GRL

Engineers, Inc.

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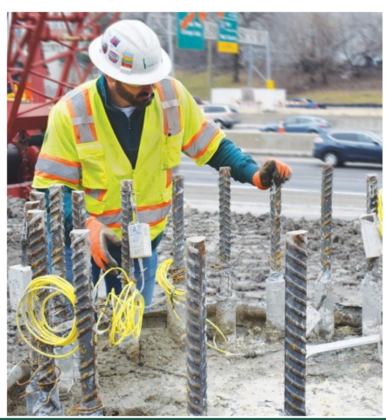

STATEMENT OF QUALIFICATIONS

www.grlengineers.com | info@grlengineers.com | +1 (216) 831-6131

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1.0 INTRODUCTION AND HISTORY

GRL Engineers, Inc, is a professional engineering firm established to provide specialized testing, analysis, and consulting services to the deep foundation industry. Under the direction of professor G.G. Goble, and with the participation of F. Rausche and G. Likins, a research project was begun in 1964 at Case Institute of Technology in Cleveland, Ohio. This research pioneered the basic concept of dynamic pile testing which is now known as the Case Method. The success of the research project provided the basis for a valuable new tool for pile design and construction control known as the Pile Driving Analyzer (PDA). The CAPWAP® software program for deriving the soil resistance from pile top measurements was also developed as part of this research effort.

In the early 1970's, the research team began a consulting practice to provide services based on the Case Method and utilizing the PDA for the deep foundation industry. Since its incorporation in 1975, GRL has continued to expand its capabilities in the dynamic testing field. In 1976, GRL developed the Wave Equation Analysis Program (WEAP) for pile driving evaluation for the Federal Highway Administration (FHWA). This program was updated in 1980 and again in 1987 before becoming the proprietary program known today as GRLWEAP. In 1986, *The Performance of Pile Driving Systems*, was developed for and published by the FHWA. GRL has also authored the last three editions of the FHWA manual *Design and Construction of Driven Pile Foundations* in 1996, 2006, and 2016.

GRL operates the largest dynamic pile testing firm in the world. The dynamic test methods, originally developed by the founding principals of the firm, are applied worldwide on a routine basis, both on land and offshore. The methods provide improved foundation solutions, better quality control, and often significant savings in foundation cost or construction time.

GRL's service line has also expanded to cover the vast majority of all deep foundation testing needs for driven piles, drilled shafts, augured cast-in-place piles, drilled displacement piles, barrettes, diaphragm wall panels, micropiles, and helical piles. GRL is an industry leading provider of integrity test methods for deep foundations including thermal integrity profiling, crosshole sonic logging, gamma gamma logging, and low strain integrity testing. We offer a variety of load testing services including our APPLE drop weight dynamic load testing system, GRL-Cells for bi-directional static load testing, and multiple load frames and hydraulic jacks for static load testing.

With a unique history and unequaled wealth of experience, GRL is internationally recognized for major contributions to its deep foundation area of expertise.

2.0 OFFICE LOCATIONS

GRL maintains its corporate headquarters and a testing office in Cleveland, Ohio, USA. GRL is licensed to provide professional engineering services in every US state. To provide a faster response to its clients at reduced travel costs, personnel and testing equipment is positioned in 13 additional office locations across the US.

