FIELD TESTING OF JET-GROUTED PILES AND DRILLED SHAFTS

BDK-75-977-41

Project Managers: Peter Lai, P.E.
Rodrigo Herrera, P.E.

Principal Investigator: Michael McVay, Ph.D.
Co-Principal Investigator: David Bloomquist, Ph.D., P.E.
Primary Researcher: Sudheesh Thiyyakkandi, Ph.D.

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Background

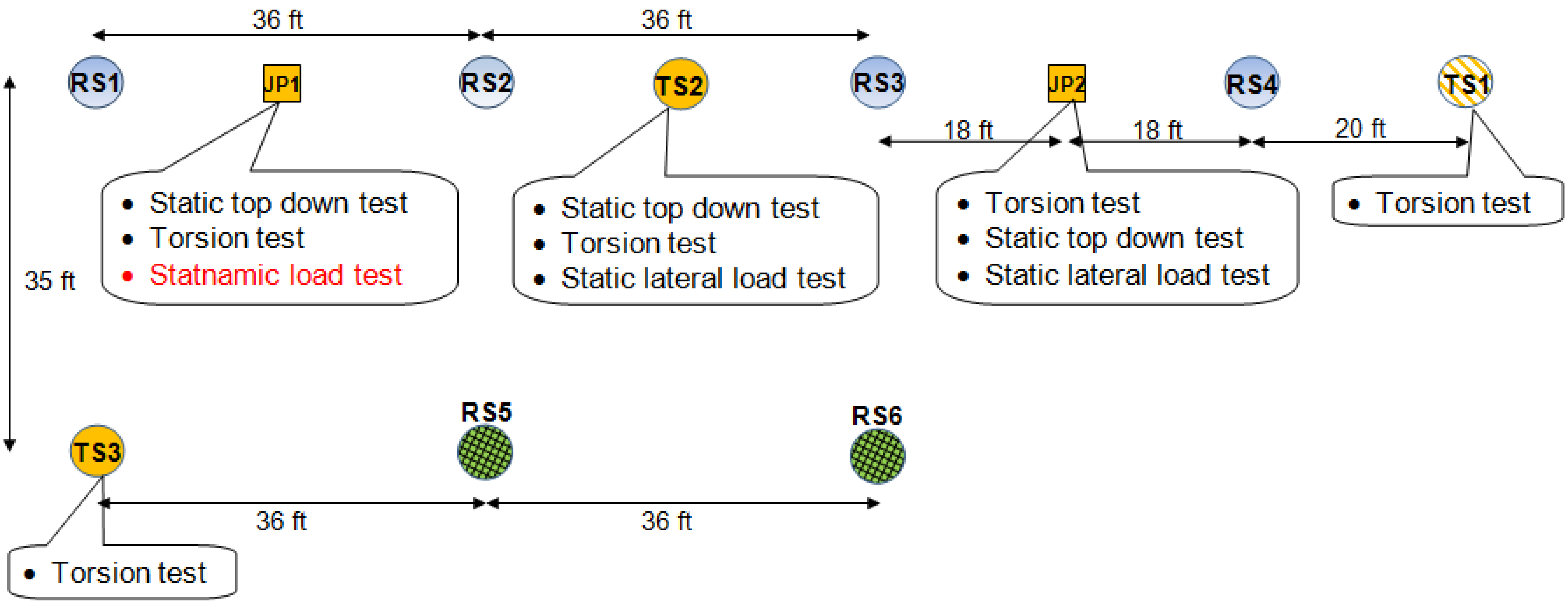
- Recently, FDOT developed a new foundation system -"jet-grouted pile" (BD545-31 and BDK-75-977-07)
- Previous chamber tests showed that the pile has high axial and torsional resistance
- Requires verification in typical field condition
- Recently FDOT revised design approach (torsional resistance) for drilled shaft supporting Mast Arms
- Past FDOT laboratory research (i.e. centrifuge testing, BC354-09) showed that lateral resistance was reduced significantly by torsion

Objectives of the Research

- Validate design and constructability of jet-grouted piles
- Obtain combined torsion and lateral load response of drilled shafts
- Verify FDOT's revised design approach for drilled shafts supporting Mast arm structures
- Compare axial, lateral, and combined torsion & lateral response of jet-grouted pile *vs.* drilled shaft
- Cost comparison of jet-grouted piles *vs.* drilled shafts

Test Layout

Test site: FDOT site, Kingsley, Keystone Heights, FL



- Two, 4ft diameter x 18ft deep **Test** drilled shafts
- One, 4ft diameter x 12ft deep **Test** drilled shaft
- Two, 28in square x 18ft deep **jet-grouted piles**
- Four, 4ft diameter x 40ft deep **Reaction** drilled shafts
- Two, 4ft diameter x 55ft deep **Reaction** drilled shafts

Presentation Overview

- Soil Exploration
- Construction of reaction and test drilled shafts
- Construction of jet-grouted piles
- Axial response of drilled shaft and jet-grouted piles
- Combined torsion and lateral response of drilled shafts and jet-grouted piles
- Lateral response of drilled shaft and jet-grouted pile
- Cost comparison: Jet-grouted pile vs. Drilled shaft

Soil Exploration at Test Site

- Performed by State Material Office, Gainesville.
  - In-situ tests:
    - ✓ SPT - at the foot print of each shaft/pile
    - ✓ CPT - at an interval of 6ft between shafts/piles
    - ✓ PMT - at the foot print of jet grouted piles
    - ✓ DMT - near jet grouted piles and shaft TS2
  - Laboratory Tests:
    - ✓ Classification tests
    - ✓ Direct shear Tests –Sand
    - ✓ UU-test - Clay

Construction of Reaction and Test Drilled shafts

- Wet construction method (using bentonite slurry)
- Test Shaft Instrumentation/Monitoring tubes:
  - ✓ 4 CSL tubes @ 90^0 apart
  - ✓ Inclinometer casing in 18ft long shafts (TS2 and TS3)
  - ✓ Sister-bar strain gages in pairs at 4 different levels (TS2)

Pipe and flange connector
(for combined torsion and lateral loading)

Construction of Jet-grouted Piles

Stages:

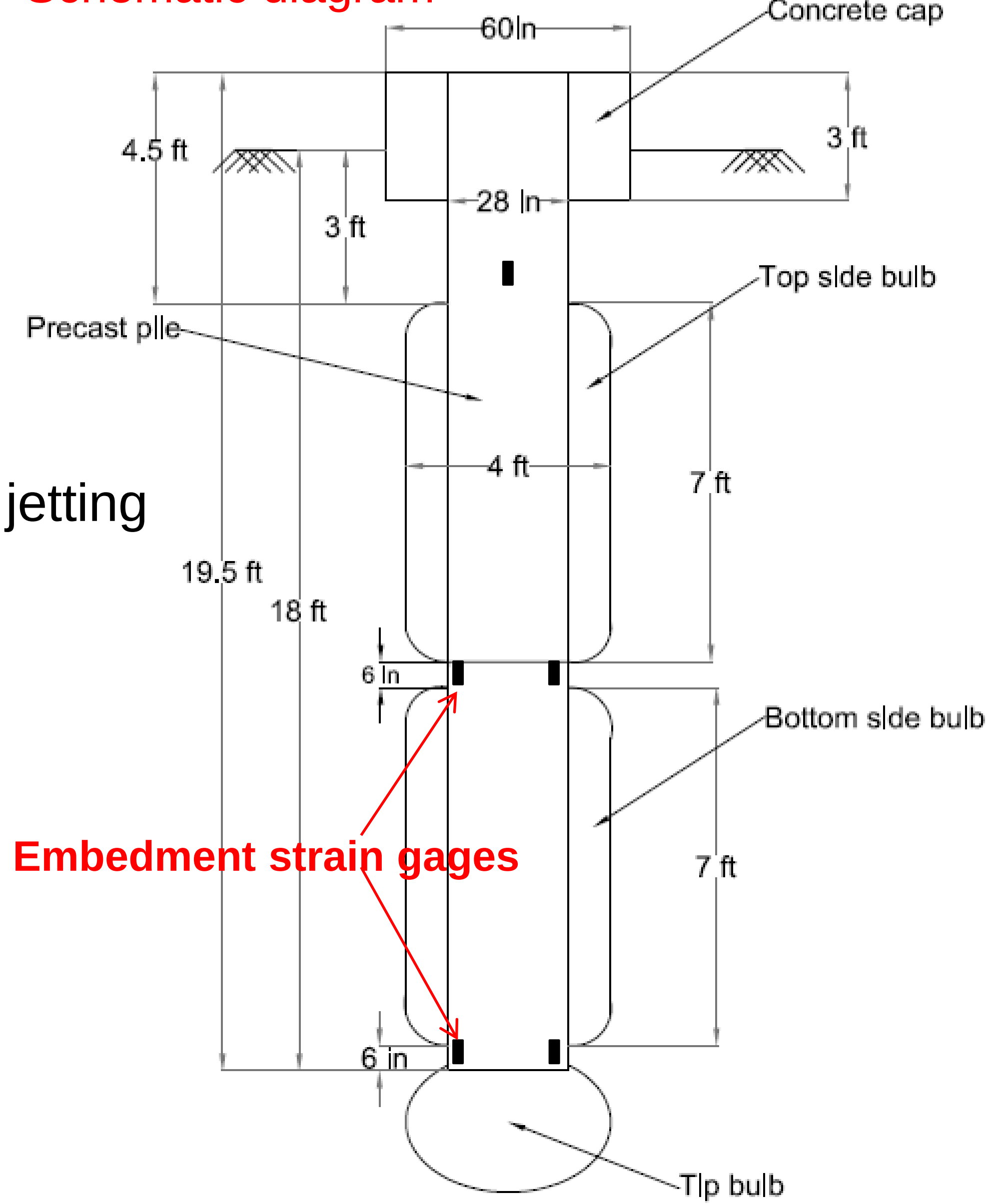
a) Construction of precast piles

b) Preparation of precast piles for jetting

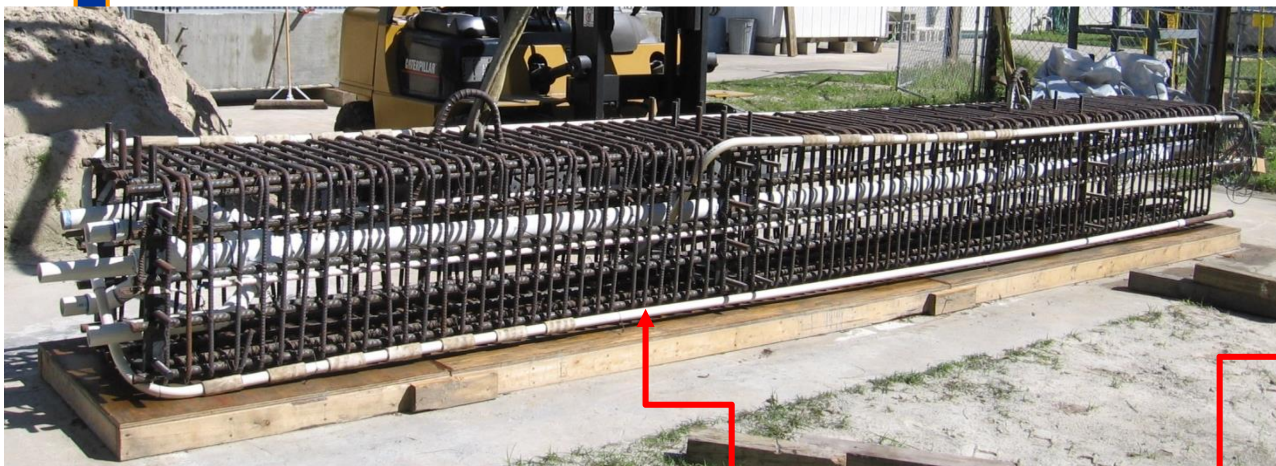
c) Jetting of piles

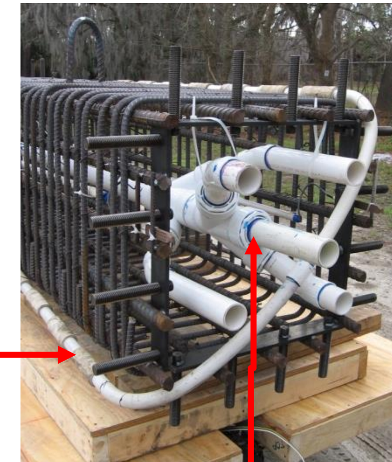
d) Side and tip grouting

Schematic diagram



Construction of Jet-grouted Piles (cont..)

