FIELD TESTING OF JET-GROUTED PILES AND DRILLED SHAFTS

BDK-75-977-41

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GRIP 2013
August 8-9

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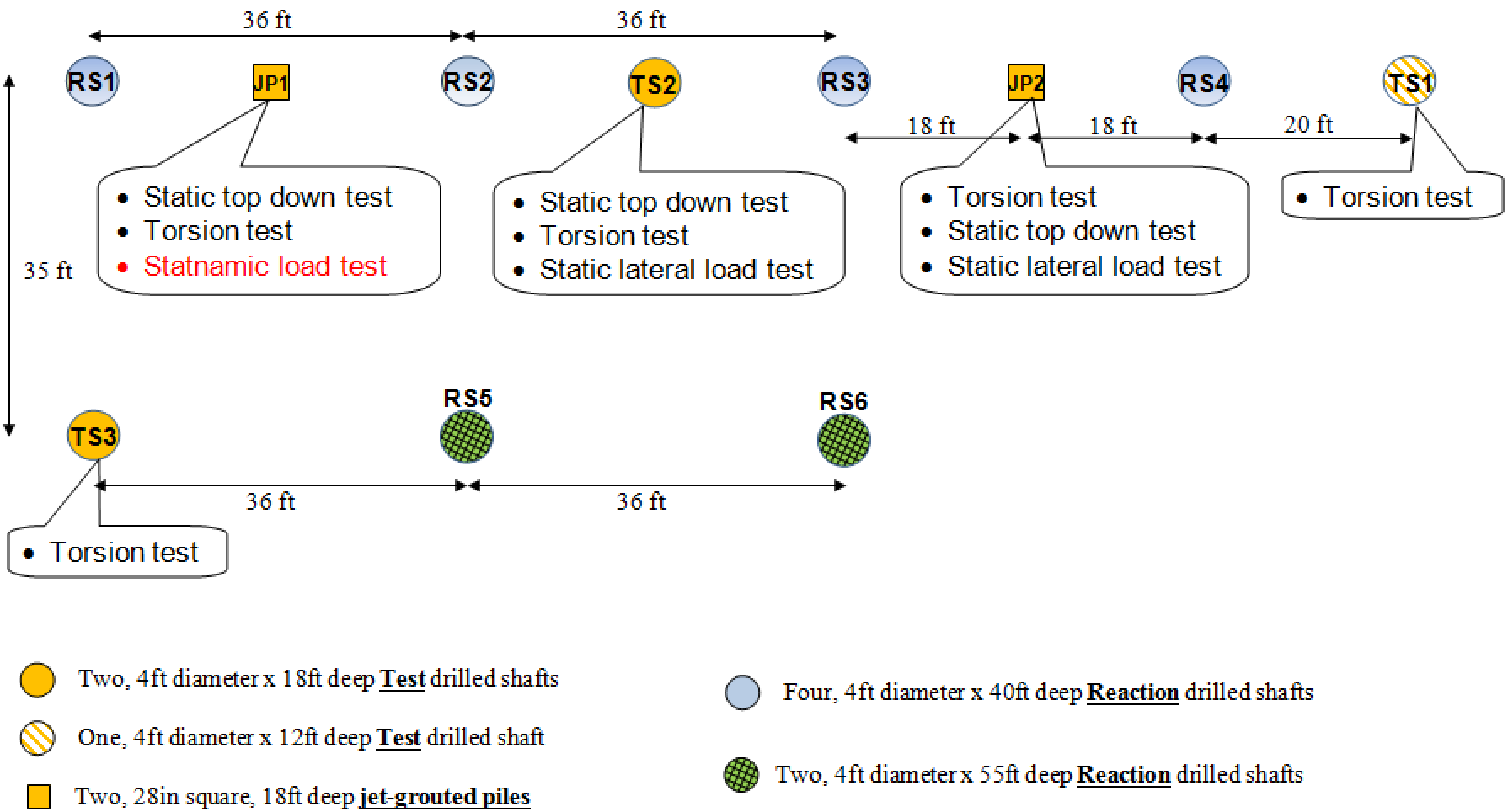
Objectives of the Research

- 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



Review of GRIP'11 &12 Presentations

GRIP 2011:

- Background of the research
- Design of Jet-grouted piles and Drilled shaft
- Instrumentations
- Soil exploration

GRIP 2012:

- Construction of Reaction and Test drilled shafts
- CSL Tests on Drilled shafts
- Design and fabrication of Mast arm assembly
- Combined torsion and lateral load test on 12-ft deep shaft
- Construction of precast piles, preparation and jetting
- Design and construction of concrete cap

Presentation Overview

- Side and tip grouting of 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

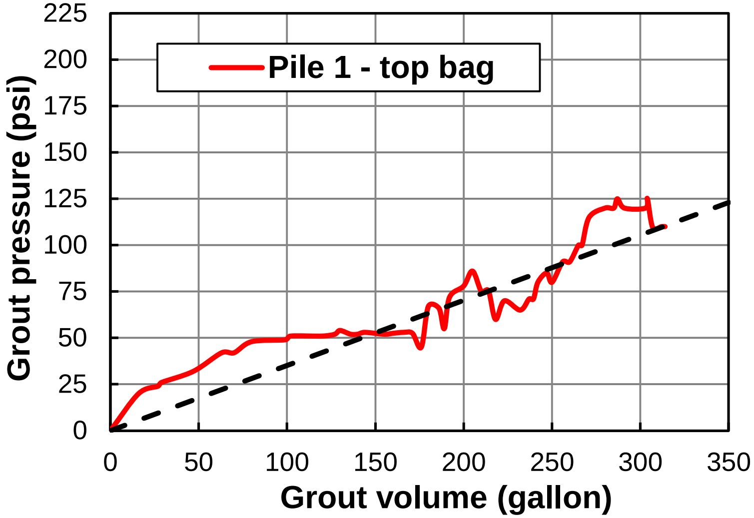
Side Grouting of Piles

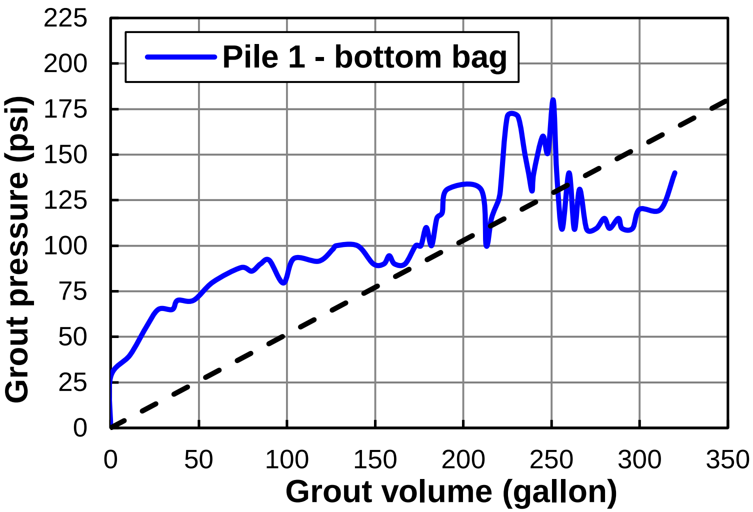
Performed with the help of Applied Foundation Testing Inc. (AFT)

Grout mixing and pumping

Pile displacement and grout pressure monitoring

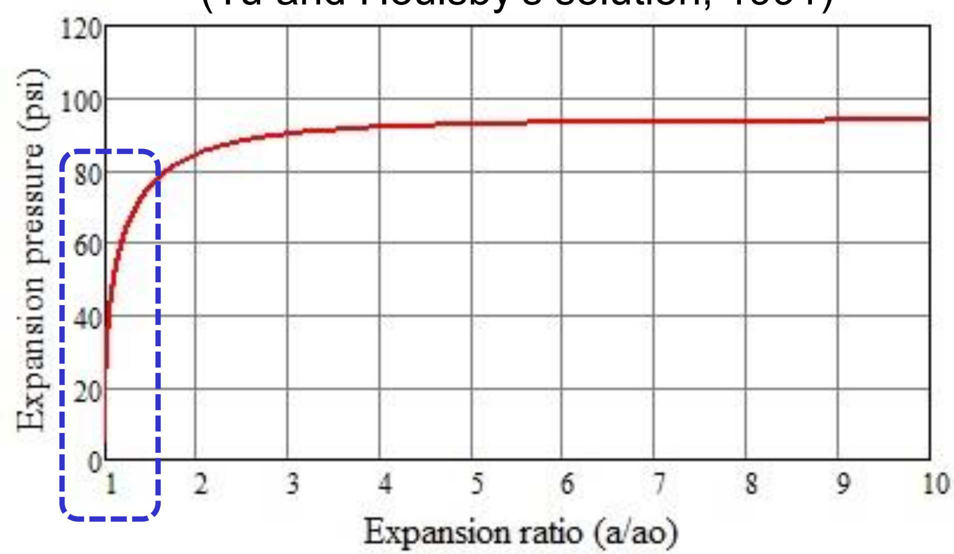
Side Grouting of Piles



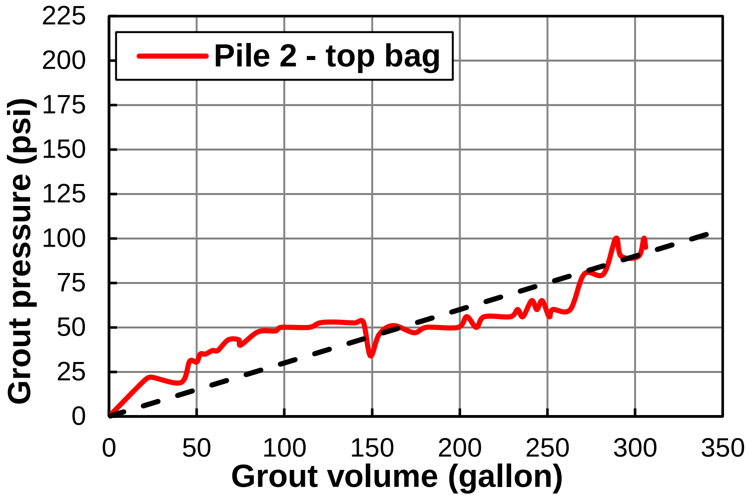


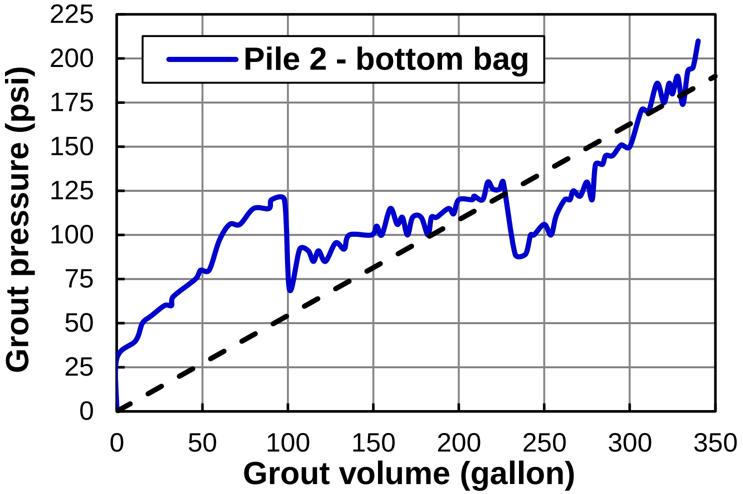
Expansion ratio = Initial radius /final radius ≈ 1.64