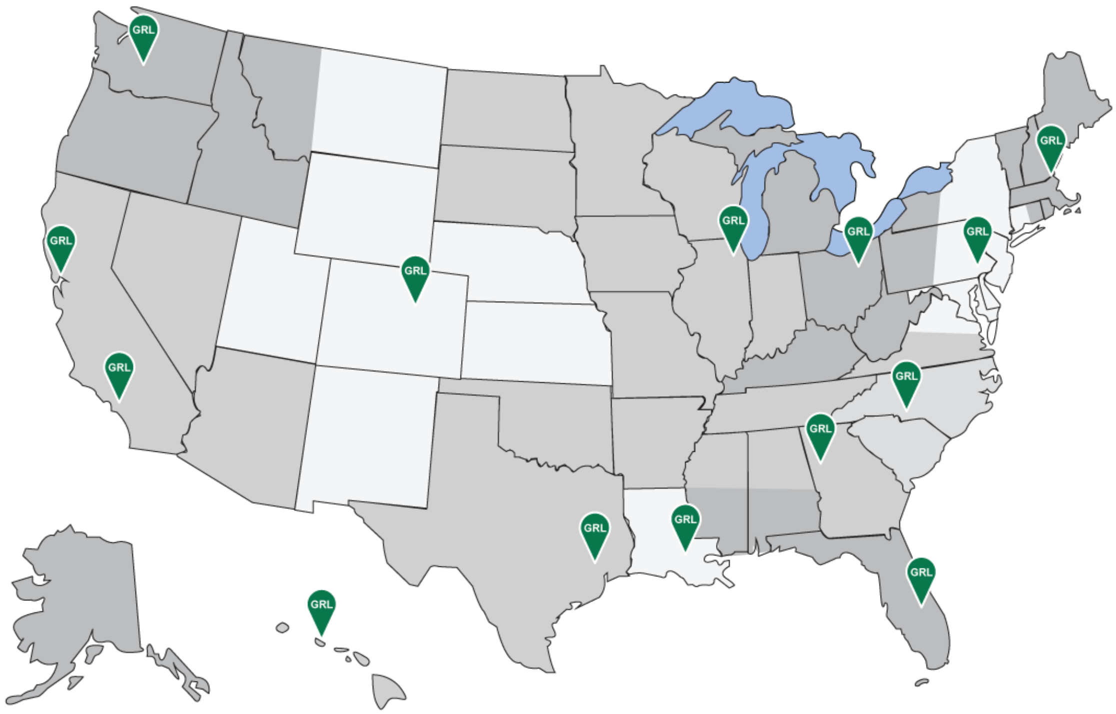


Figure 1. GRL Engineers, Inc. office locations.

GRL offices are located near Atlanta GA, Boston, MA, Charlotte NC, Chicago IL, Cleveland OH, Denver CO, Houston TX, Los Angeles CA, New Orleans LA, Orlando FL, Philadelphia, PA, San Francisco CA, Seattle WA, and Honolulu, HI.

GRL maintains corporate licensure to provide engineering services in all 50 US states as well as the District of Columbia. GRL also holds corporate licensure in five Canadian provinces.

For more information https://www.grlengineers.com/contact-us/

3.0 PROFESSIONAL STAFF

The construction industry has rapidly changing and demanding schedules. Services are often requested on short-notice, either when problems occur, or when sudden scheduling changes need to be accommodated. GRL's professional staff of over 45 deep foundation specialists in our thirteen offices are aware of this industry requirement of immediate response and have at their disposal sufficient personnel and equipment to quickly respond whenever or wherever testing services are required.

Over half of GRL's engineers hold advanced university degrees in civil, structural, or geotechnical engineering, and are registered professional engineers. GRL personnel hold professional engineer licenses in every US state, the District of Columbia, and five Canadian provinces.

For more information https://www.grlengineers.com/our-engineers/

Our engineers with over 6 months of experience who provide dynamic testing services have completed the Pile Driving Contractors Association (PDCA) Dynamic Measurement and Analysis Proficiency Test. This exam evaluates and documents their expertise in dynamic testing data acquisition and analysis. Over 80% of GRL dynamic testing personnel have achieved a rating of Advanced or higher on this exam.

For more information, visit the Dynamic Measurement & Analysis Proficiency Test website.

4.0 SERVICES

4.1 Dynamic Pile Monitoring (PDA) includes the measurement of pile top force and velocity with a Pile Driving Analyzer (PDA) during impact pile driving or restrike testing of driven piles. Dynamic pile monitoring during pile installation (Figure 2) calculates pile driving stresses, assesses pile integrity, determines hammer and driving system performance through transferred energy calculation, and evaluates the mobilized soil resistance at the time of driving. Restrike tests after an appropriate waiting period are used to determine time dependent pile capacity changes resulting from soil setup or relaxation. Tests can be performed with a GRL engineer at the project site or in real time from the office using the SiteLink® remote testing capability. SiteLink® has been used to test piles remotely at international and offshore locations from a GRL office.

Figure 2. Dynamic Pile Monitoring with PDA 8G and wireless data transmission during pile installation.

Dynamic pile monitoring results are typically plotted as a function of pile penetration depth for initial driving sequences (Figure 3) and versus blow number for restrike events. A tabular summary of the test results (Figure 4) is also provided. CAPWAP analyses, discussed in Section 4.3, are performed on selected data sets for further evaluation of the pile capacity and the soil resistance distribution. For more information - https://www.grlengineers.com/services/pdm/