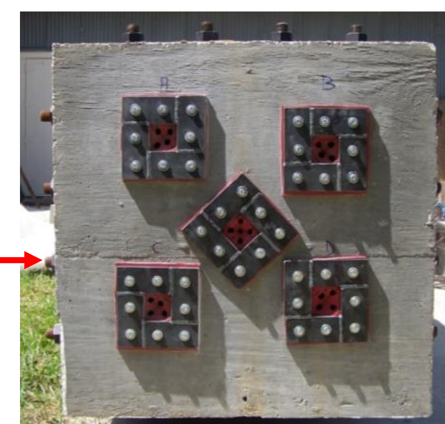




Side grout delivery system

Jetting system

Attaching Grout Membrane

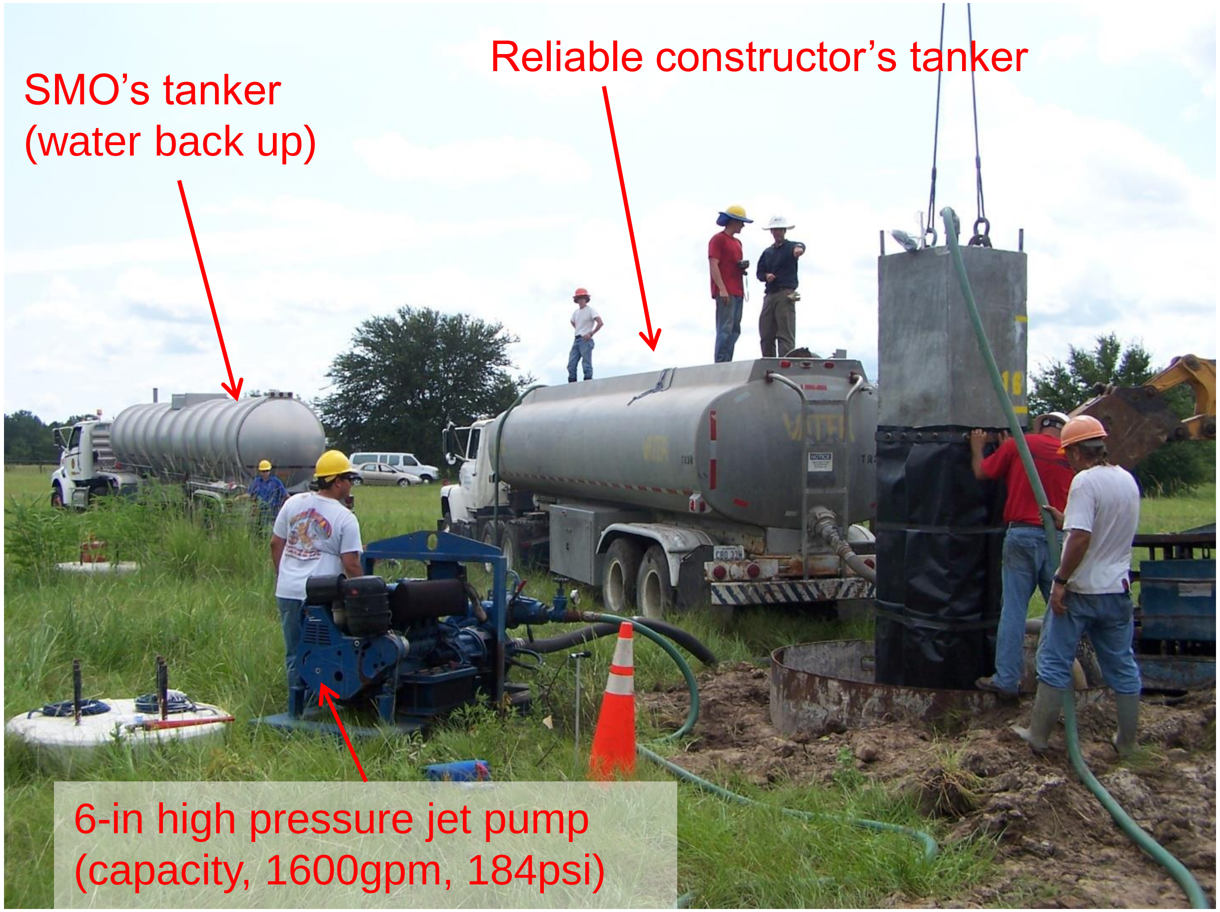


Attaching nozzles

Construction of Jet-grouted Piles (cont..)

Pile Jetting

Performed with the help of Reliable constructors Inc. and SMO, Gainesville



Construction of Jet-grouted Piles (cont..)

Concrete cap for jet grouted piles

- To transfer forces and moments from Mastarm assembly to pile during combined torsion and lateral load test

Precast Cap

Cast-in Place Cap

Construction of Jet-grouted Piles (cont..)

Side Grouting of Piles

Performed with the help of Applied Foundation Testing Inc. (AFT)

Grout volume = 300-340 gallons

Side grout pressure and cylindrical cavity expansion pressures

	Top membrane		Bottom membrane	
	JP1	JP2	JP1	JP2
Measured Maximum Pressures (psi)	100-120	90-100	140-160	180-200
Yu and Houlsby's solution (psi)	110	110	224	224
Salgado and Randolph's chart (psi)	116	116	210	210
PMT (psi)	113	85	198	153

Construction of Jet-grouted Piles (cont..)

Tip Grouting of Piles

	Grout volume (gallon)
JP1	140
JP2	59

Tip grout pressure and spherical cavity expansion pressure (psi)

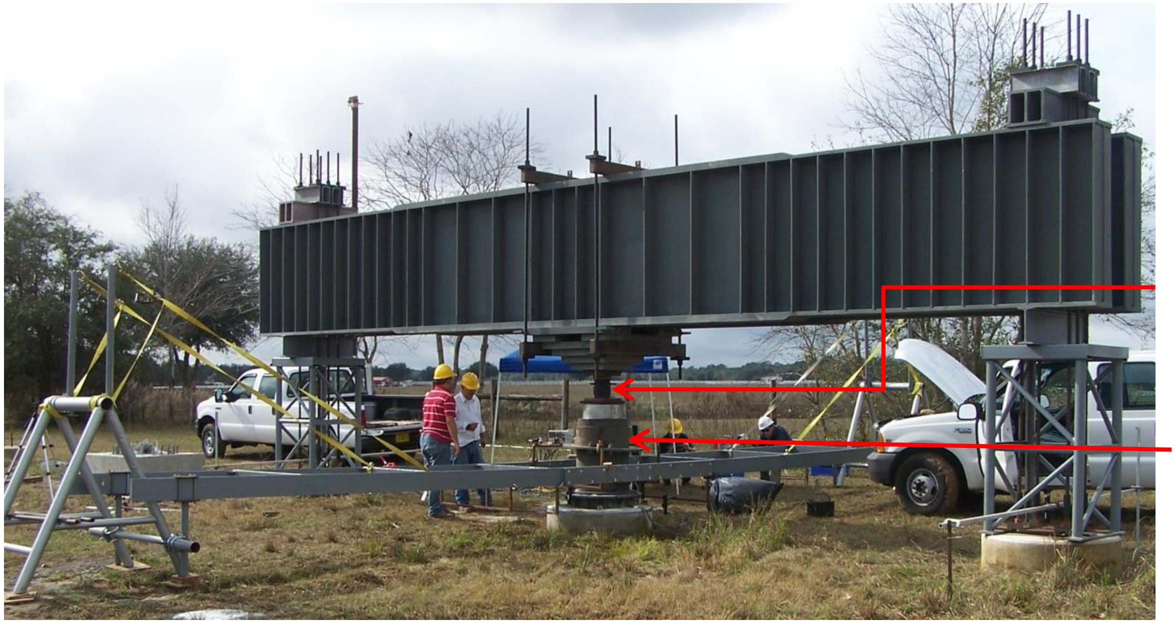
	Pile 1	Pile 2
Measured tip grout pressure	290	280-300
Yu and Houlsby's (1991)	509	509
Salgado and Randolph (2001)	522	522

60% of spherical cavity limit pressures

Axial response of drilled shaft and jet-grouted piles

Axial Response – 4ft Ø x 18ft deep drilled shaft (TS2)

- Static top down load test (ASTM D 1143/D 1143M – 07)



Load cell – 600 kips

Hydraulic jack – 2000 kips

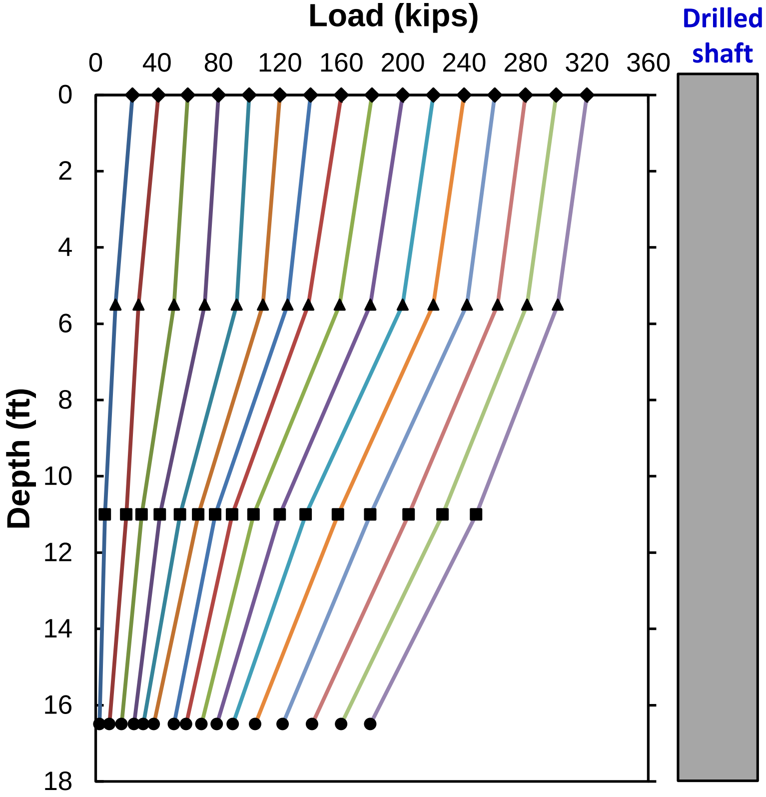
Shaft head displacement monitoring:

- Digital dial gages
- Mirrored scale with wire line reference

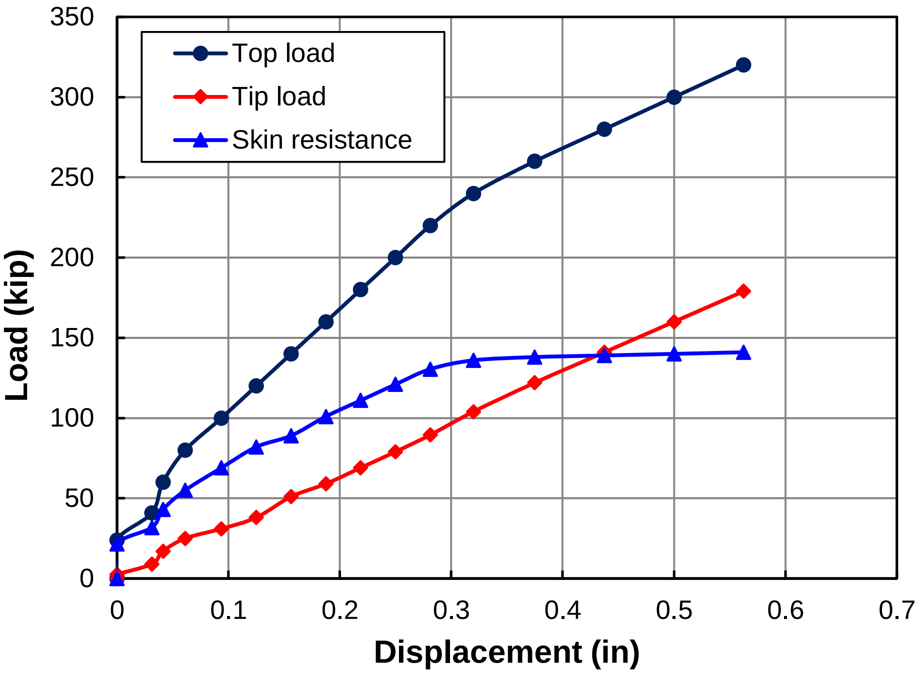
Axial Response – 4ft Ø x 18ft deep drilled shaft (TS2)

Maximum top displacement = 0.563in

Load distribution



Load-displacement response



Axial Response – 4ft Ø x 18ft deep drilled shaft (TS2)