Cylindrical cavity expansion curve (top bag)
(Yu and Houlsby's solution; 1991)



Side Grouting of Piles

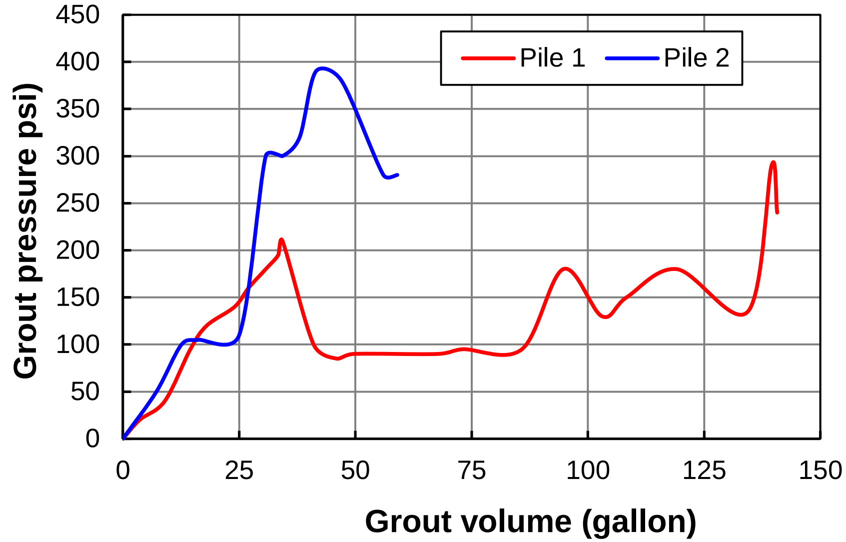


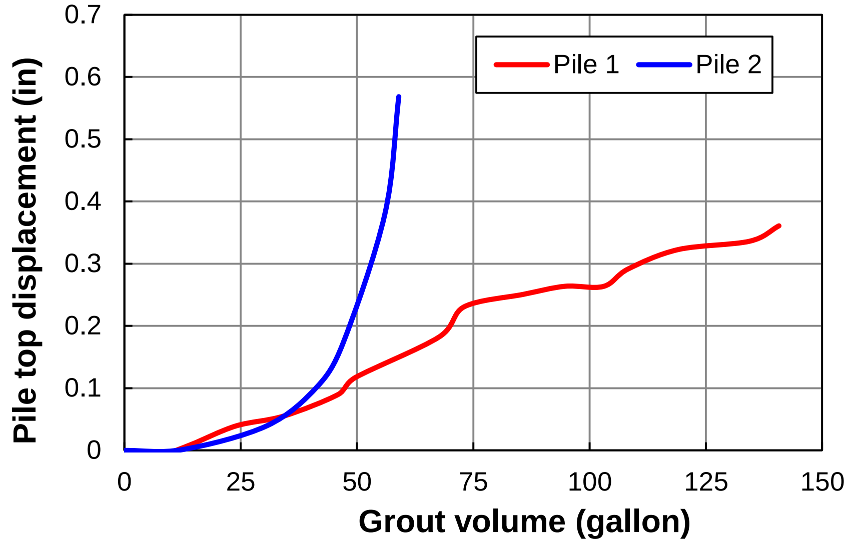


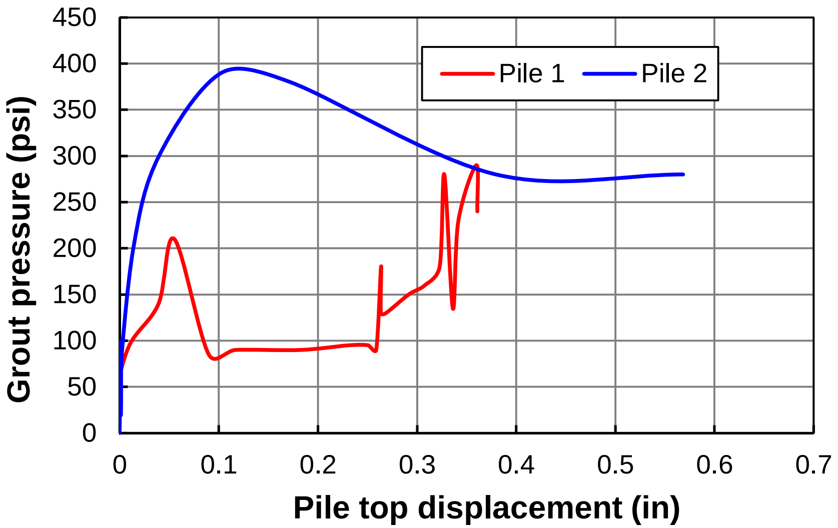
Side grout pressure and cylindrical cavity expansion pressures

	Top membrane		Bottom membrane	
	Pile 1	Pile 2	Pile 1	Pile 2
Measured Maximum Pressures (psi)	100-120	90-100	140-160	180-200
Yu and Houlsby's solution (psi)	94	92	191	181
Salgado and Randolph's chart (psi)	101	101	203	196
PMT (psi)	113	85	198	153

Tip Grouting of Piles







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)	318	318
Salgado and Randolph (2001)	420	420

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:

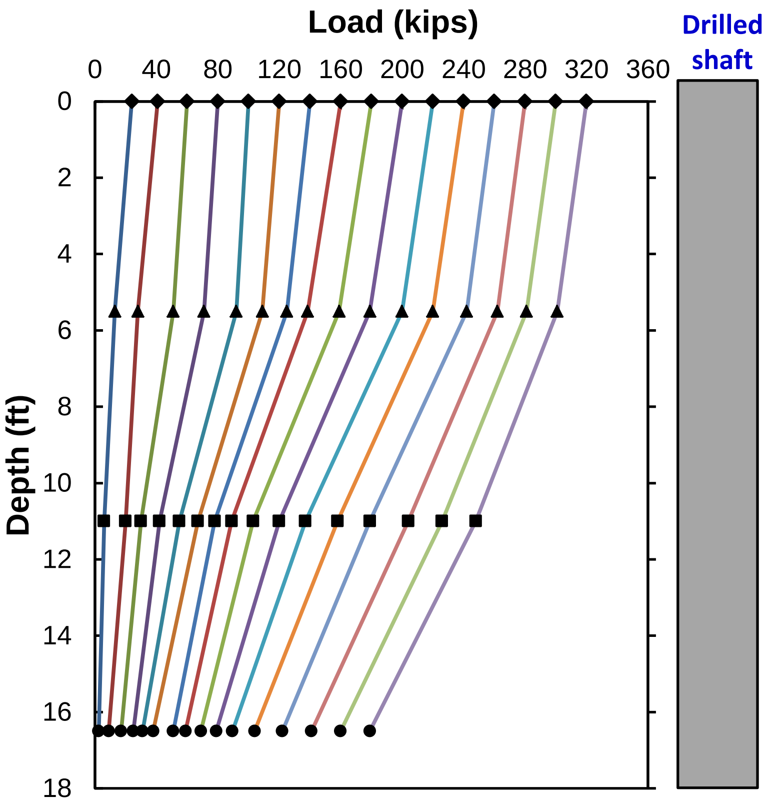
- Digital dial gages
- Mirrored scale with wire line reference

Load increment = 20 kips
Time interval - 10 minutes

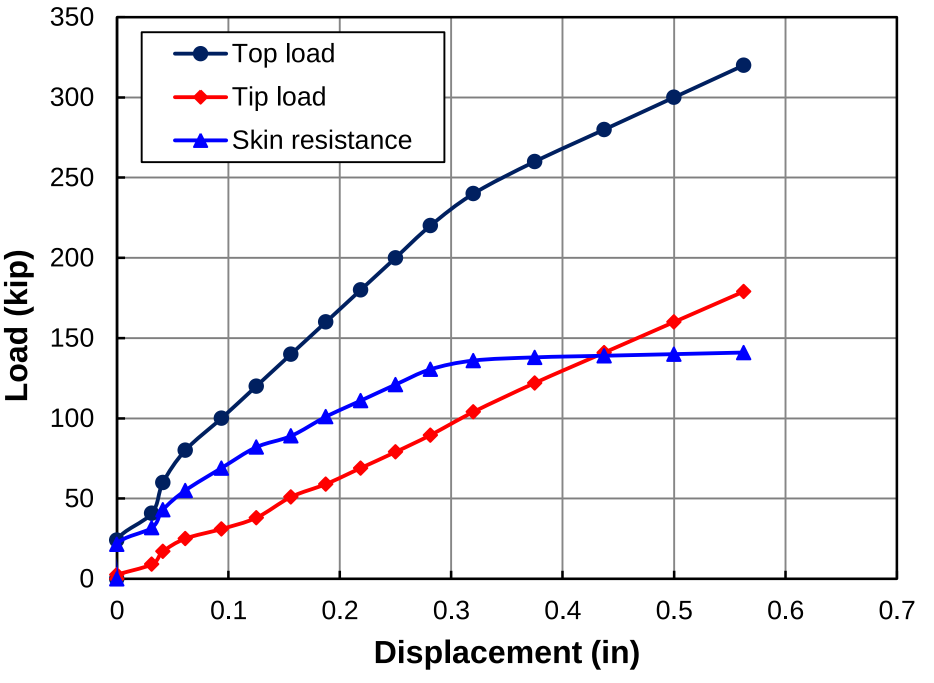
Axial Response – 4ft Ø x 18ft deep drilled shaft (TS2)