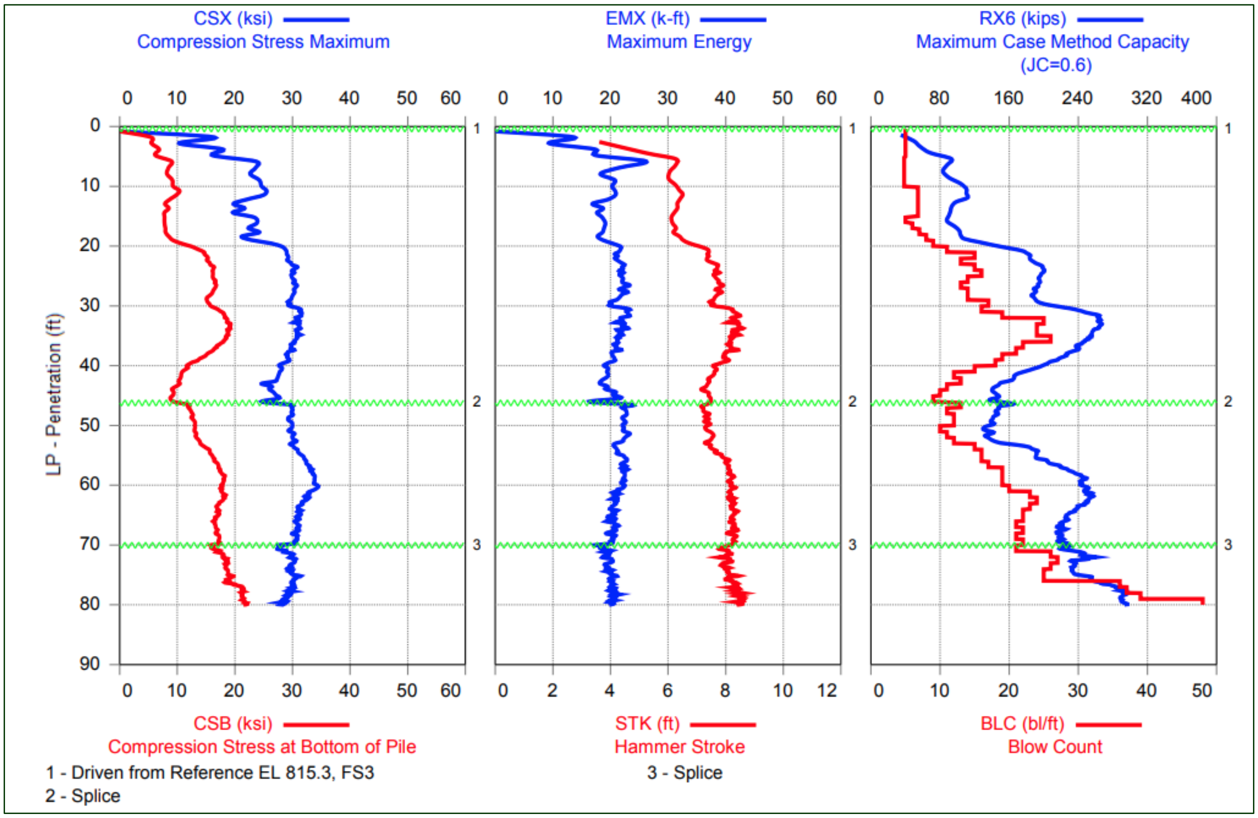


Figure 3. Dynamic pile monitoring versus pile penetration depth.

Case Method & iCAP® Results

Pier 2 - Pile 16 EOID — ICE - I-19 - 14"x0.375" CEP

OP: JS — Date: 05-April-2019

BL#	Depth ft	BLC bl/ft	TYPE	CSX ksi	CSI ksi	CSB ksi	STK ft	EMX k-ft	BPM bpm	RX6 kips
724	59.00	19	AV19	33.8	35.0	18.1	8.2	22	41.3	244
743	60.00	19	AV19	33.9	37.3	18.0	8.2	22	41.4	243
763	61.00	20	AV20	34.0	40.3	17.6	8.2	22	41.2	249
786	62.00	23	AV23	32.6	41.2	18.0	8.2	21	41.4	253
810	63.00	24	AV24	32.2	40.4	17.8	8.2	21	41.2	252
833	64.00	23	AV23	31.2	37.0	17.0	8.2	20	41.2	242
855	65.00	22	AV22	31.2	34.6	17.1	8.3	21	40.9	232
877	66.00	22	AV22	30.8	32.8	16.6	8.2	20	41.3	226
898	67.00	21	AV21	30.9	32.0	16.5	8.3	21	41.1	219
920	68.00	22	AV22	30.7	31.7	16.8	8.3	20	41.1	220
941	69.00	21	AV21	30.6	31.3	17.2	8.3	20	41.2	219
963	70.00	22	AV22	30.5	31.4	17.3	8.3	20	41.1	221
984	71.00	21	AV21	27.5	38.3	16.2	7.9	18	40.1	225
1010	72.00	26	AV26	29.5	40.0	17.7	8.1	19	41.6	247
1037	73.00	27	AV27	30.2	40.1	18.5	8.1	20	41.6	242
1063	74.00	26	AV26	29.6	37.9	18.5	7.9	19	41.9	234
1088	75.00	25	AV25	29.8	37.3	18.8	8.1	20	41.5	234
1113	76.00	25	AV25	30.7	37.6	19.2	8.2	20	41.4	253
1149	77.00	36	AV36	30.0	36.2	19.6	8.3	20	41.0	271
1186	78.00	37	AV37	29.7	37.8	21.3	8.4	20	40.9	290
1225	79.00	39	AV39	29.2	40.1	21.3	8.5	21	40.5	292
1273	80.00	48	AV46	28.3	41.9	21.7	8.5	20	40.5	292
			Average	29.4	35.1	16.1	7.9	21	41.7	213

Total number of blows analyzed: 1271

Figure 4. Tabular summary of dynamic pile monitoring results over selected penetration depths.