Unit skin prediction methods

SPT based methods

1) O'Neill and Hassan (1994) method

$f_s = \beta \sigma'_v$

$\beta = 1.5 - 0.135\sqrt{z}$ for N_{60} >15, 0.25 ≤ β ≥ 1.2

$\beta = \frac{N_{60}}{15}(1.5 - 0.135\sqrt{z})$ for N_{60} <15

2) Rational method (FHWA 2010)

$f_s = \beta \sigma'_v$

$\beta = (1 - \sin\phi')\left(\frac{\sigma'_p}{\sigma'_v}\right)^{\sin\phi'} \tan\phi' \le K_p \tan\phi'$

$\frac{\sigma'_p}{P_a} \approx 0.47(N_{60})^m$

Alpha (α) method (for cohesive soils)

$f_s = \alpha s_u$

$\alpha = 0$, for top 5ft depth

$\alpha = 0.55$, for $(s_u/P_a) \le 1.5$

$\alpha = 0.55 - 0.1\left(\frac{s_u}{P_a} - 1.5\right)$, for $1.5 \le (s_u/P_a) \le 2.5$

CPT based methods

1) Aoki and Velloso's method

$f_{si} = \frac{\alpha}{F_2} \cdot q_{ci}$

F_2 = 6-7 for drilled shafts

α = resistance factor depends on soil types

2) LCPC method

$f_{si} = \frac{q_{ci}}{\alpha_{LCPC}}$

α_{LCPC} - depends on pile and soil types

3) UIUC Method (Alsamman 1995)

Sand / silty Sand:

$f_s = 0.015\ q_c$ for $q_c \le 50$ tsf

$f_s = 0.0012\ q_c + 0.7 \le 1.0$ for $q_c \ge 50$ tsf

Clay:

$f_s = 0.023\ (q_c - \sigma_{vo}) \le 0.9$

Axial Response – 4ft Ø x 18ft deep drilled shaft (TS2)

Estimation of soil parameters for the prediction

Unit weight: $$\frac{\gamma}{\gamma_w} = 0.27[\log R_f] + 0.36\left[\log\left(\frac{q_c}{P_a}\right)\right] + 1.236$$

Robertson and Cabal (2010)

Angle of internal friction: $$\phi' = \tan^{-1}\left[\frac{N_{60}}{12.2 + 20.3(\sigma'_{v0}/P_a)}\right]^{0.34}$$

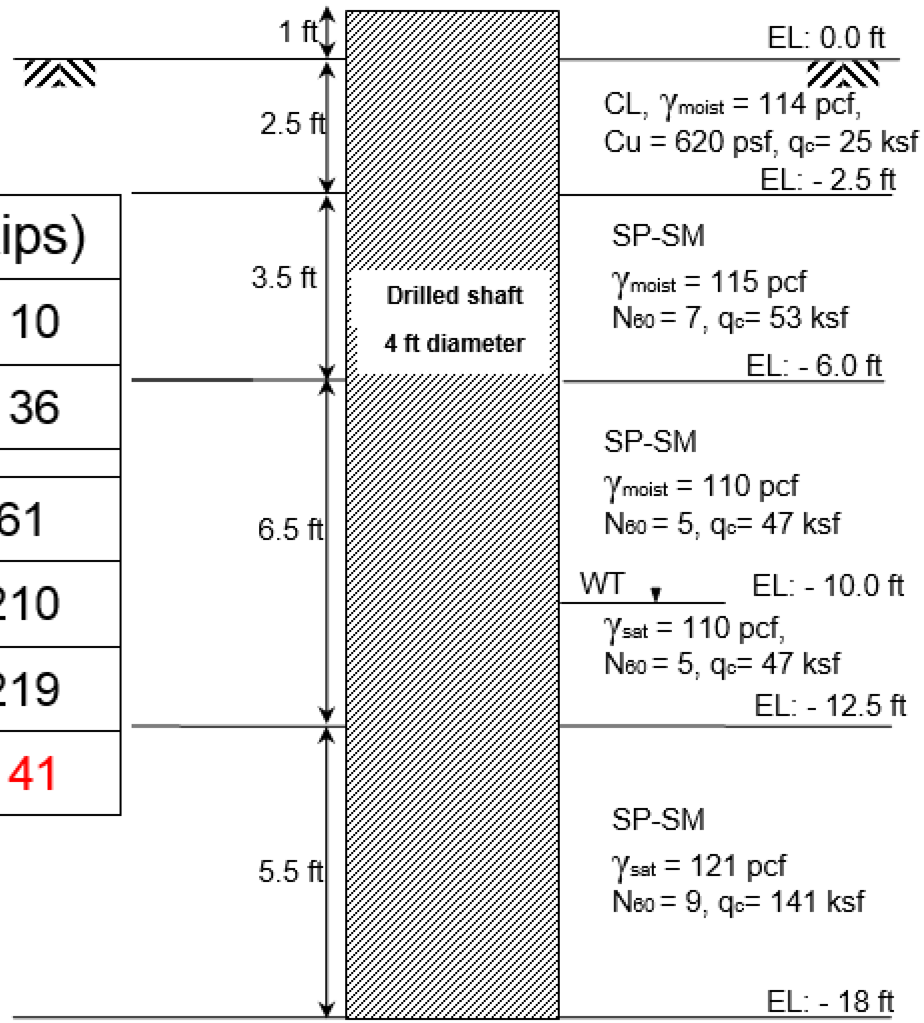
Schmertmann (1975)

Undrained shear strength: UU test

Axial Response – 4ft Ø x 18ft deep drilled shaft (TS2)

Predicted vs. Measured

	Method	(kips)
SPT	O'Neill and Hassan (1994) method	110
	Rational method (FHWA 2010)	136
CPT	Aoki and Velloso's method	61
	LCPC method	210
	UIUC Method (Alsamman 1995)	219
	Measured value	141



Axial Response – Jet-grouted piles

Static Load Test

Loading sequence: JP1 - Axial load test BEFORE torsion test

JP2 – Axial load test AFTER torsion test

Data acquisition

Displacement monitoring: Leica Digital levels

Digital dial gages

▪ Mirrored scale with wire line reference

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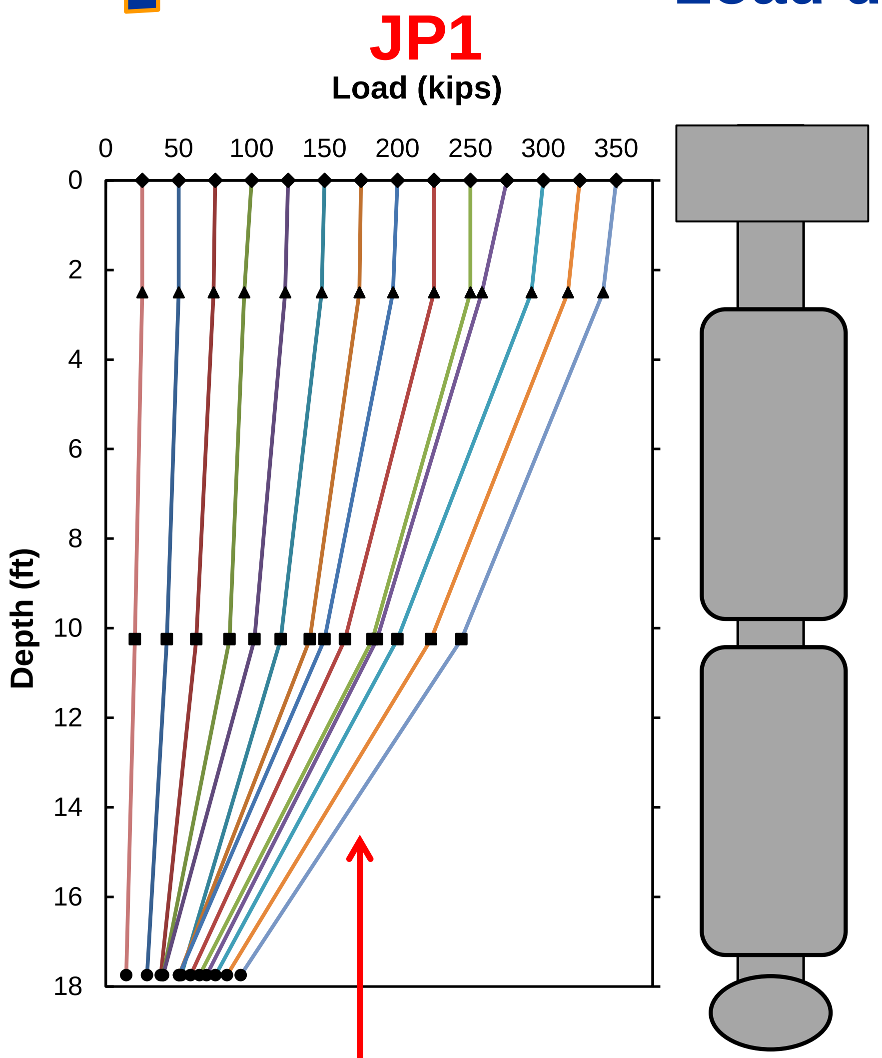
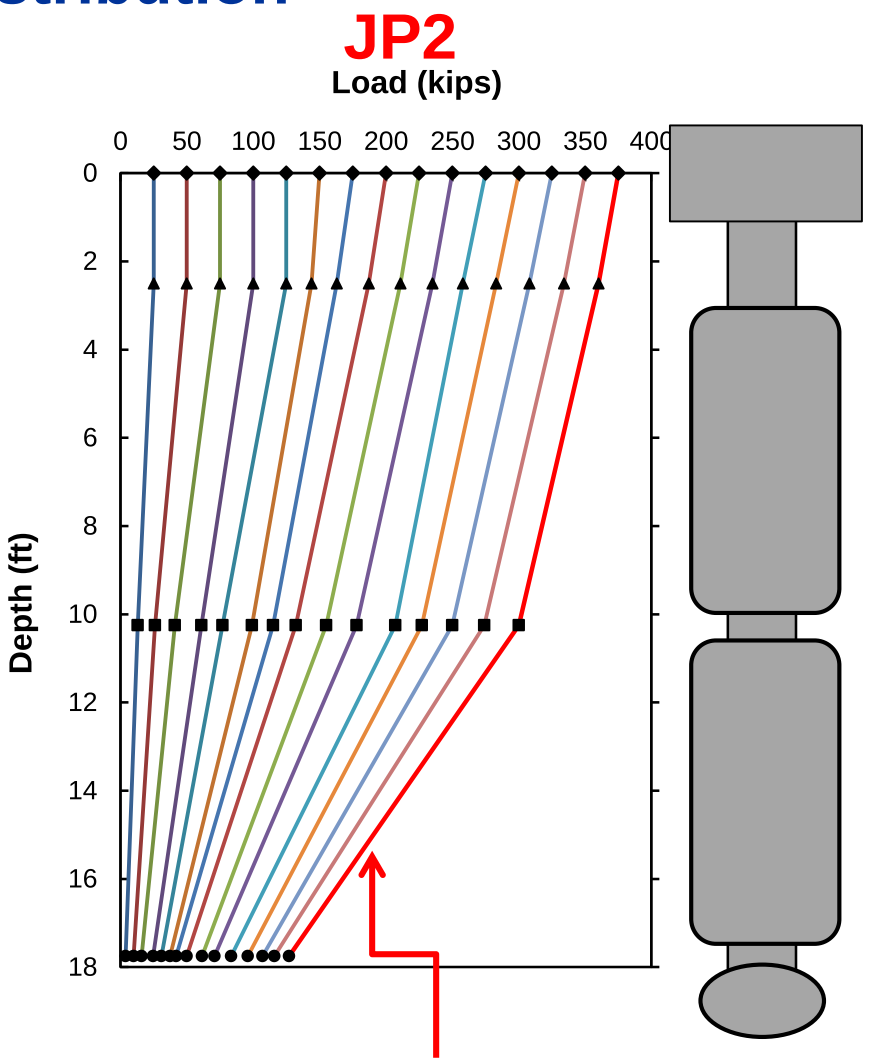
Axial Response – Jet-grouted piles