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

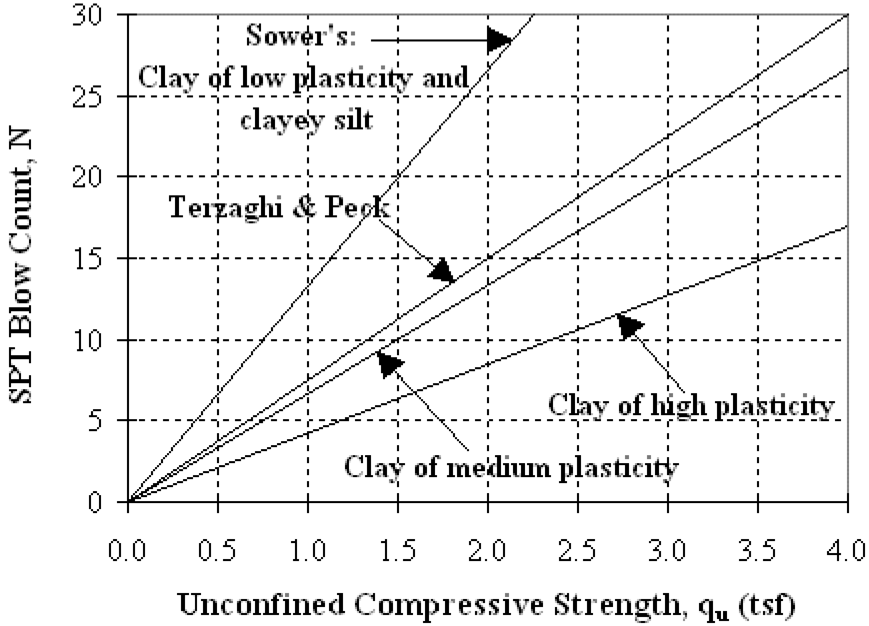
Unit weight: $\frac{\gamma}{\gamma_w} = 0.27[\log R_f] + 0.36\left[\log\left(\frac{q_c}{P_a}\right)\right] + 1.236$ Robertson and Cabal (2010)

Angle of internal friction: $\phi' = [15.4(N_1)_{60}]^{0.5} + 20^0$ Hatanaka and Uchida (1996)

Where, $(N_1)_{60} = \frac{N_{60}}{(\sigma'_{vo}/P_a)^{0.5}}$

Undrained shear strength:

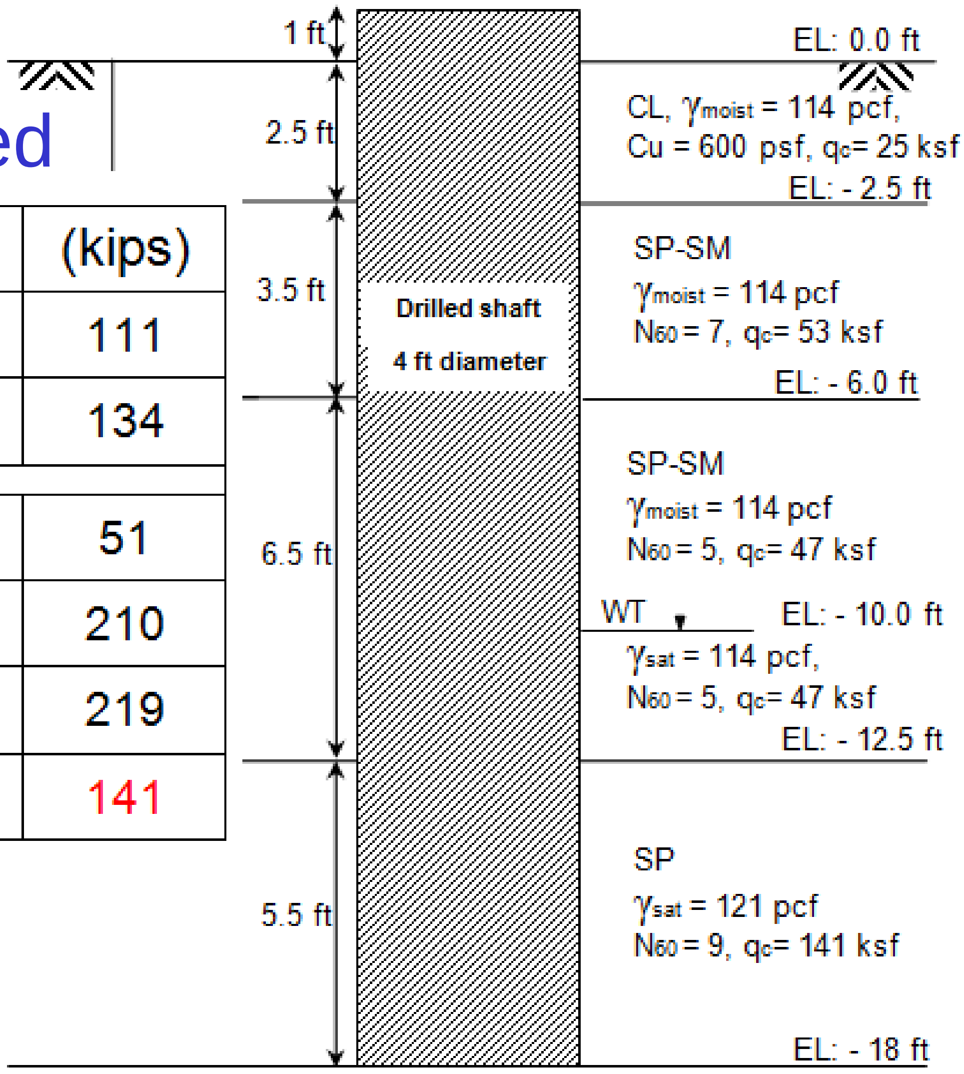
Used in FB-Multipier



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

Predicted vs. Measured

	Method	(kips)
SPT	O'Neill and Hassan (1994) method	111
	Rational method (FHWA 2010)	134
CPT	Aoki and Velloso's method	51
	LCPC method	210
	UIUC Method (Alsamman 1995)	219
	Measured value	141



Axial Response – Jet-grouted piles

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

Pullout failure of reaction drilled shafts in both tests

JP1 test

JP2 test

Maximum top displacement of test piles:

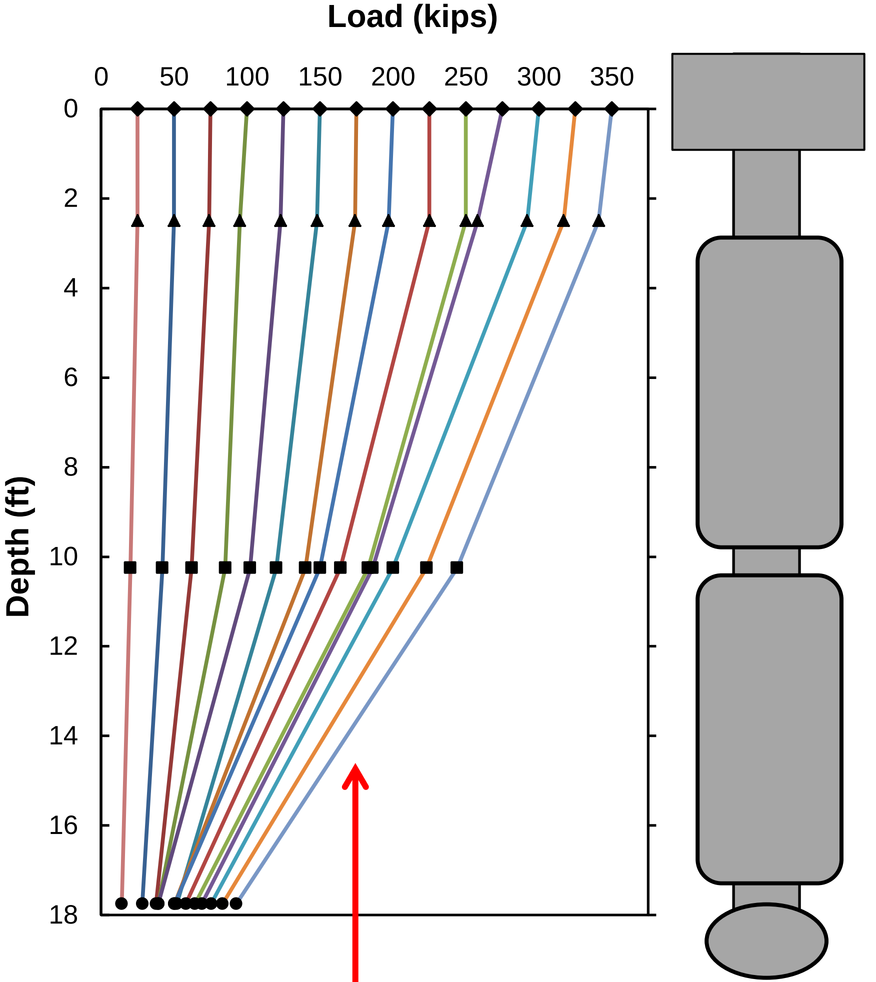
JP1: 0.16 in

JP2: 0.198 in

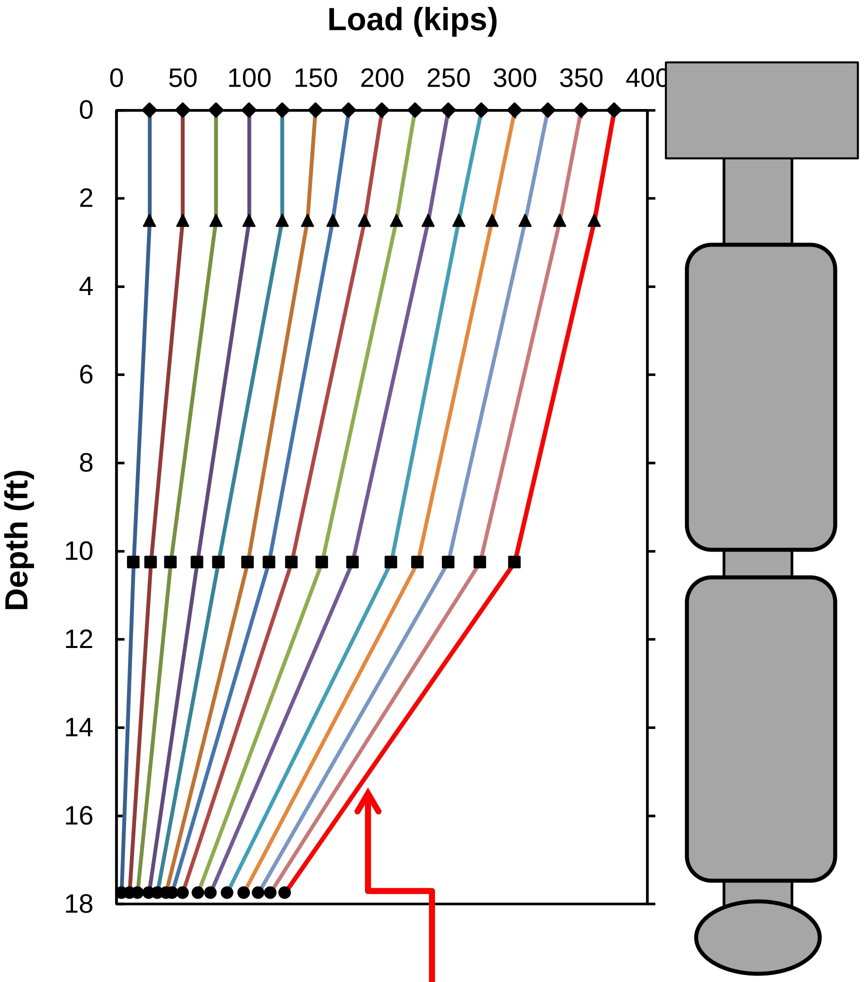
Axial Response – Jet-grouted piles

Load distribution

JP1



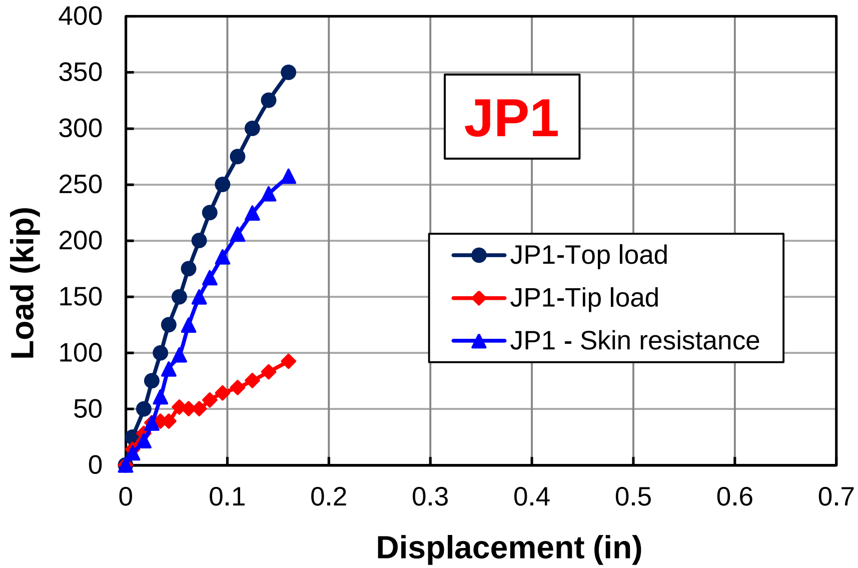
JP2

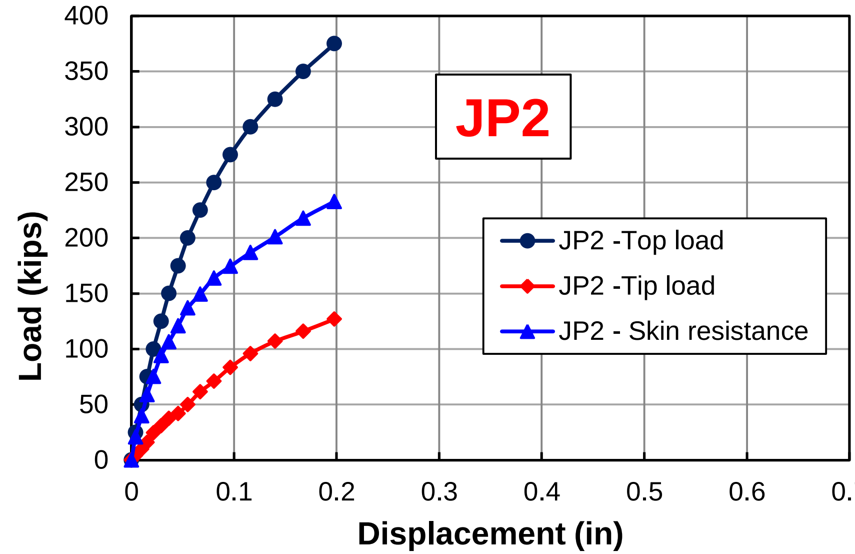


Skin resistance not fully mobilized…..

Axial Response – Jet-grouted piles

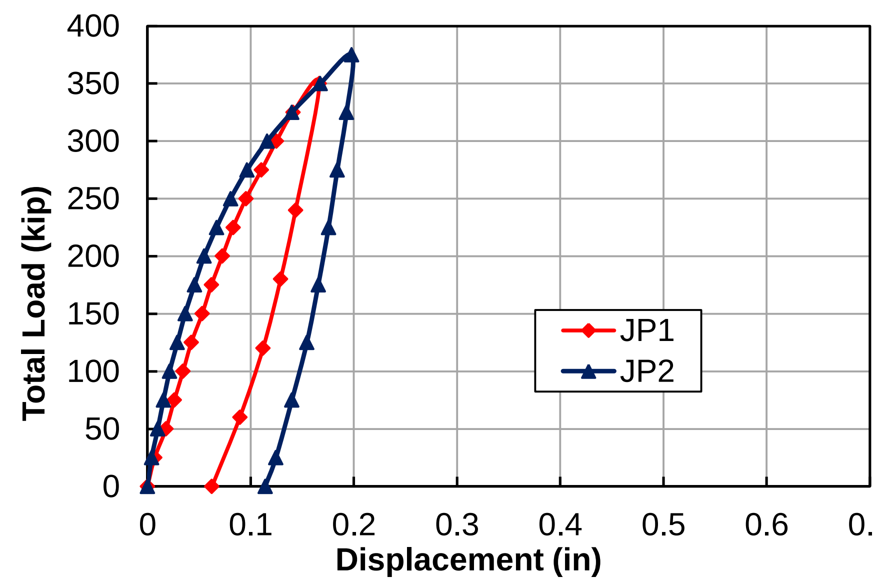
Load Displacement responses





Comparison: JP1 vs. JP2

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



Axial Response – Jet-grouted piles

Prediction of skin resistance

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

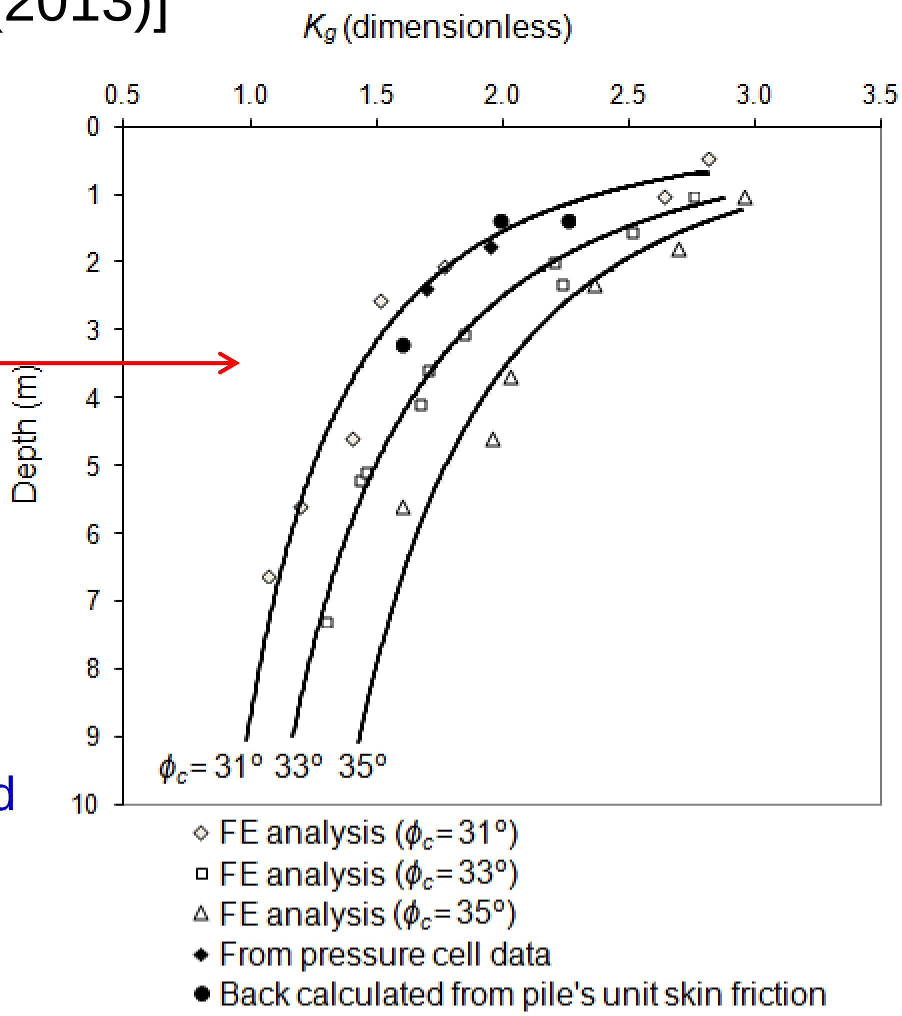
$$f_s = \sigma'_{vg}\left[\frac{\sin\phi_c}{1-\sin\phi_c}\right]\sin(90-\phi_c)$$

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

γ' - Submerged unit wt of soil

h - depth

A purely cylindrical grout zone is assumed for surface area calculation



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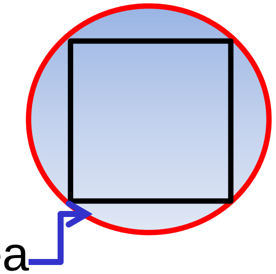
Axial Response – Jet-grouted piles