4.2 Dynamic Load Testing (DLT) with an APPLE drop weight system is performed to evaluate the bearing capacity of a drilled shaft, augured cast-in-place pile, drilled displacement pile, micropile, or helical pile. APPLE systems with ram weights ranging from 1-ton (Figure 5) to 80-tons (Figure 6) are available. In a dynamic load test, a limited number of impacts (typically 3 to 5) with an appropriately sized drop weight system are applied to the deep foundation element. A dynamic load test can also be performed on a driven pile with a drop weight system sized to mobilize a higher pile capacity than might be possible with the original pile installation hammer.

Figure 5. APPLE VII 2G with 1-ton ram testing a helical pile.

Figure 6. APPLE VIII with 80-ton ram testing a 10 ft diameter drilled shaft.

Dynamic load test results are subsequently analyzed with CAPWAP® analysis to assess the foundation's load-movement behavior. CAPWAP simulated static load test load-movement plots for each blow are frequently plotted sequentially to provide a load-movement envelope (Figure 7).

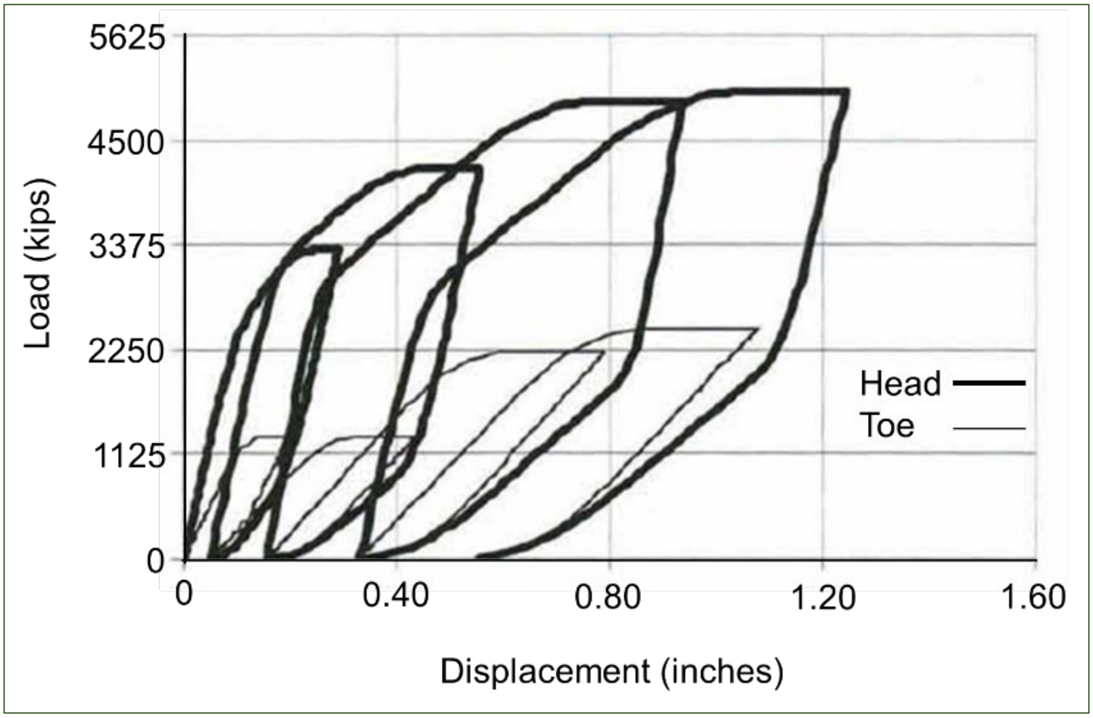


Figure 7. *Dynamic load test load-movement envelope*.

For more information - https://www.grlengineers.com/services/dlt/

4.3 CAPWAP Analysis uses a rigorous numerical signal matching process to determine the soil model from measured force and velocity records. The CAPWAP analysis procedure yields the mobilized pile capacity including the shaft resistance distribution and toe/base resistance as well as the dynamic soil parameters (quake and damping). These results are used to calculate a simulated static load test load-movement plot. The compression and tension stresses along the length of the pile/shaft foundation element are also obtained for the analyzed test record. Output includes a graphical summary (Figure 8) of the analysis results along with numerical tables summarizing the soil resistance versus depth, pile stresses, and the pile model.