Load distribution

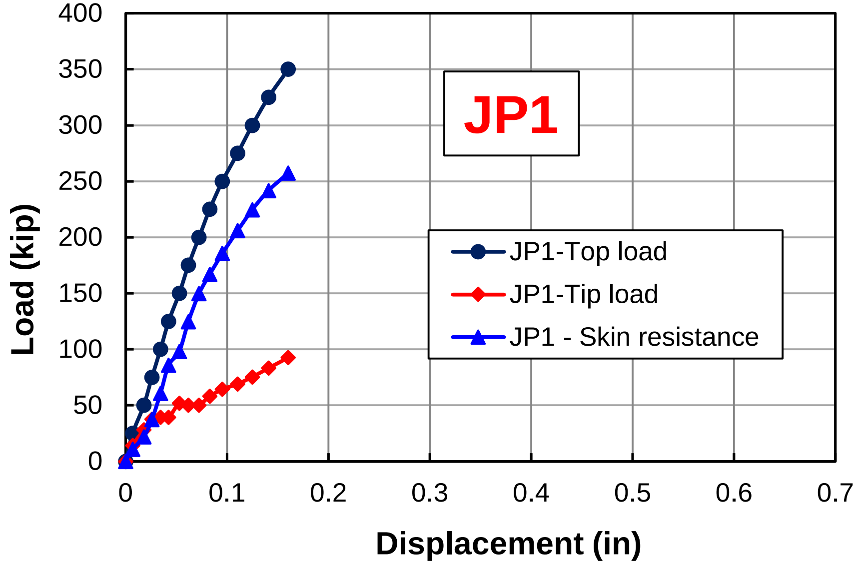


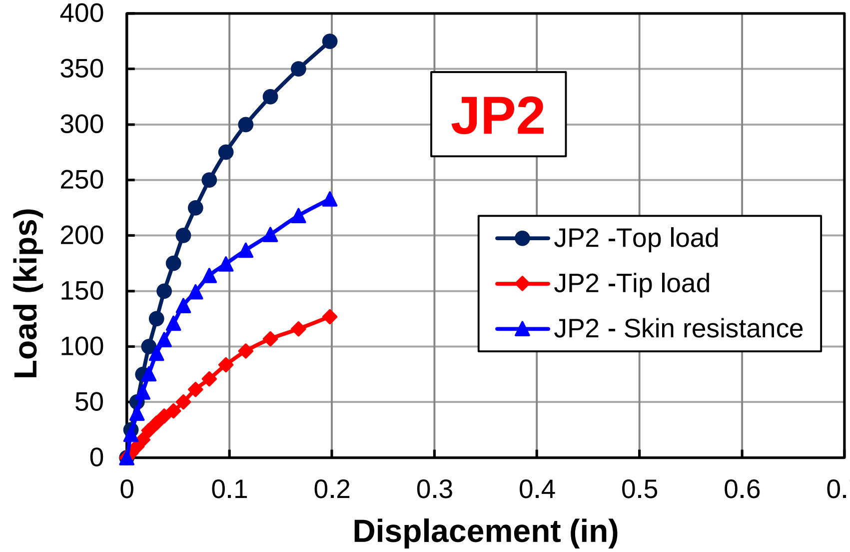


Skin resistance not fully mobilized…..

Axial Response – Jet-grouted piles

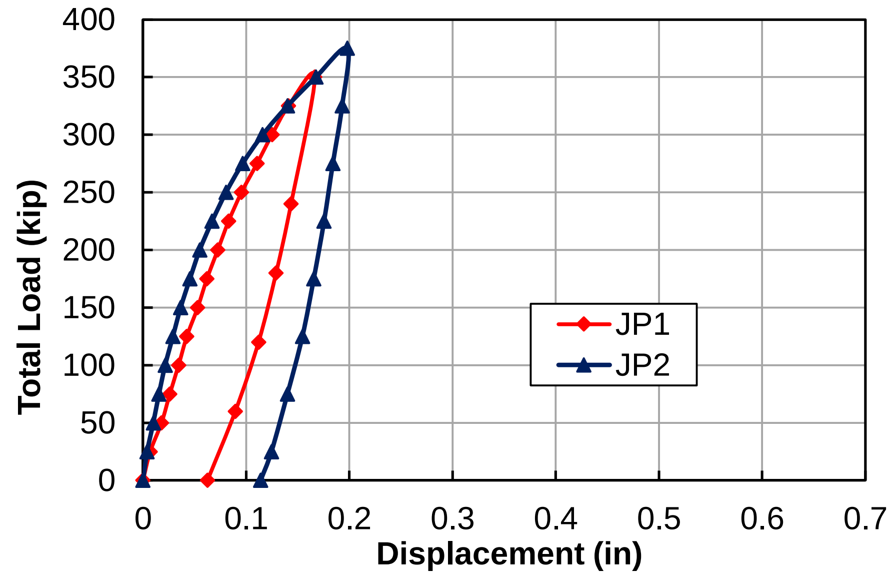
Load Displacement responses





Comparison: JP1 vs. JP2

- Similar stiffness response
- Negligible influence of prior torque test in JP2



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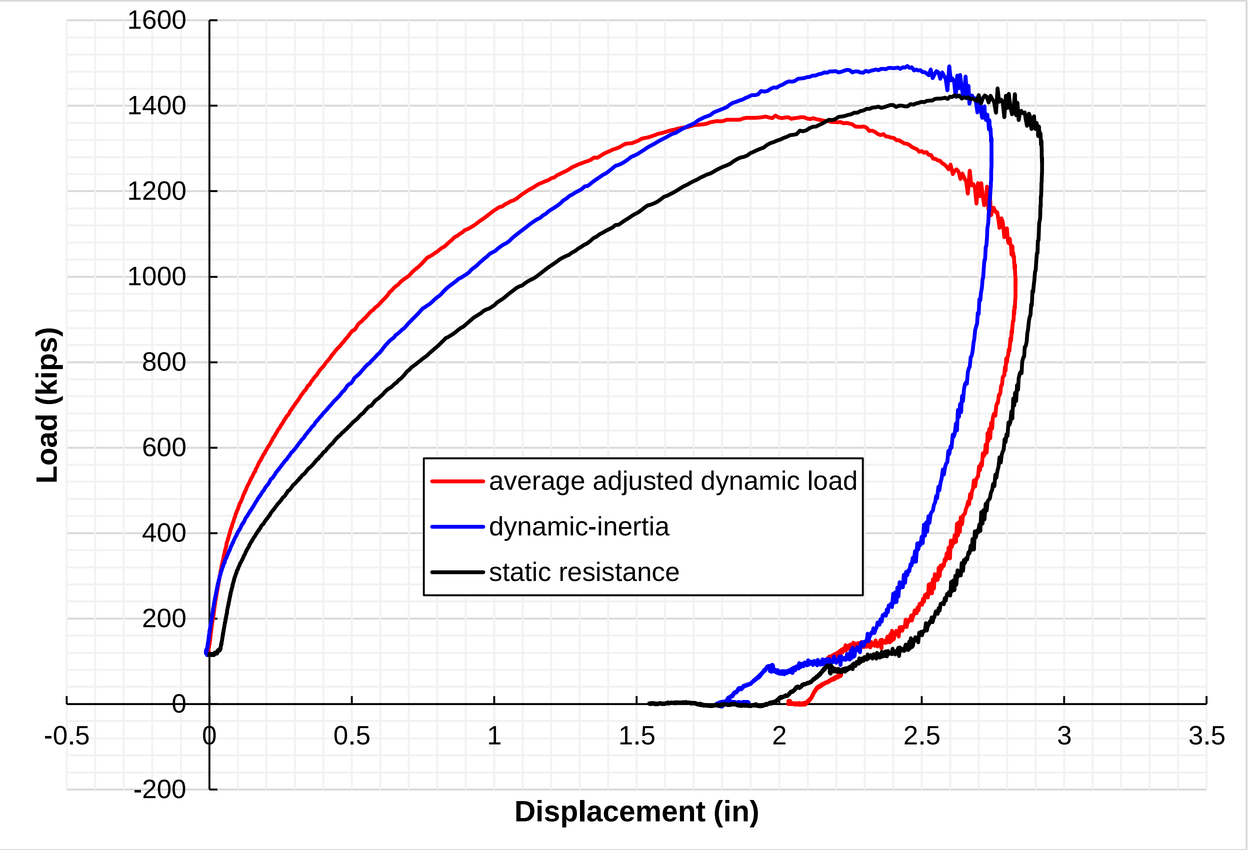
Axial Response – Jet-grouted piles

Statnamic Load Test – JP1

- Performed by Applied Foundation Testing, Inc.



Measured Skin resistance = 450 kips

Axial Response – Jet-grouted piles

Prediction of skin resistance

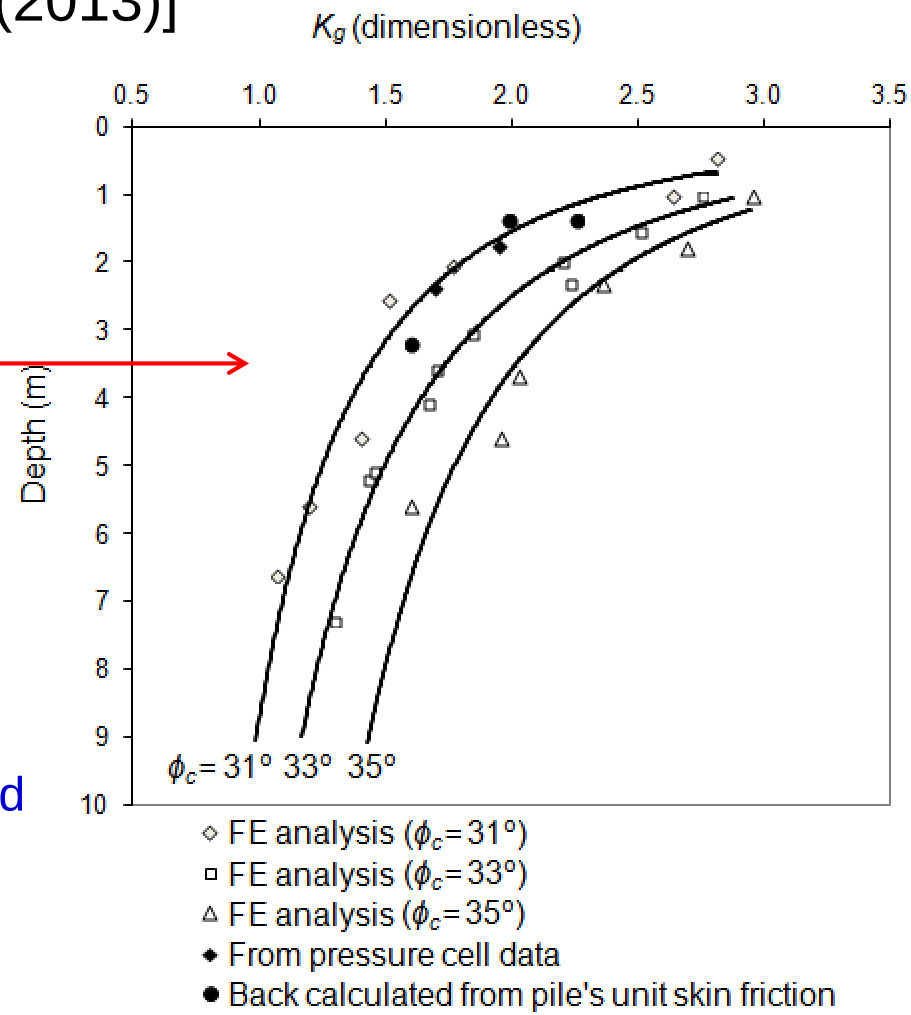
1) K_g method [Thiyyakkandi et al. (2013)]

$$f_s = \sigma'_{vg}\left[\frac{\sin\phi_c}{1-\sin\phi_c}\right]\sin(90-\phi_c)$$

$$\sigma'_{vg} = K_g\sigma'_{v0} = K_g\gamma' h$$

γ' - Submerged unit wt of soil

h - depth



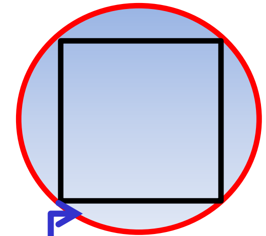
A purely cylindrical grout zone is assumed for surface area calculation