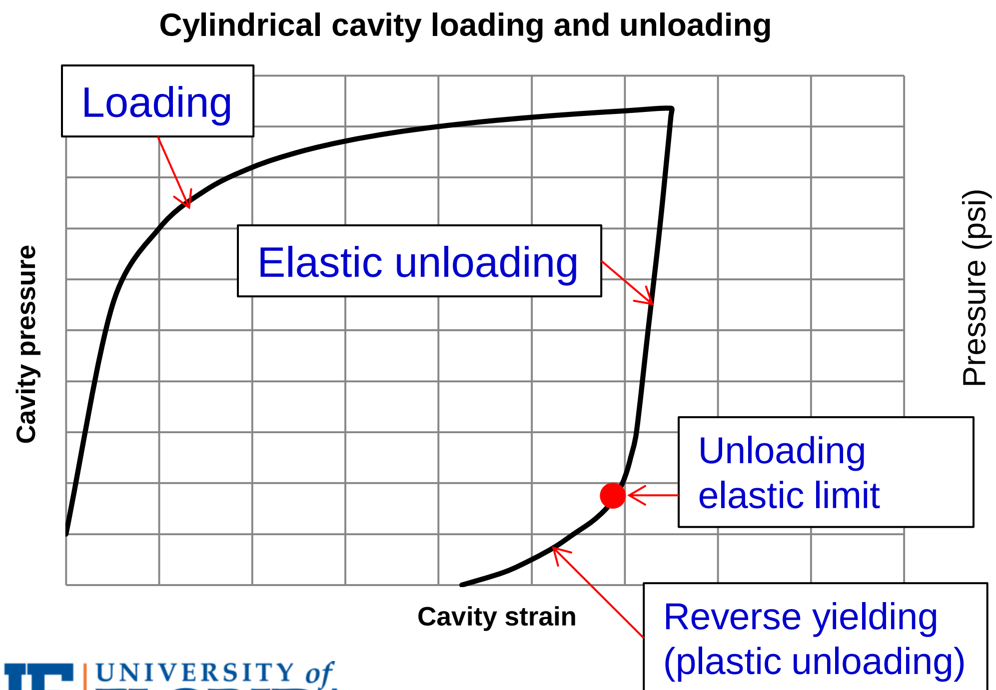
Prediction of skin resistance

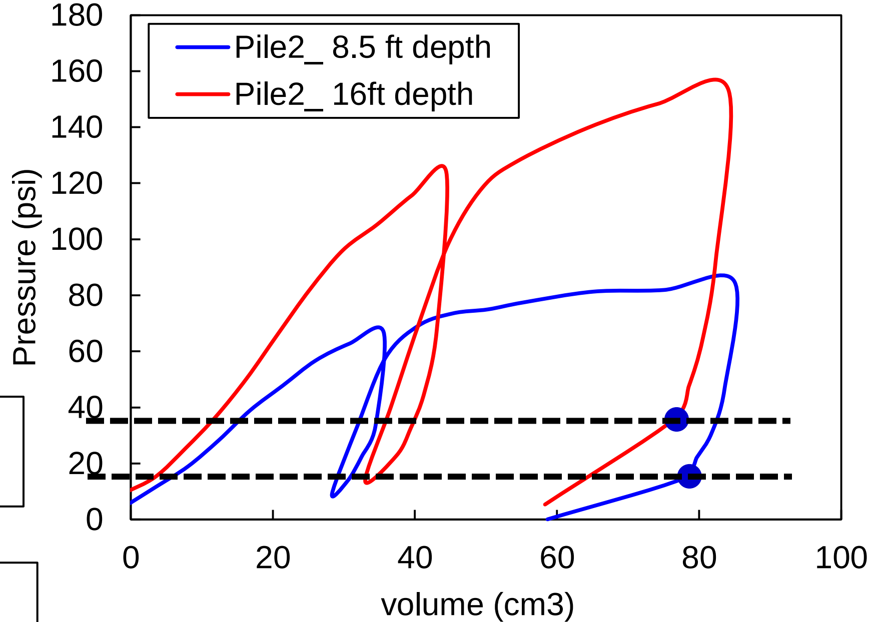
2) Using tip grout pressure

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



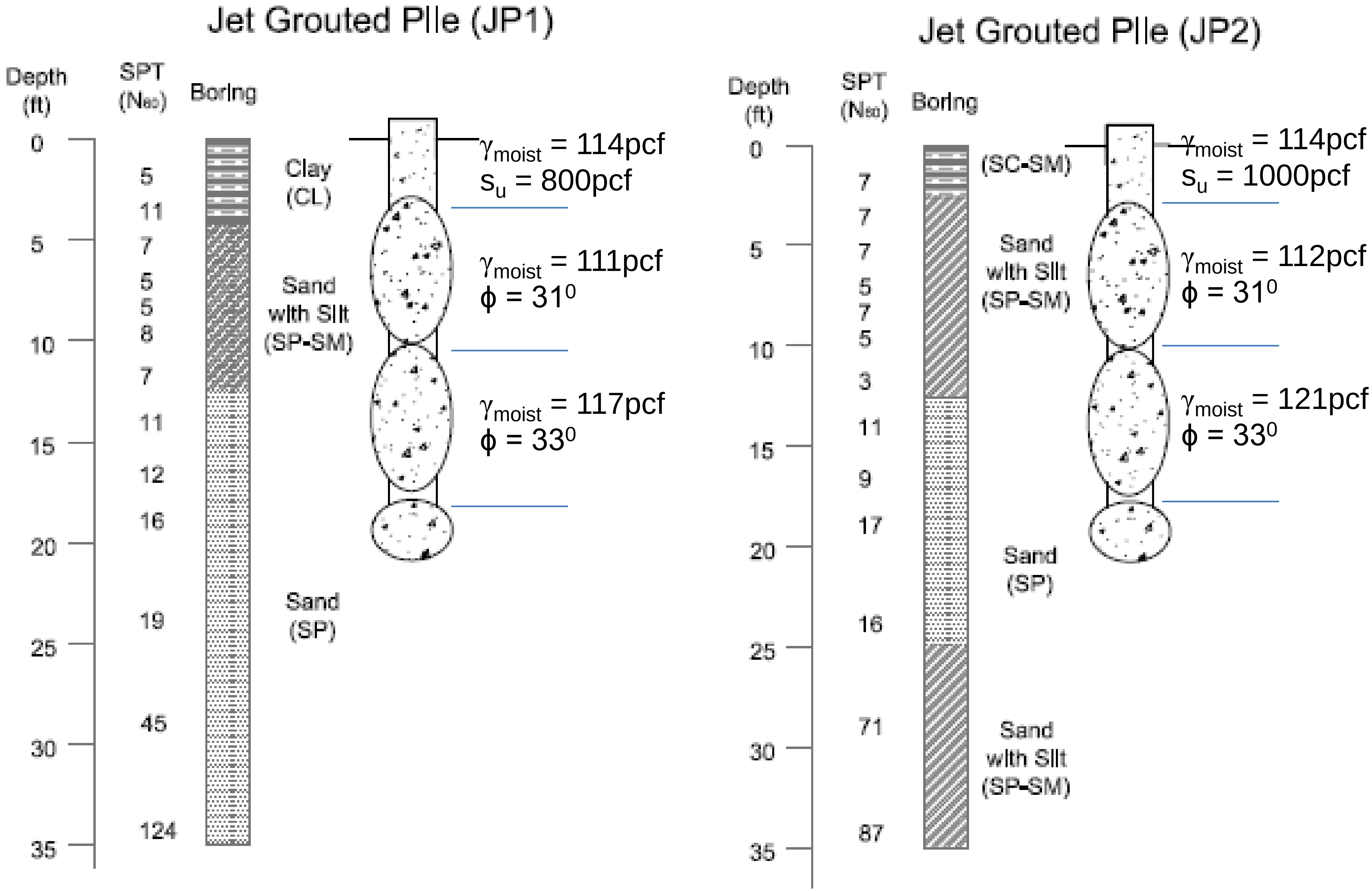
3) Using Pressuremeter data





Axial Response – Jet-grouted piles

Soil Profile



Axial Response – Jet-grouted piles

Predicted vs. Measured

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	Grouted vertical eff. stress $\sigma'_{vg}=K_g\,\sigma'_{vo}$ (psf)	ϕ	f_s (psf) (Eq. 1)	A_s Surface area (ft^2)	Qs Side resistance (kips)	**Total (kips)**
JP1	Top	7	6.5	733.5	1.85	1357	31°	1235.3	83.84	103.6	**277.2**
	Bottom	7	14	1244	1.65	2053	33°	2059.2	84.29	173.6	
JP2	Top	7	6.5	733	1.85	1356	31°	1234.4	83.39	102.9	**281.9**
	Bottom	7	14	1261	1.65	2081	33°	2087.2	85.77	179.0	

Using PMT

Grout zone	Zone length H(ft)	ϕ	Horizontal stress after grouting, σ_h (psi)	$f_s = \sigma_h \tan(\phi)$ (psf)	A_s Surface area (ft^2)	Qs Side resistance (kips)	**Total (kips)**
Top	7	31°	16	1440	83.39	115.4	**415.2**
Bottom	7	33°	36	3496	85.77	299.8	

Using TGP

Pile	Tip grout pressure (psi)	Effective tip area (in^2)	**Side resistance (kips)**
JP1	290	1231	**357**
JP2	280-300	1231	**345-369**

Measured

	JP1	JP2
Top	97	60
Bottom	151	173
Total	**248**	**233**

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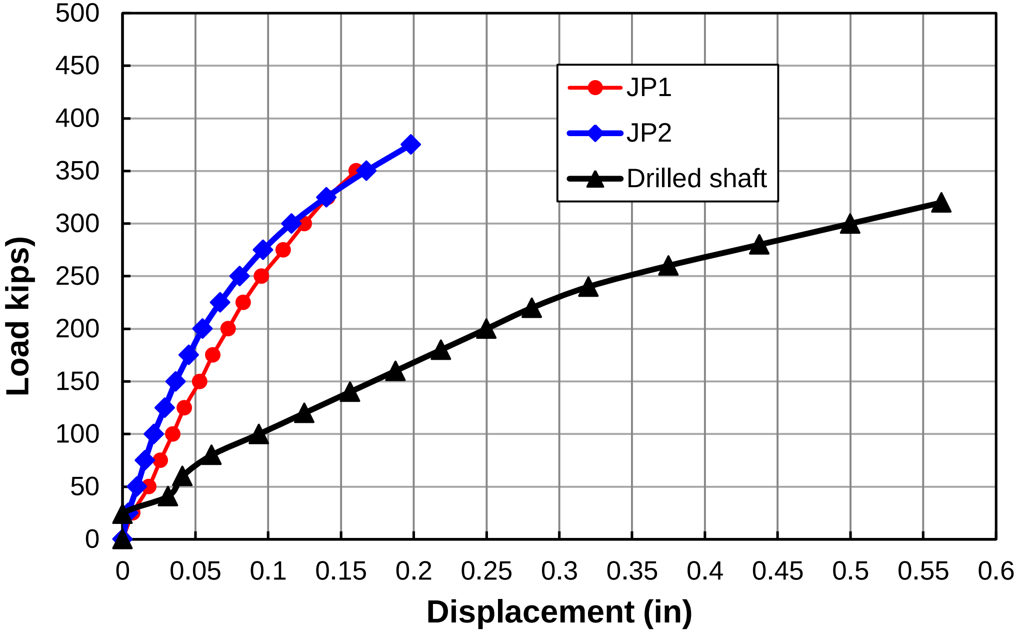
Axial Response Comparison

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

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*Not fully mobilized – 1000 kip Statnamic being Scheduled