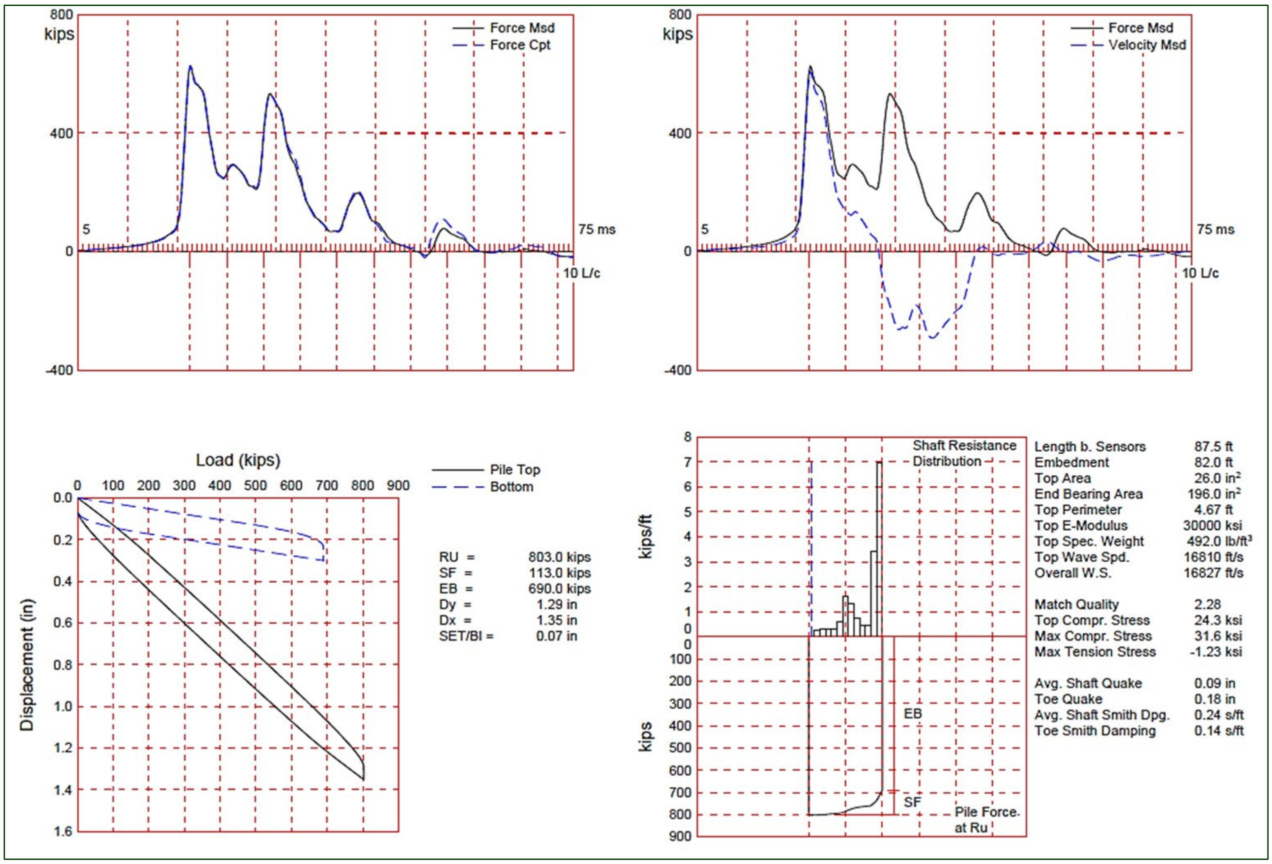


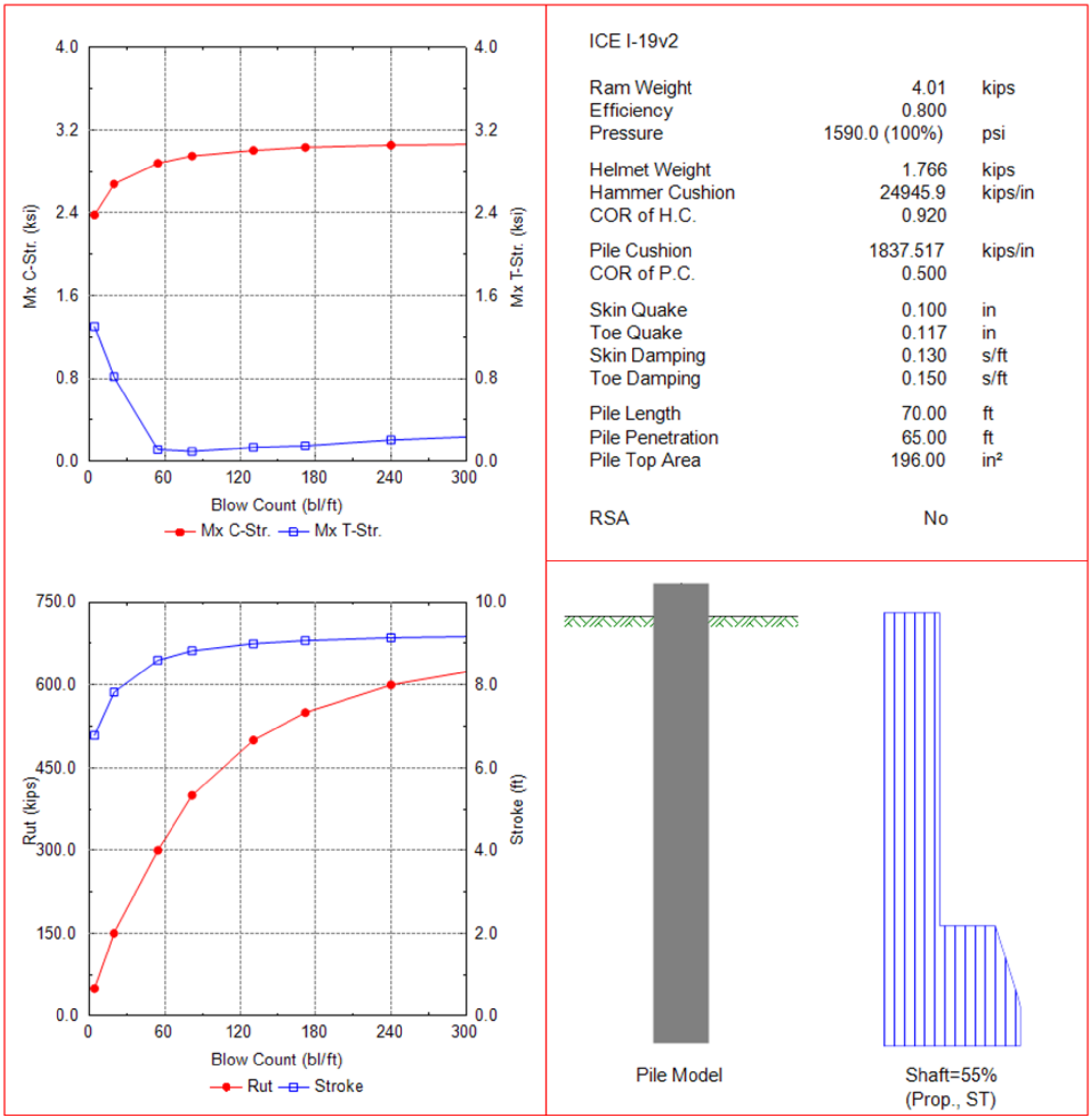
Figure 8. Final CAPWAP analysis output including load-displacement plot.

The capacity and soil resistance distribution information determined from CAPWAP analyses are frequently used to optimize pile foundation designs.

For more information: https://www.grlengineers.com/services/capwap/

4.4 GRLWEAP Analysis is a computer simulation of the pile installation process that is used for both driving system and pile type or section selection. For an impact driven pile, a traditional bearing graph analysis (Figure 9) provides the computed blow count, hammer stroke, compression stress, and tension stress for a given capacity (R_{ut}). This analysis is frequently used to establish the pile driving criteria. The key input parameters along with the soil resistance distribution are displayed next to the bearing graph results.

Figure 9. Example GRLWEAP bearing graph analysis result on concrete pile.



GRLWEAP is also routinely used to conduct drivability analyses. For impact driven piles, drivability analyses evaluate whether the blow counts and driving stresses will be acceptable for pile installation to the required pile penetration depth and capacity. For vibratory installed piles, drivability analyses assess whether the penetration rate and driving stresses will be acceptable. Partial graphic output for drivability analyses on an impact driven (left two graphs) and vibratory installed (right two graphs) H-pile are presented side by side (Figure 10).