Axial Response – Jet-grouted piles

Prediction of skin resistance

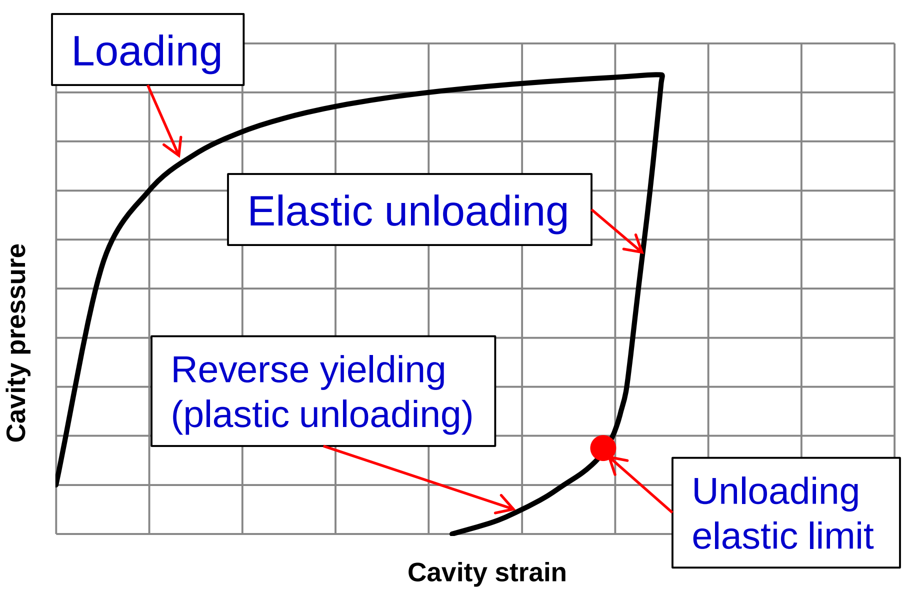
2) Using tip grout pressure

Skin resistance = Max. Sustained tip grout pressure x Eff. Tip area

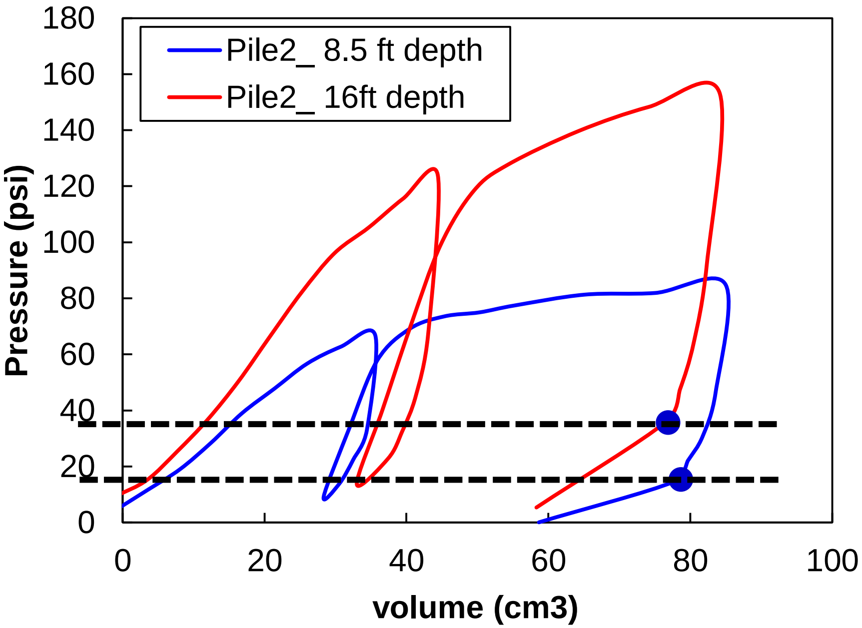


3) Using Pressuremeter data

Cylindrical cavity loading and unloading curve



Pressuremeter curve



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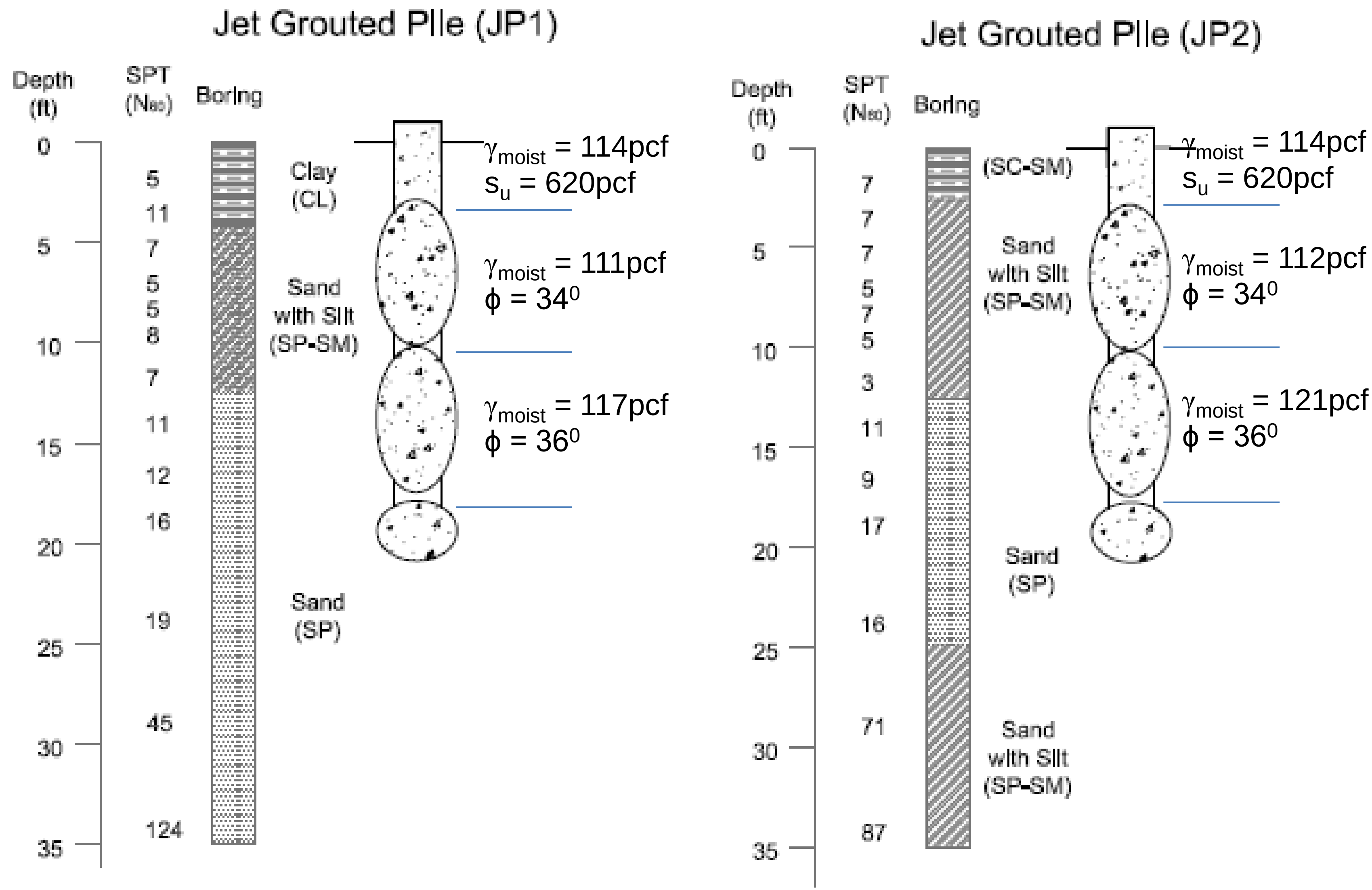
Axial Response – Jet-grouted piles

Soil Profile



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Predicted vs. Measured Skin resistance

K_g method

Pile	Grout zone	Zone length H(ft)	Depth to middle of zone (ft)	Initial vertical eff. stress at middle σ'_{vo} (psf)	K_g at middle Fig.2-6	Grouted vertical eff. stress $\sigma'_{vg}=K_g\,\sigma'_{vo}$ (psf)	δ - ϕ	f_s (psf) (Eq. 2-2) (δ - ϕ)	A_s Surface area (ft²)	Qs Side resistance (kip) (δ - ϕ)	**Total (kip)** (δ - ϕ)
JP1	Top	7	6.5	717.3	2.33	1671.3	$23.8^0 - 34^0$	1035-1758	83.84	87-147	**235-401**
	Bottom	7	14	1305.6	2.00	2611.2	$25.2^0 - 36^0$	1752-3012	84.29	148-254	
JP2	Top	7	6.5	730.0	2.33	1700.9	$23.8^0 - 34^0$	1053-1789	83.39	88-150	**239-409**
	Bottom	7	14	1331.4	2.00	2662.8	$25.2^0 - 36^0$	1787-3072	85.77	151-259	

Using PMT

Pile	Grout zone	Zone length H(ft)	δ	Horizontal stress after grouting, σ_h (psi) Fig. 6-16	$f_s = \sigma_h \tan(\delta)$ (psf)	A_s Surface area (ft²)	Qs Side resistance (kip)	**Total (kip)**
JP1	Top	7	23.8°	22	1397	83.84	117	**403**
	Bottom	7	25.2°	50	3388	84.29	286	
JP2	Top	7	23.8°	16	1016	83.39	85	**311**
	Bottom	7	25.2°	39	2643	85.77	227	

Using TGP

Pile	Tip grout pressure (*psi*)	Effective tip area (*in²*)	**Side resistance (*kips*)**
JP1	290	1231	**357**
JP2	280-300	1231	**345-369**

Measured

	JP1	**JP2**
Top zone	97	60
Bottom Zone	151	173
Total	**248 (450*)**	**233**

***Statnamic**

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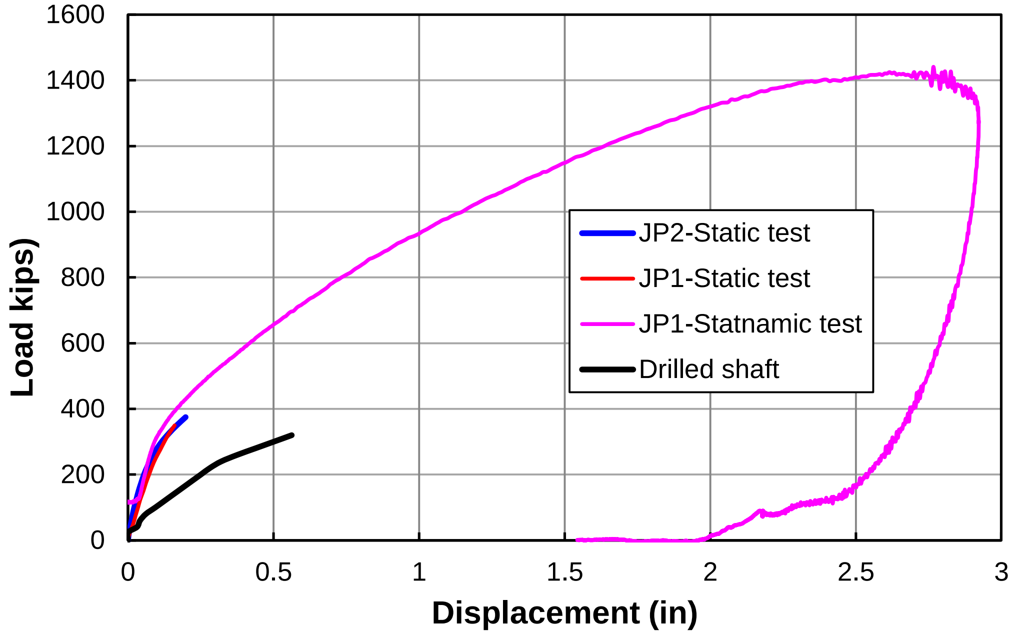
Axial Response Comparison

Total load vs. top displacement



Unit skin

Segment	Unit skin (*ksf*)		
	JP1	JP2	Drilled shaft
Top membrane (3 – 10ft)	1.16	0.720	0.591
Bottom membrane (10.5- 17.5ft)	1.79*	2.02*	0.852

*Not fully mobilized

Combined Torsion and Lateral Response

Mast arm-Pole assembly

- Designed to ensure pile/shaft - soil failure (no structural failure)
- Fabricated at Coastal Engineering lab, UF

	Length (ft)	Diameter (in)	Thickness (in)	Taper angle (deg)
Arm	40	20	0.625	0
Pole	22	24	0.625	0