Combined Torsion and Lateral Response

Drilled shafts

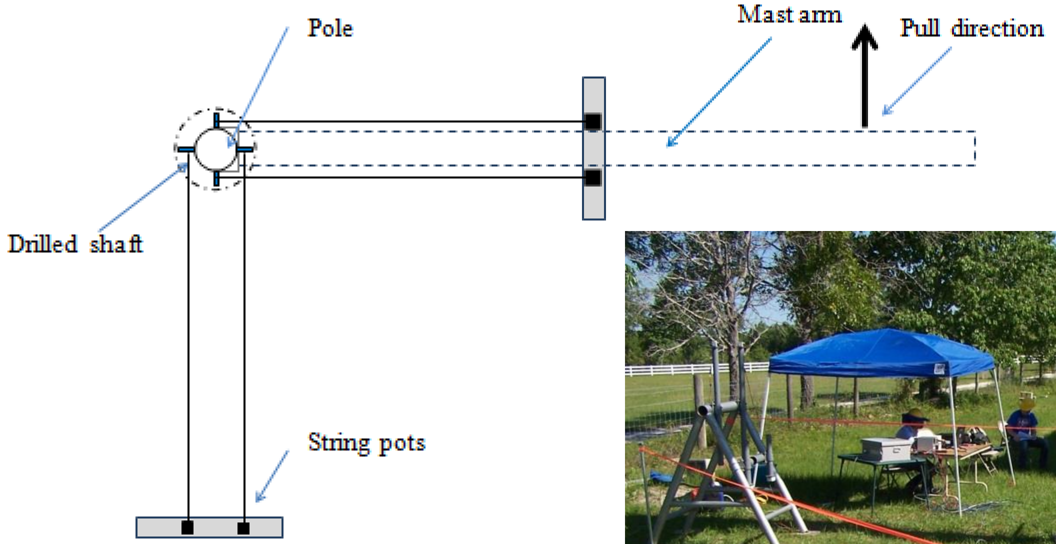
20kips tension load cell

Lateral load applied at an eccentric distance of 35ft

Combined Torsion and Lateral Response

Rotation and translation monitoring

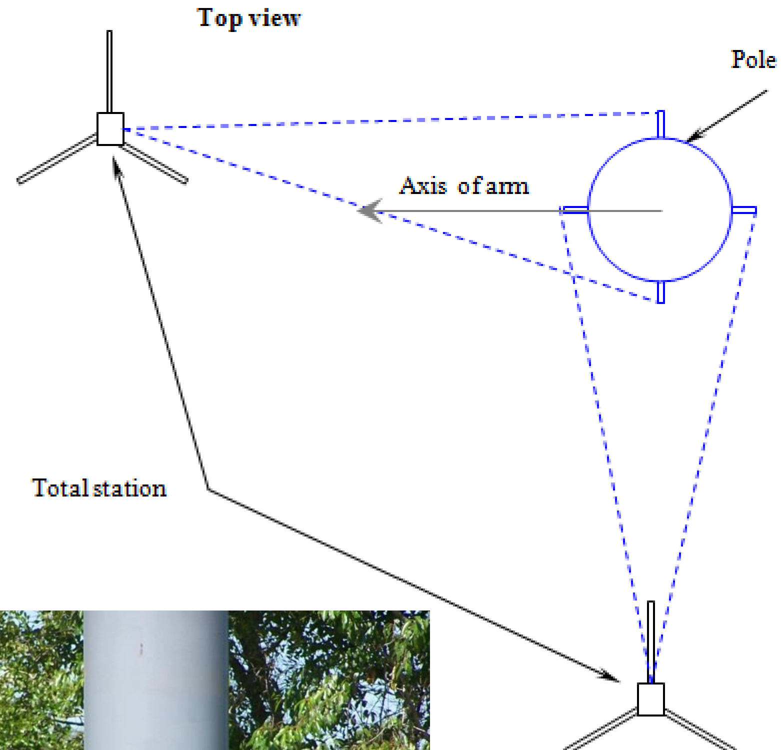
1) String pots



Combined Torsion and Lateral Response

Rotation and translation monitoring

2) Total Stations

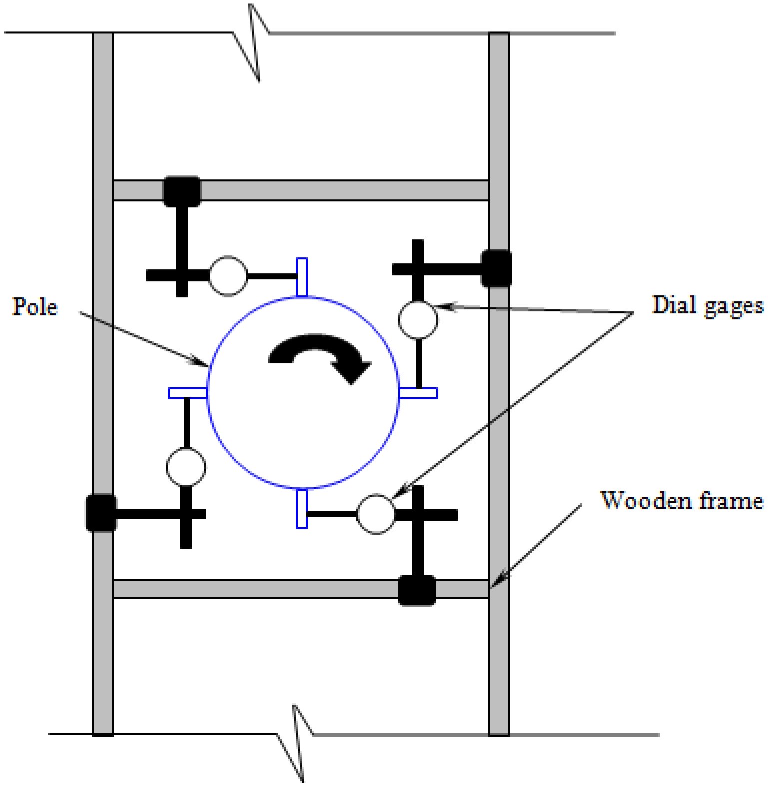


Reflective Targets

Combined Torsion and Lateral Response

Rotation and translation monitoring

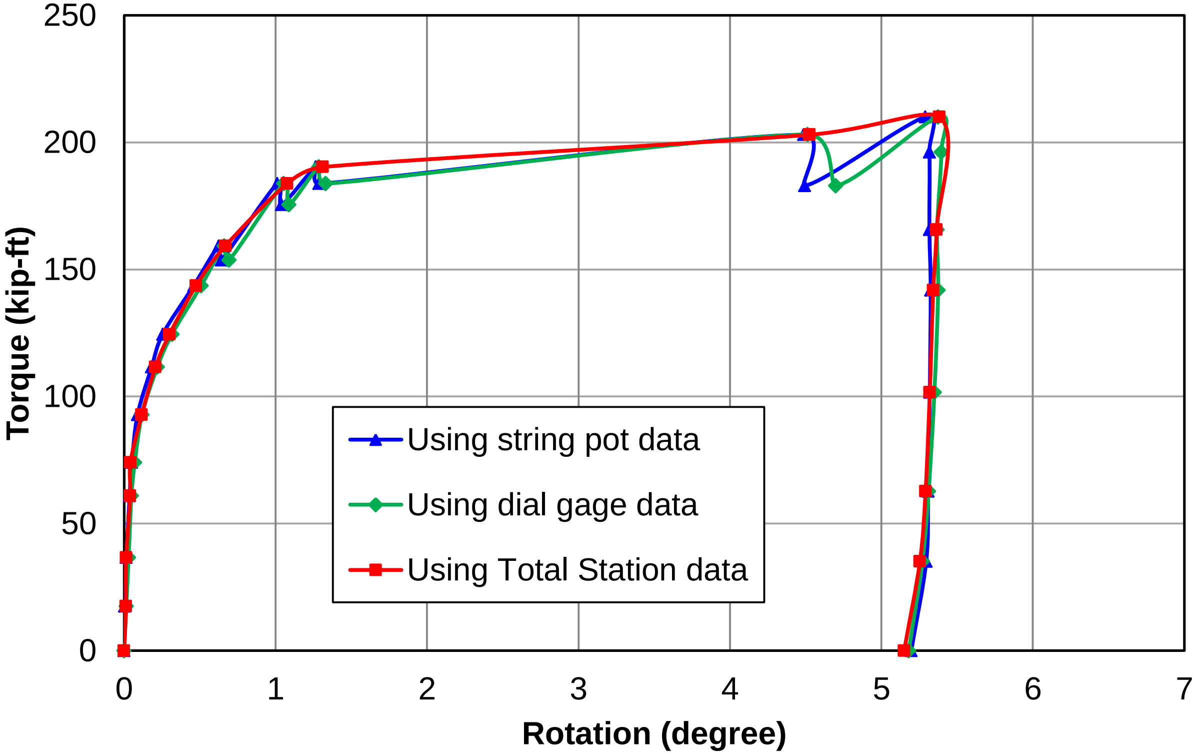
3) Digital dial gages



Combined Torsion and Lateral Response

Drilled shafts

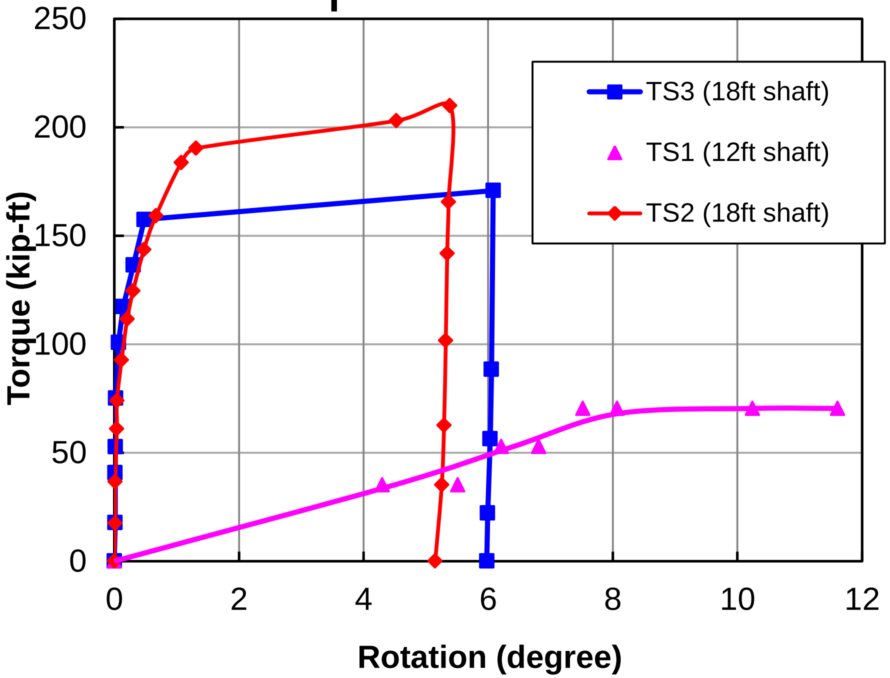
Comparison of rotation response from different instrumentations (TS2)