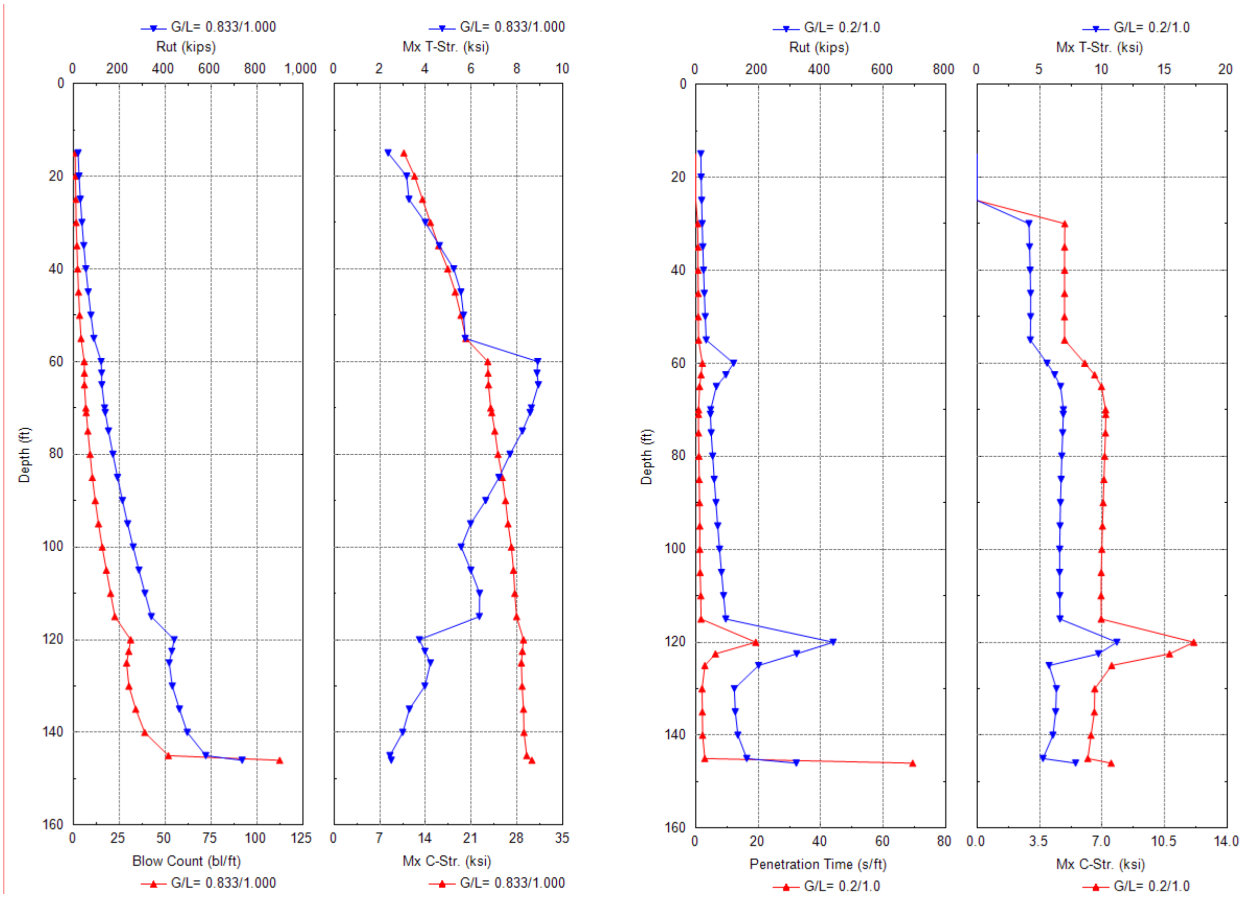


Figure 10. Example GRLWEAP drivability analysis results for impact (left) and vibratory (right) hammers.

Drivability results are also presented in tabular form for the impact hammer (Figure 11) and vibratory hammer (Figure 12). Drivability analyses are routinely used for hammer selection and cost comparison among available hammer type and installation options. Following GRLWEAP modeling guidance, the soil's gain-loss factor as well as its dynamic soil parameters and dynamic resistance model vary in the two analyses based on the selected hammer type (impact or vibratory) and its effect on soil behavior.

For more information: -https://www.grlengineers.com/services/grlweap/

D30-23 (Impact) and V-30 (Vibro), HP14 x 117									GRLWEAP 14.1.20.16
				Gain/Loss 1 at Shaft and Toe 0.833/1.000					
Depth ft	Rut kips	Rshaft kips	Rtoe kips	Blow Ct bl/ft	Mx C-Str. ksi	Mx T-Str. ksi	Stroke ft	ENTHRU kip-ft	Hammer -
15.000	20.5	5.5	15.0	1.0	10.69	2.37	4.04	45.2	D 30-23
20.000	24.8	9.8	15.0	1.1	12.32	3.17	4.17	45.5	D 30-23
25.000	30.3	15.4	15.0	1.3	13.53	3.27	4.31	44.9	D 30-23
30.000	37.1	22.1	15.0	1.5	14.73	3.99	4.47	44.0	D 30-23
35.000	45.1	30.1	15.0	1.9	15.98	4.60	4.63	42.7	D 30-23
40.000	54.3	39.3	15.0	2.3	17.38	5.23	4.80	41.4	D 30-23
45.000	64.7	49.8	15.0	2.8	18.53	5.54	4.98	40.1	D 30-23
50.000	76.4	61.4	15.0	3.4	19.39	5.66	5.16	38.9	D 30-23
55.000	89.3	74.3	15.0	4.2	20.15	5.73	5.35	37.9	D 30-23
60.000	121.1	106.2	15.0	5.9	23.49	8.89	6.18	35.1	D 30-23
62.500	123.1	108.1	15.0	6.0	23.55	8.86	6.20	34.9	D 30-23
65.000	124.1	109.1	15.0	6.0	23.61	8.92	6.21	34.9	D 30-23
70.000	136.0	121.0	15.0	6.8	23.95	8.62	6.33	34.4	D 30-23
71.000	139.1	124.1	15.0	7.0	24.11	8.56	6.36	34.4	D 30-23
75.000	153.2	138.3	15.0	7.9	24.58	8.22	6.49	34.2	D 30-23
80.000	172.3	157.3	15.0	9.1	25.06	7.68	6.64	33.9	D 30-23
85.000	192.5	177.6	15.0	10.3	25.71	7.20	6.79	33.9	D 30-23
90.000	214.1	199.1	15.0	11.9	26.20	6.62	6.97	33.7	D 30-23
95.000	236.8	221.8	15.0	13.7	26.60	5.96	7.13	33.3	D 30-23
100.000	260.7	245.8	15.0	15.7	27.10	5.55	7.30	33.2	D 30-23
105.000	285.9	271.0	15.0	18.0	27.43	5.97	7.46	32.7	D 30-23
110.000	312.4	297.4	15.0	20.3	27.62	6.36	7.56	32.2	D 30-23
115.000	340.0	325.0	15.0	22.6	27.90	6.35	7.69	31.7	D 30-23
120.000	439.7	424.7	15.0	31.2	28.95	3.73	7.94	34.0	D 30-23
122.500	429.2	414.2	15.0	30.2	28.77	3.97	7.90	33.7	D 30-23
125.000	418.0	403.0	15.0	29.0	28.63	4.21	7.85	33.5	D 30-23
130.000	431.4	416.4	15.0	30.3	28.74	3.97	7.91	33.6	D 30-23
135.000	462.9	448.0	15.0	34.0	28.95	3.29	8.03	33.7	D 30-23
140.000	496.7	481.7	15.0	38.9	29.02	3.00	8.14	33.5	D 30-23
145.000	577.6	547.7	29.9	51.8	29.45	2.44	8.34	34.0	D 30-23
146.000	736.2	563.2	173.0	112.5	30.24	2.50	8.61	35.3	D 30-23