Combined Torsion and Lateral Response

Drilled shafts

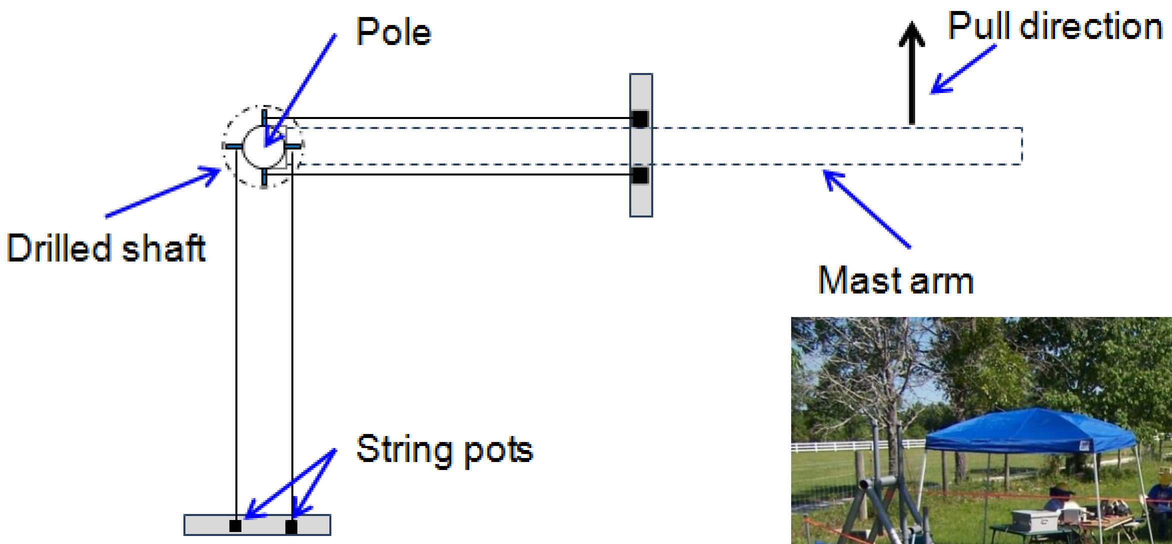
Lateral load applied at an eccentric distance of 35ft

20kips tension load cell

Combined Torsion and Lateral Response

Rotation and translation monitoring

1) String pots



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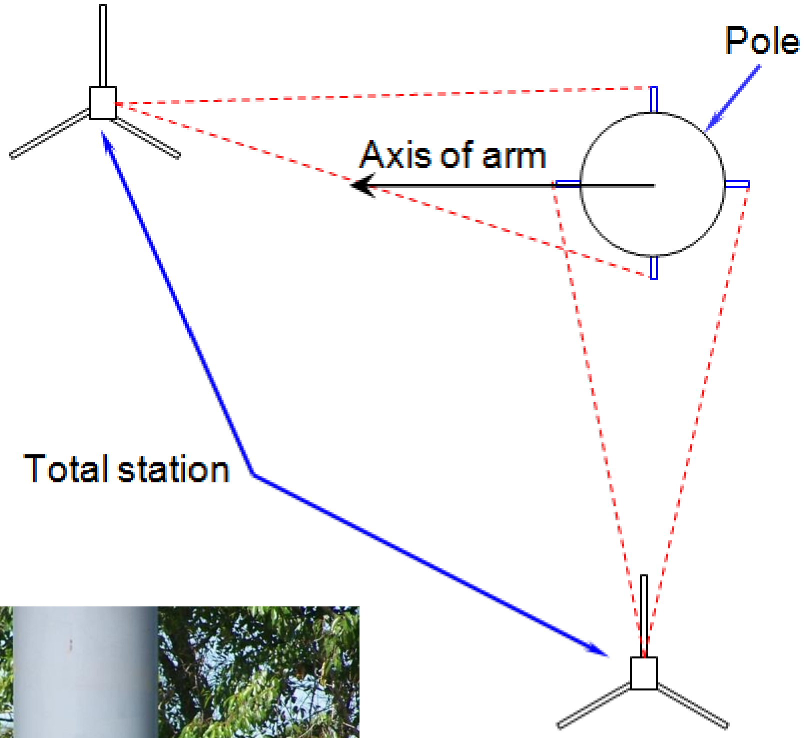
Combined Torsion and Lateral Response

Rotation and translation monitoring

2) Total Stations

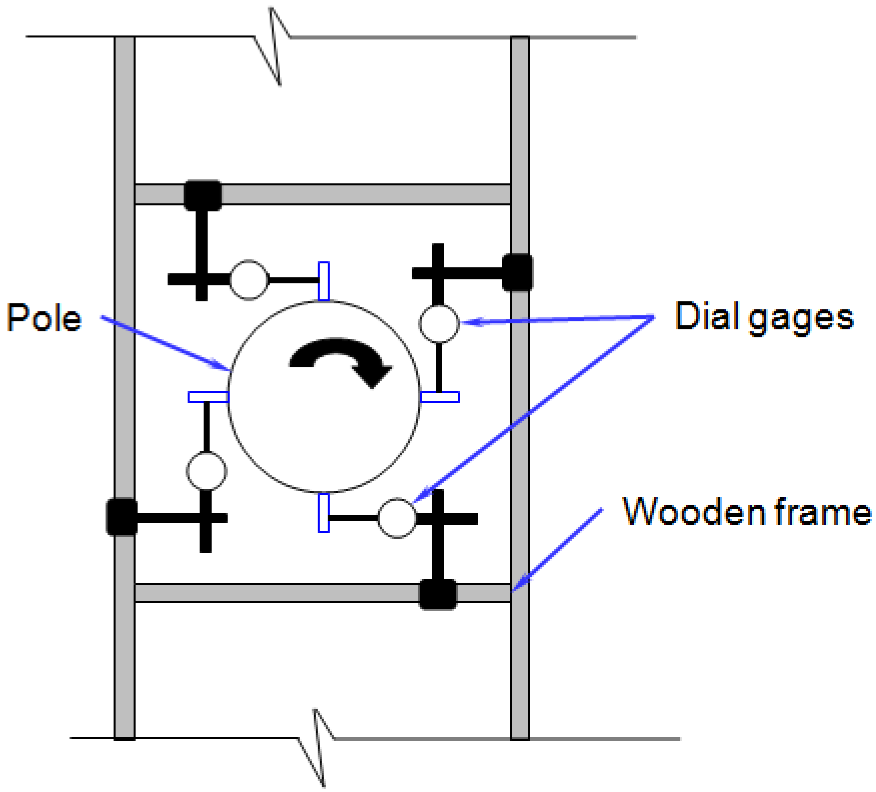


Reflective Targets

Combined Torsion and Lateral Response

Rotation and translation monitoring

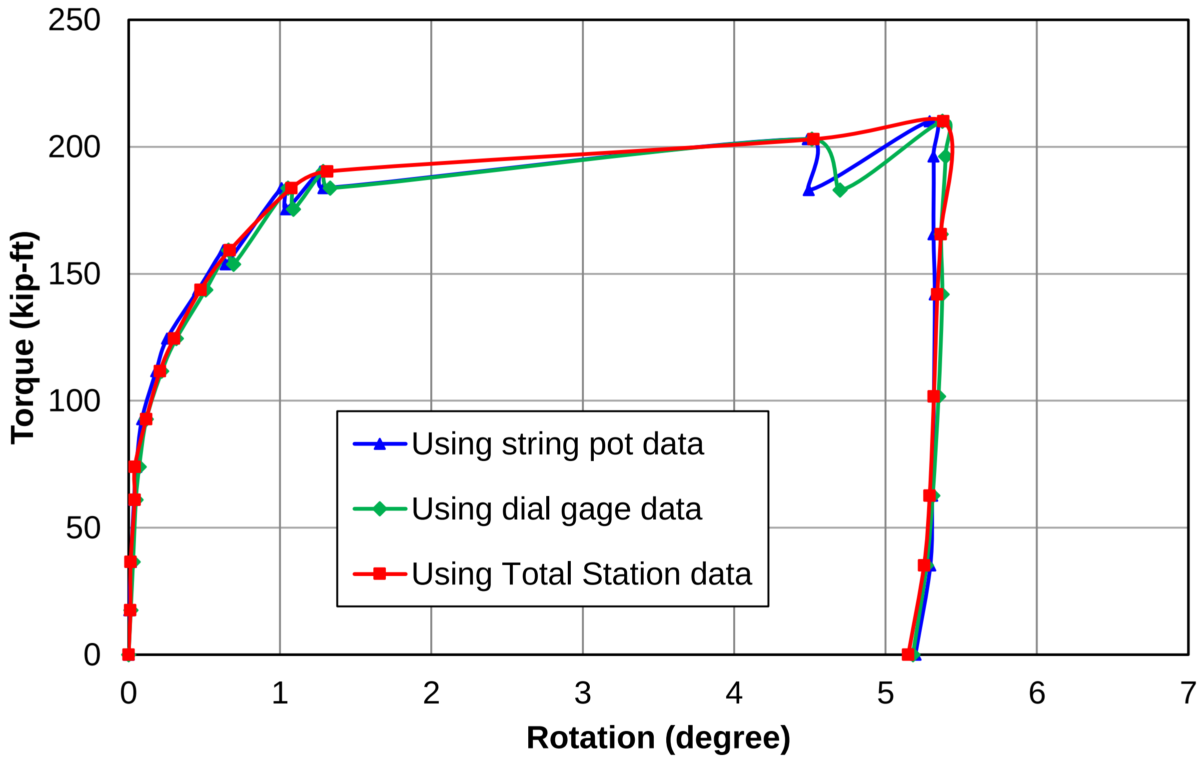
3) Digital dial gages



Combined Torsion and Lateral Response

Drilled shafts

Comparison of rotation response from different instrumentations (TS2)



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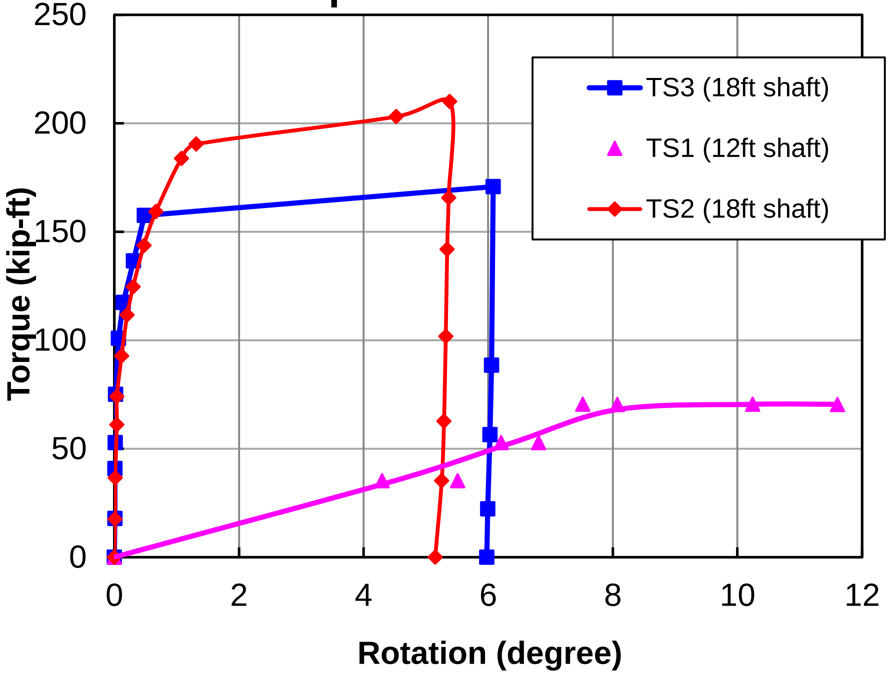
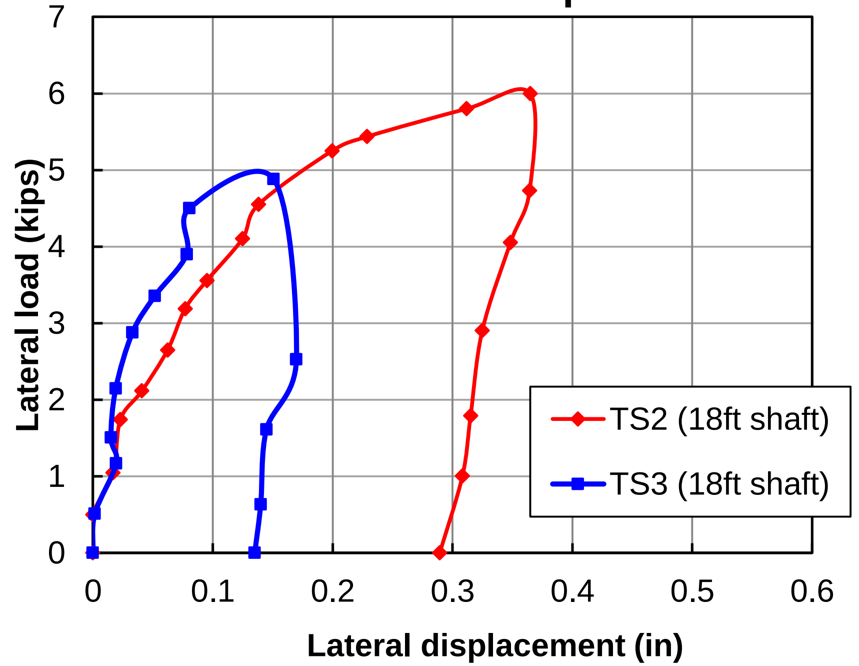
Combined Torsion and Lateral Response