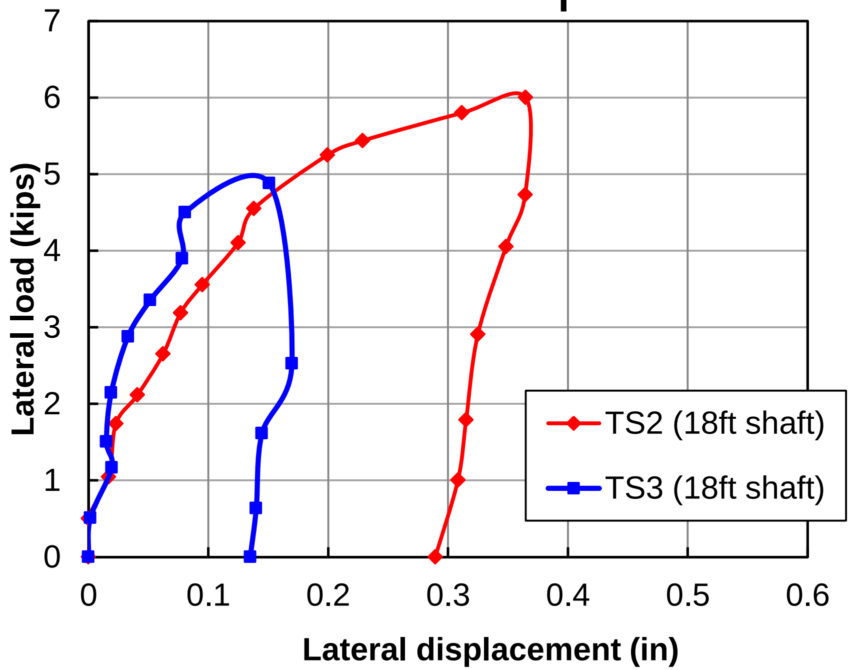
Combined Torsion and Lateral Response

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

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

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

$$\omega_{FDOT} = 1.5$$

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

2) FDOT's REVISED *ω* method (2013)

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

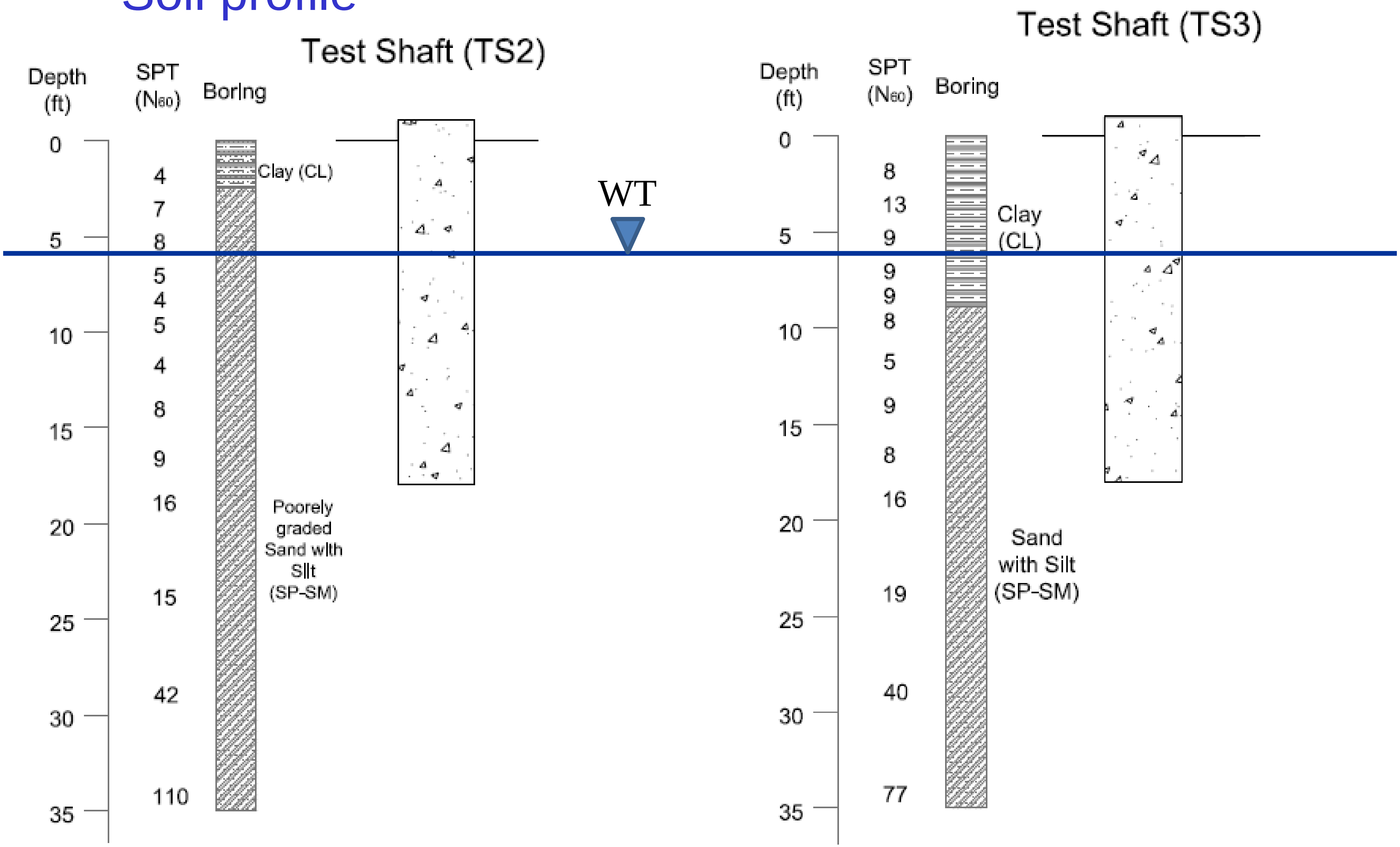
$$\omega_{FDOT} = 1.5\left(\frac{N_{60}}{15}\right) \qquad \text{for } 5 < N_{60} < 15$$

3) O'Neill and Hassan (1994) method

4) Rational method (FHWA 2010)

Combined Torsion and Lateral Response

Soil profile



Combined Torsion and Lateral Response

Drilled shafts: Torsional resistance prediction

Method	TS2			TS3		
	Skin	Tip	Total	Skin	Tip	Total
Measured	--	--	**210 kip-ft**	--	--	**171 kip-ft**
FDOT's ω method	632 kip-ft	28 kip-ft	**660 kip-ft**	438 kip-ft	28 kip-ft	**466 kip-ft**
FDOT's Revised ω method	312 kip-ft	28 kip-ft	**340 kip-ft**	235 kip-ft	28 kip-ft	**263 kip-ft**
O'Neill and Hassan (1994)*	191 kip-ft	--	**191 kip-ft**	178 kip-ft	--	**178 kip-ft**
Rational method) FHWA 2010*	250 kip-ft	--	**250 kip-ft**	213 kip-ft	--	**213 kip-ft**
Based on axial load test*	282 kip-ft	--	**282 kip-ft**	--	--	**--**

*No tip contribution (Hu et al. 2006)

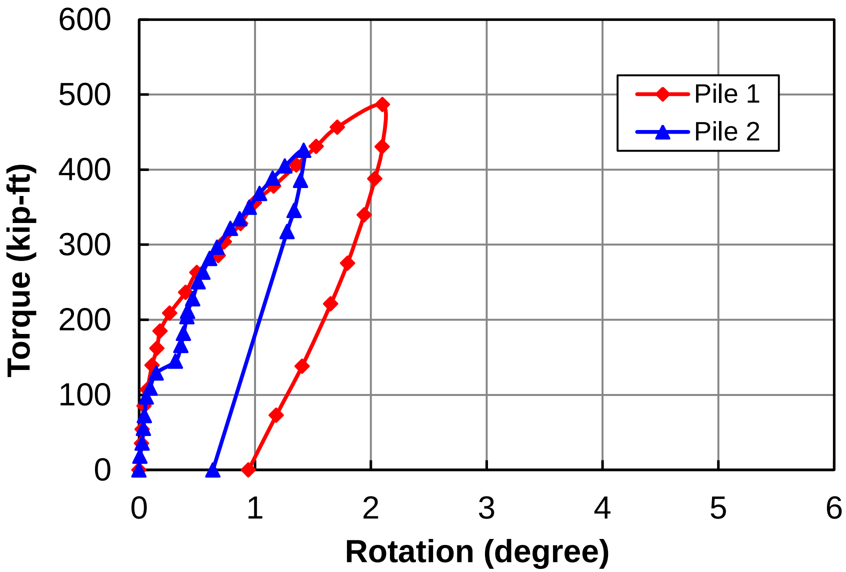
The prediction was similar for TS1 (12ft shaft) also – **GRIP 2012**

Combined Torsion and Lateral Response

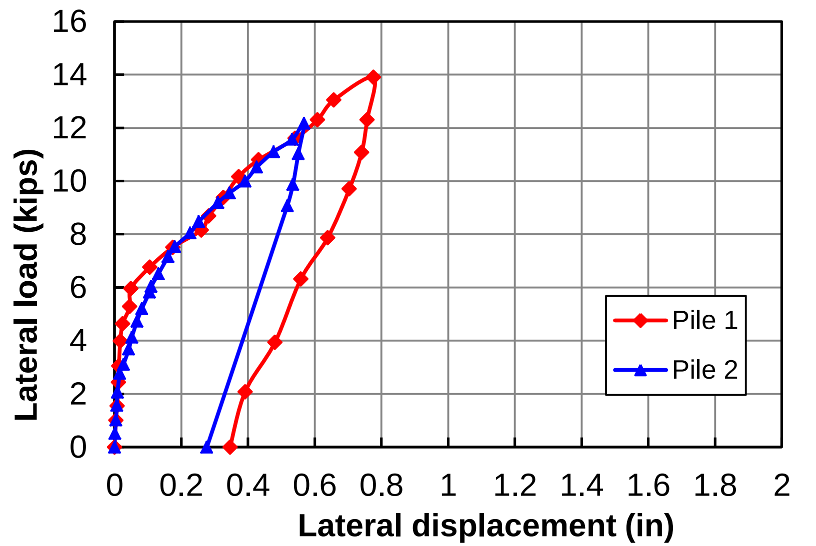
Jet-grouted pile

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

Method	JP1	JP2
Measured (kip-ft)*	487*	429*
Kg method (kip-ft)	534	540
Tip grout data (kip-ft)	684	684
Pressuremeter data (kips)	795	795

