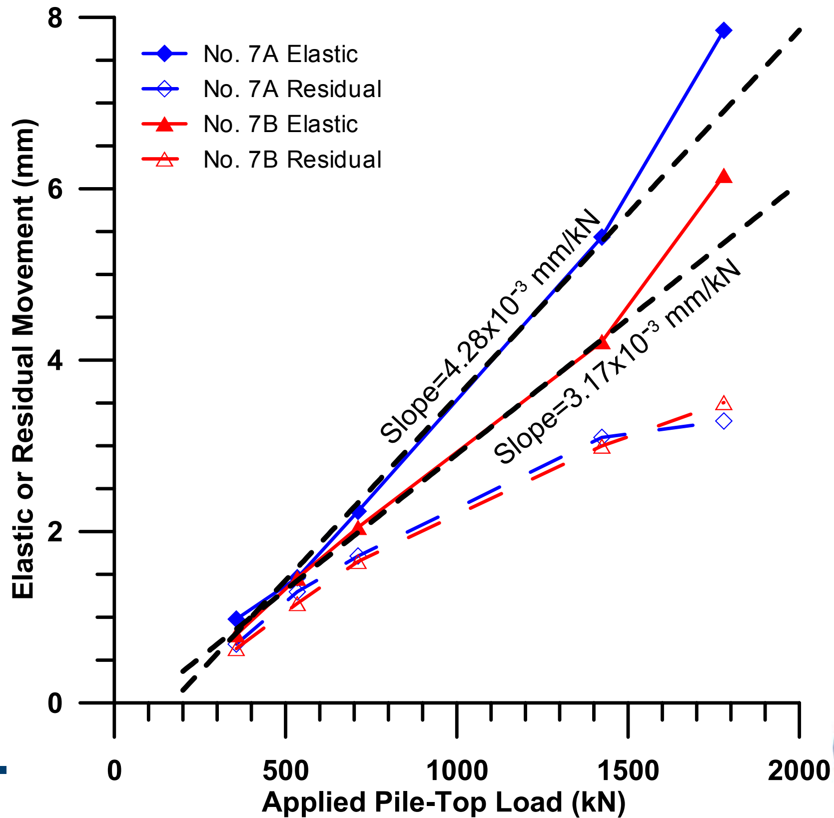




Elastic k_e from Cyclic Compression Tests

- Decomposition of total deformations into elastic and residual (plastic), $\delta_e = \delta_t - \delta_r$
- Elastic response has a linear portion, residual nonlinear
- k_e ranges from 3.15-4.28x10^{-3} mm/kN for Cases 6 and 7





Elastic k_e from Cyclic Compression Tests

- k_e is significant mechanical feature of micropile response
  - Tied to A_pE_p and mobilized geotechnical resistance

$$k_e = \frac{\delta_e}{P} = \frac{L_e}{A_p E_p}$$

  - A_pE_p is not constant for micropile
  - Already showed that E_{tan} or E_p is nonconstant

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Summary of Inelastic and Elastic k

Case No.	Test Type	No. Cycles	Cycle Length (kN)	Cycle Length (% DL)	Range of Unload-Reload k_c ($x10^{-3}$ mm/kN)	Elastic k_e ($x10^{-3}$ mm/kN)
3A	UR	5	1112	100	2.50-3.79	-
3B	UR	5	1112	100	2.99-3.91	-
5	UR	1	623	100	3.11	-
6A	QTC	6	Variable	25-150	-	3.15
6B	QTC	6	Variable	25-150	-	3.82
7A	QTC	5	Variable	25-250	3.07-3.37	4.28
7B	QTC	5	Variable	25-250	2.65-3.20	3.17
8A	QTC	4	Variable	50-200	-	18.50
8B	QTC	4	Variable	50-200	-	17.20

UR=Monotonic compression loading with one or more fixed-length unload-reload cycles
QTC=Cyclic quick compression loading with multiple unload-reload cycles of increasing length

- k_c and k_e typically between 3.0-3.5x10^{-3} mm/kN for working loads
- Must consider residual/plastic movements for total response

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Conclusions

- Pseudo-elastic properties important for load test analysis and predicting structure response
- E_{tan} is variable for pile sizes and steel/grout ratios
- Degradation rate falls within range of $0.1 < b < 0.01$ GPa/$\mu\varepsilon$
- Initial grout modulus $E_{gi} > E_{gu}$ by 2x
- Spring stiffness values fall within relatively narrow range at working loads
  - 3.5×10^{-3} mm/kN $< k_c, k_e < 3.0 \times 10^{-3}$ mm/kN

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