Drilled shafts

Torque vs. rotation



Lateral load vs. displacement



TS1: Max. lateral displacement ≈4in

Combined Torsion and Lateral Response

Drilled shafts: Torsional resistance prediction

1) FDOT's ω method:

$$T_s = \frac{\pi D^2}{2}\int_0^L f_{sz}\,dz$$

$$f_{sz} = \sigma'_{vz}\omega_{FDOT}$$

$$\omega_{FDOT} = 1.5 \quad \text{for } N_{60} > 15$$

$$\omega_{FDOT} = 1.5\left(\frac{N_{60}}{15}\right) \quad \text{for } 5 < N_{60} < 15$$

Skin contribution

$$T_t = \pi\left(\frac{D}{2}\right)^2 L\gamma_{conc}\left(\frac{D}{3}\right)\tan\delta$$

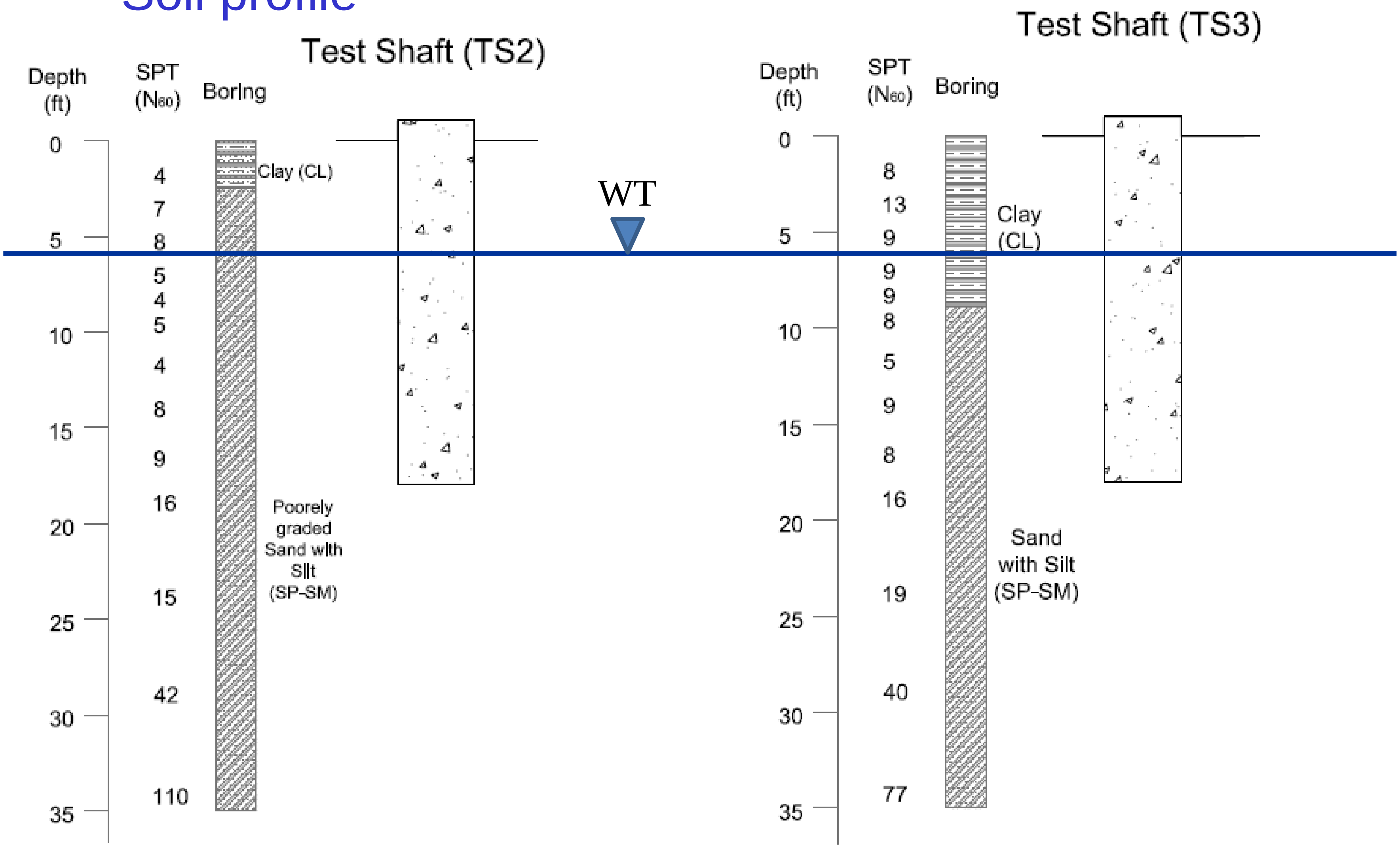
Tip contribution

2) O'Neill and Hassan (1994) method

3) Rational method (FHWA 2010)

Combined Torsion and Lateral Response

Soil profile



Combined Torsion and Lateral Response

Drilled shafts: Torsional resistance prediction

Method	TS1			TS2			TS3		
	Skin (kip-ft)	Tip (kip-ft)	Total (kip-ft)	Skin (kip-ft)	Tip (kip-ft)	Total (kip-ft)	Skin (kip-ft)	Tip (kip-ft)	Total (kip-ft)
Measured	--	--	70	--	--	210	--	--	171
FDOT's ω method	99	25	124	264	30	294	249	28	277
O'Neill and Hassan (1994)*	80	--	80	189	--	189	191	--	191
Rational method) FHWA 2010*	119	--	119	253	--	253	236	--	236
Based on axial load test*	--	--	--	(282) 251**	--	(282) 251**	--	--	--

*No tip contribution is considered (Hu et al. 2006)
**Corrected for Water Table

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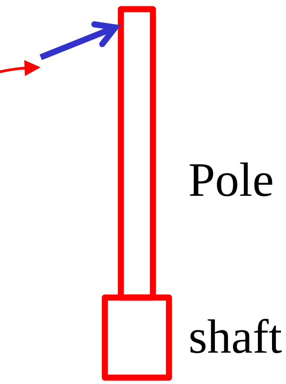
Combined Torsion and Lateral Response

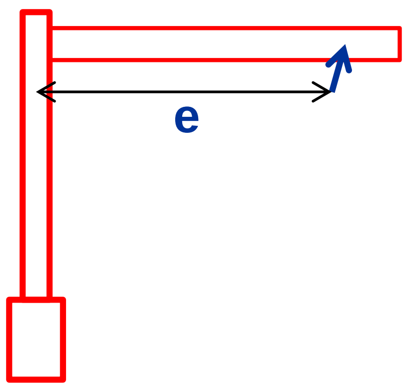
Lateral resistance Reduction:

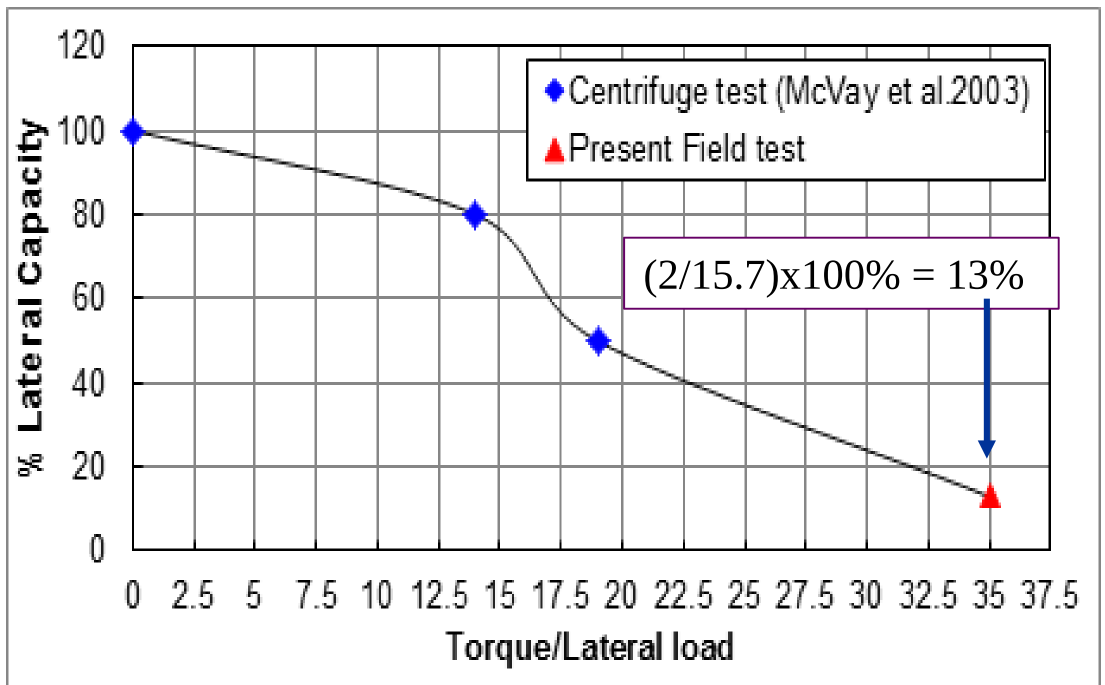
Using the force and moment equilibrium approach (Hu et al. 2006):

For TS1, Ultimate lateral resistance (no torsion) = 15.7 kips



According to Hu et al. (2006) lateral overturning resistance is significantly reduced by torsion. (function of lateral load eccentricity, e)





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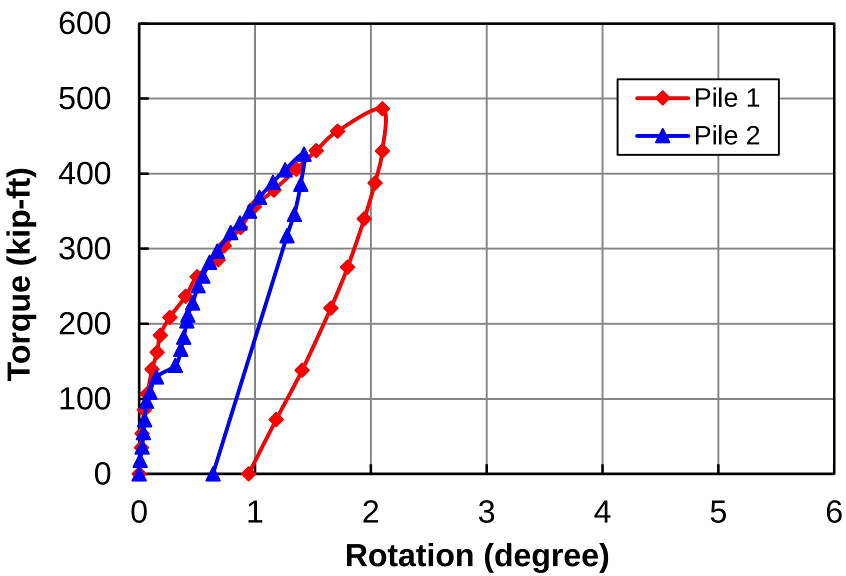
Combined Torsion and Lateral Response

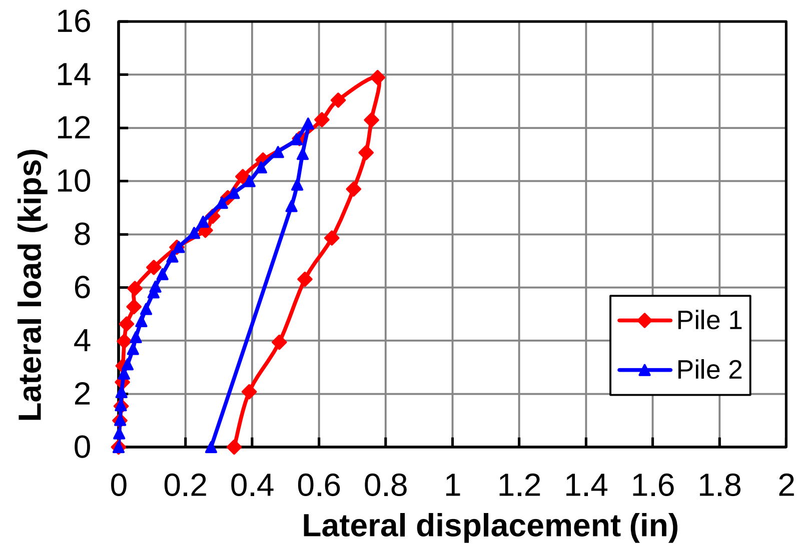
Jet-grouted pile

Loading sequence: JP1 - Torsion test AFTER axial load test
JP2 – Torsion test BEFORE axial load test