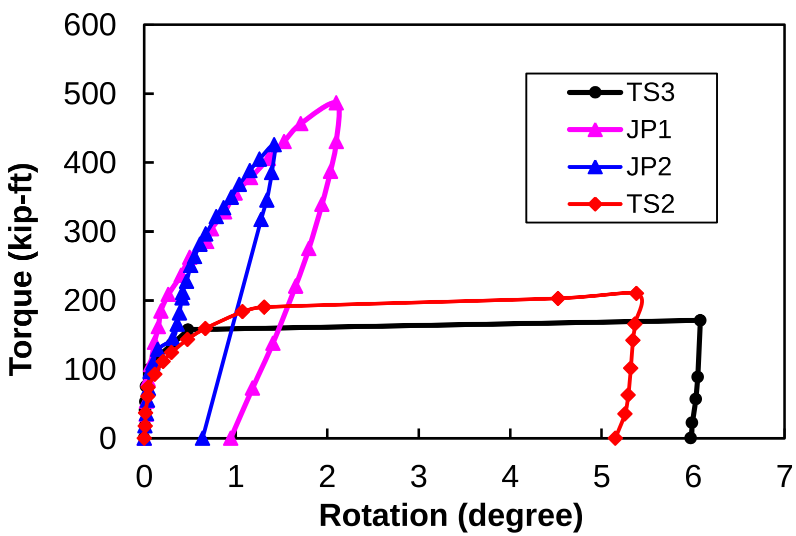
* Not fully mobilized

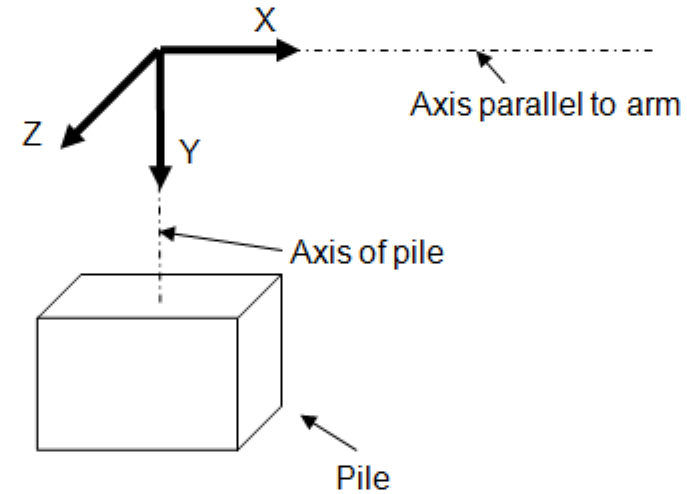
Combined Torsion and Lateral Response

Jet-grouted pile

Design wind speed =130mph

Forces and moments	JP1	JP2	TS1	TS2	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

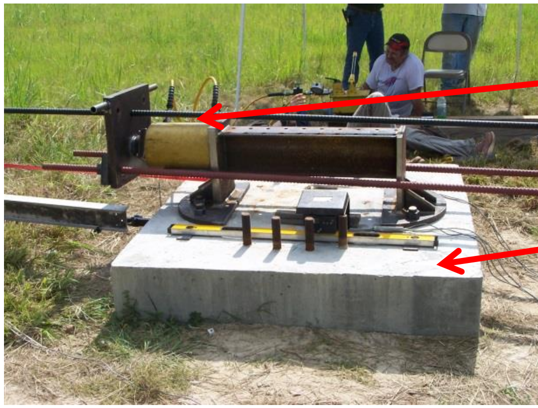




Coordinate system

Lateral Response

Lateral load test

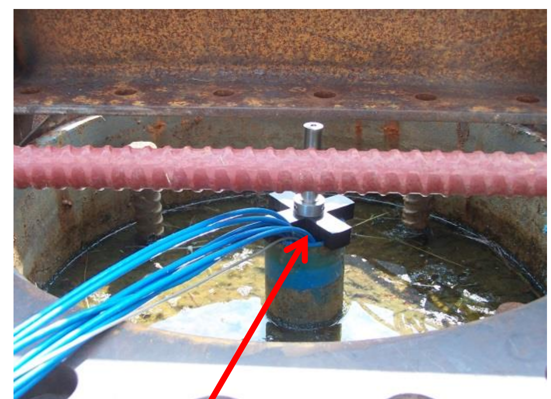


Hydraulic jack

Test pile

Load cell

Test shaft

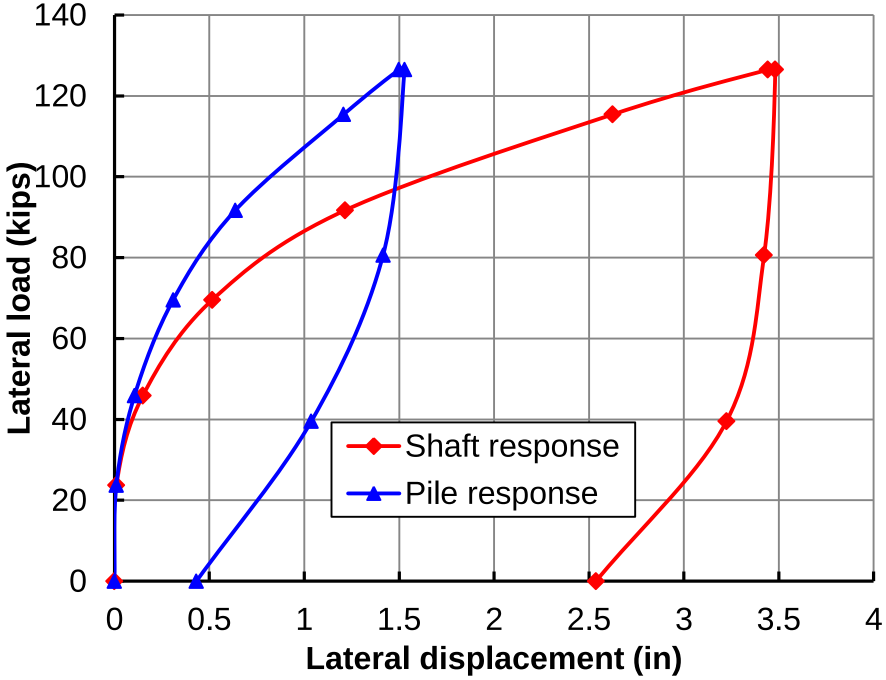


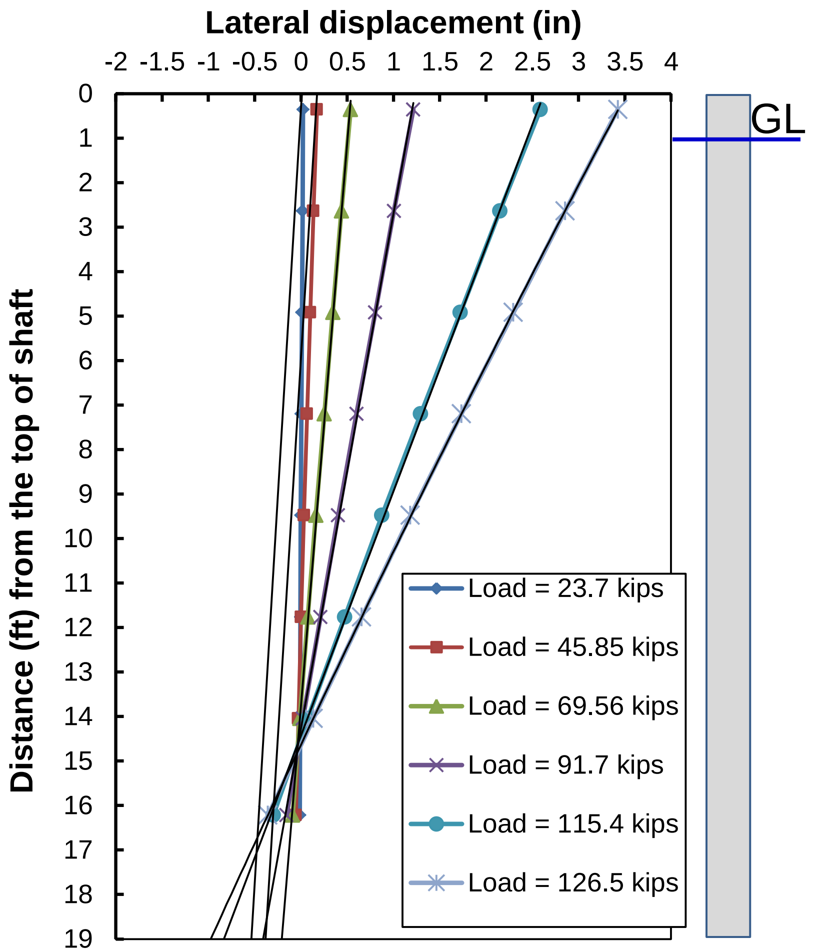
In-place Inclinometers

Lateral Response

Drilled shaft's displacement profile using inclinometer data

Lateral load vs. displacement





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Conclusions

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

  Axial resistance: > 2.5 x similar sized drilled shaft

  Torsional resistance: > 2.5 x similar sized drilled shaft

- Jet-grouted piles are well suited for Mast arm structures

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

- Torsional resistance prediction for drilled shafts:
  - FDOT's revised ω-method over-predicts by 35-50%
  - O'Neill and Hassan method (1994) predicts reasonably well (±10%)
  - FHWA's rational method over-predicts by 20-25%

References

1. Brown, D.A, Turner, J.P, and Castelli, R.J (2010) Drilled shafts: Construction Procedures and LRFD design methods, FHWA NHI-10-016.
2. FDOT MathCAD Program: Mastarm v4.3.
3. FDOT Structures Manual, Vol. 9, 2013.
4. Hu, Z., McVay, M., Bloomquist, D.,; Herrera, R., Peter Lai, P., (2005) “Influence of Torque on Lateral Capacity of Drilled Shafts in Sands”, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 132, No. 4, p.456-464.
5. O’Neil, M. W., and Reese, L. C. (1999). “Drilled shafts: Construction procedures and design methods,” FHWA, Publication No. FHWA-IF-95-025.
6. Salgado, R., and Randolph, M. F. (2001). “Analysis of Cavity Expansion in Sand,” *International Journal of Geomechanics,* ASCE, 1(2), 175-192.
7. Thiyyakkandi, S., McVay, M., Bloomquist , D., and Lai P. (2013), “Measured and Predicted Response of a New Jetted and Grouted Precast Pile with Membranes in Cohesionless Soils,” *Journal of Geotechnical and Geoenvironmental Engineering*, 139 (8), 1334-1345.
8. Yu, H. S., and Houlsby, G.T. (1991). “Finite Cavity Expansion in Dilatant Soils – Loading Analysis,” *Geotechnique,* 41(2), 173-183.

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Thank You