Torque vs. rotation



Lateral load vs. displacement



Combined Torsion and Lateral Response

Jet-grouted pile

Measured and predicted torsional resistance

Pile	Method	Torsional Resistance (kip-ft)
JP1	Measured (kip)	487*
	Kg method (kip)	450[a] - 768[b]
	Pressuremeter data (kip)	772
	Tip grout data (kip)	684
JP2	Measured* (kip)	426*
	Kg method (kip)	456[a] - 783[b]
	Pressuremeter data (kip)	598
	Tip grout data (kip)	661-707

**not fully mobilized*

[a] *using interface friction angle (δ)*

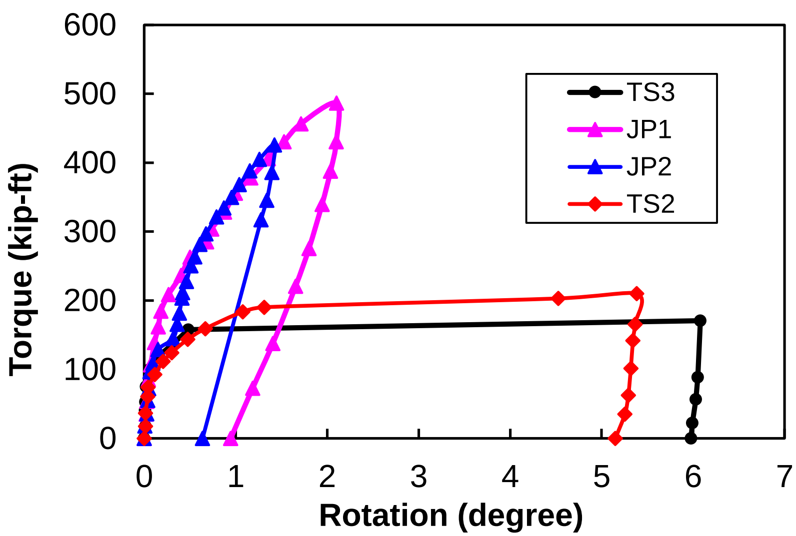
[b] *using soil's friction angle (ϕ)*

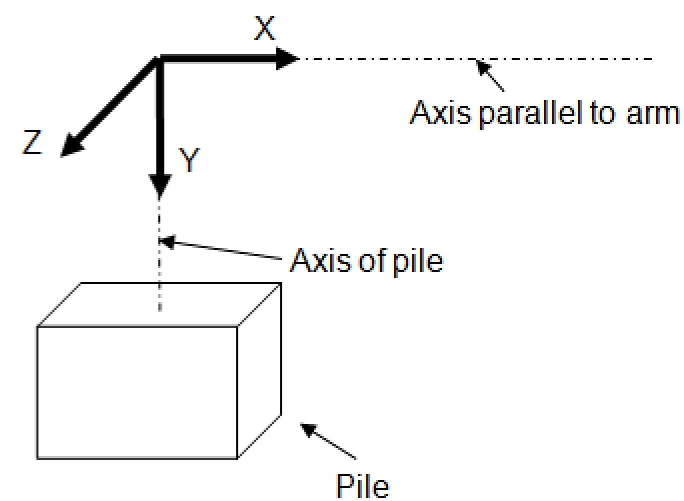
Combined Torsion and Lateral Response

Comparison

Design wind speed =130mph

Forces and moments	JP1	JP2	TS2	TS3	E7-T6 Mast arm*
Torsion, M_y (kip-ft)	487	426	210	171	258.8
Moment about axis of arm, M_x (kip-ft)	278	243	120	97.6	149
Moment about axis normal to arm, M_z (kip-ft)	118	118	118	118	116.6
Lateral load, V_x (kips)	0	0	0	0	0.3
Lateral load, V_z (kips)	13.9	12.17	6	4.88	7.4
Axial load, V_y (kips)	10.7	10.7	10.7	10.7	5.6





Coordinate system

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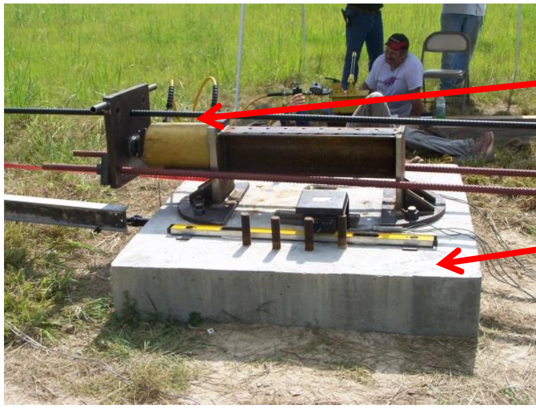
Lateral Response of Drilled Shaft and Jet-grouted Pile

Lateral load test

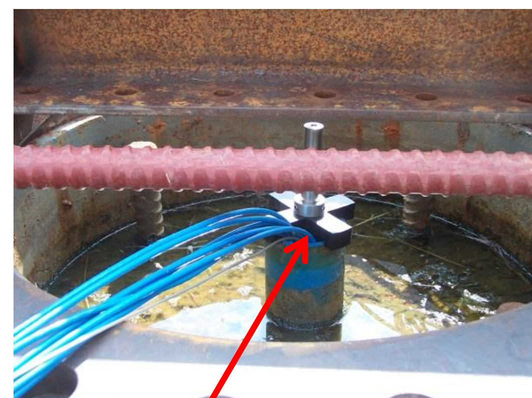


Hydraulic jack

Test pile

Load cell

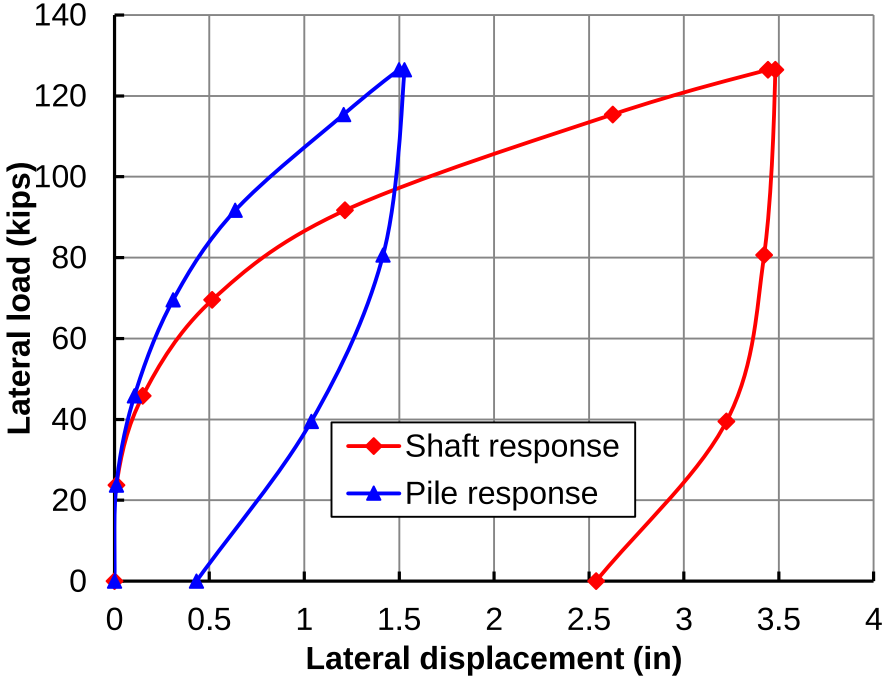
Test shaft



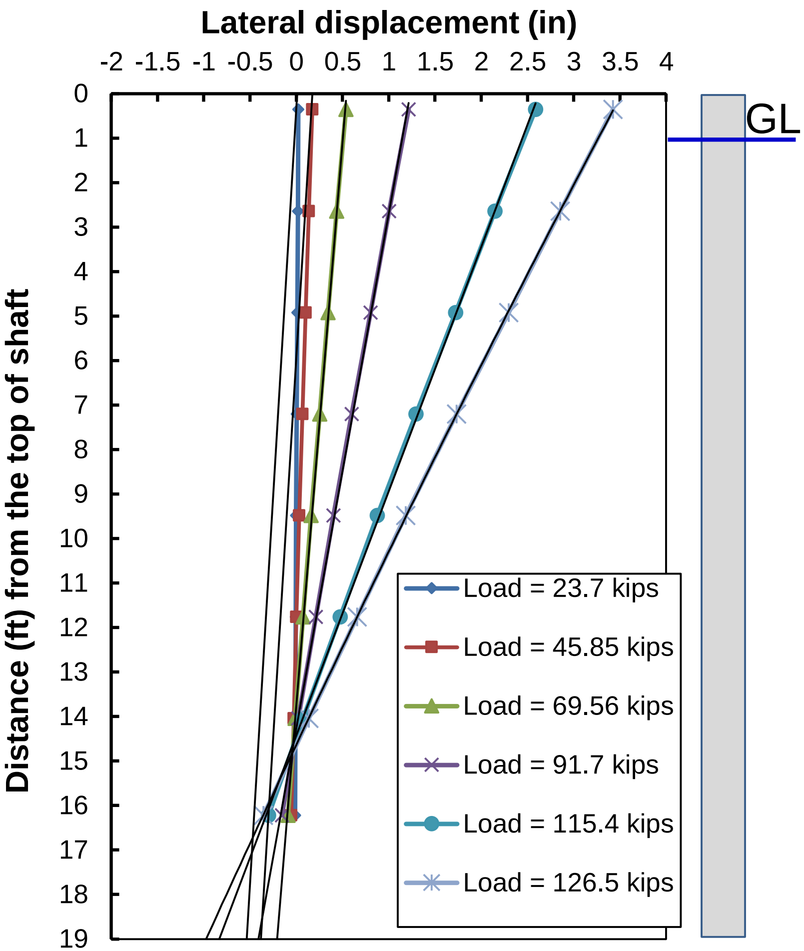
In-place Inclinometers

Lateral Response of Drilled Shaft and Jet-grouted Pile

Lateral load vs. displacement



Drilled shaft's displacement profile using inclinometer data



Cost Comparison: Jet-grouted Pile vs. Drilled Shaft

28 in square x 18 ft deep and 48-in Ø side grout zones

Axial Resistance (kip)	Torsional Resistance (kip-ft)	Cost
1000	750	$9940.00

4-ft Ø x 18-ft-deep drilled shaft

Axial Resistance (kip)	Torsional Resistance (kip-ft)	Unit price	Dirt Haul	Total
400	210	$8,500.00	$200.00	$8,700.00

Based on quote at the same site

BDR cost estimate - equivalent drilled shaft

	Shaft size	Cost	% cost > jet-grouted pile cost
Torsional equivalent	4 ft Ø x 30 ft deep	$12,900	29.8%
	5 ft Ø x 25 ft deep	$12,750	28.3%
Axial equivalent	4 ft Ø x 45 ft deep	$19,350	94.7%
	5 ft Ø x 35 ft deep	$17,850	79.6%

Conclusions

- Considerably high axial and torsional resistance for jet-grouted piles

  Axial resistance: > 3 x similar sized drilled shaft

  Torsional resistance: > 2.5 x similar sized drilled shaft

- All CPT based methods highly under/over-predict axial resistance of drilled shaft

- Torsional resistance prediction for drilled shafts:
  - ✓ FDOT's ω-method over-predicts by 25-45%
  - ✓ O'Neill and Hassan method(1994) predicts reasonably well (±10-14%)
  - ✓ FHWA's rational method over-predicts by 20-70%

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Conclusions (contd..)

- Field Tests support FDOT centrifuge study (McVay et al. 2003; Hu et al 2006), i.e., lateral resistance is significantly reduced by torque
- Lateral stiffness of jet-grouted pile was found to be greater than similar sized drilled shaft
- Construction and installation cost of jet-grouted pile is less than equivalent capacity drilled shaft
  - ✓ 22% less than torsionally equivalent shaft
  - ✓ 44% less than axially equivalent shaft
- Jet-grouted pile - a viable foundation alternative for FDOT pole/mast arm structures

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9. Yu, H. S., and Houlsby, G.T. (1991). "Finite Cavity Expansion in Dilatant Soils – Loading Analysis," *Geotechnique,* 41(2), 173-183.

Thank You