Total driving time: 43 minutes; Total Number of Blows: 1865 (starting at penetration 15.0 ft)

Figure 11. Example GRLWEAP drivability summary for diesel hammer with estimated driving time.

D30-23 (Impact) and V-30 (Vibro), HP14 x 117 GRLWEAP 14.1.20.16

Gain/Loss 1 at Shaft and Toe 0.200/1.000

Depth ft	Rut kips	Rshaft kips	Rtoe kips	Pen. Time s/ft	Mx C-Str. ksi	Mx T-Str. ksi	Freq. Hz	Power KW	Hammer -
15.000	16.3	1.4	15.0	0.0	0.00	0.00	0.0	0.0	V-30
20.000	17.4	2.4	15.0	0.0	0.00	0.00	0.0	0.0	V-30
25.000	18.8	3.8	15.0	0.0	0.00	0.00	0.0	0.0	V-30
30.000	20.5	5.5	15.0	0.6	4.90	4.14	28.4	117.6	V-30
35.000	22.5	7.5	15.0	0.6	4.89	4.19	28.3	122.8	V-30
40.000	24.8	9.8	15.0	0.7	4.89	4.23	28.3	130.1	V-30
45.000	27.4	12.4	15.0	0.8	4.89	4.27	28.3	138.8	V-30
50.000	30.3	15.3	15.0	0.8	4.89	4.27	28.3	148.8	V-30
55.000	33.5	18.5	15.0	0.9	4.89	4.25	28.3	160.5	V-30
60.000	121.1	106.2	15.0	2.1	6.02	5.58	27.8	444.9	V-30
62.500	96.5	81.5	15.0	1.7	6.57	6.19	28.3	406.4	V-30
65.000	65.9	50.9	15.0	1.2	6.96	6.67	28.4	312.0	V-30
70.000	47.6	32.7	15.0	0.9	7.19	6.89	28.3	243.8	V-30
71.000	46.9	32.0	15.0	0.9	7.20	6.88	28.3	240.6	V-30
75.000	49.4	34.4	15.0	0.9	7.18	6.83	28.3	249.0	V-30
80.000	54.1	39.2	15.0	1.0	7.14	6.77	28.3	266.4	V-30
85.000	59.2	44.2	15.0	1.1	7.10	6.71	28.3	285.1	V-30
90.000	64.5	49.6	15.0	1.2	7.05	6.66	28.3	304.7	V-30
95.000	70.2	55.2	15.0	1.2	7.01	6.62	28.3	325.4	V-30
100.000	76.2	61.2	15.0	1.3	6.97	6.59	28.3	347.3	V-30
105.000	82.4	67.5	15.0	1.4	6.95	6.59	28.3	370.6	V-30
110.000	89.0	74.0	15.0	1.6	6.93	6.60	28.3	395.0	V-30
115.000	95.9	80.9	15.0	1.6	6.94	6.62	28.3	420.7	V-30
120.000	439.7	424.7	15.0	19.2	12.13	11.17	18.2	427.5	V-30
122.500	322.7	307.7	15.0	6.2	10.77	9.70	18.1	431.8	V-30
125.000	201.0	186.0	15.0	2.9	7.53	5.75	21.5	455.4	V-30
130.000	123.4	108.4	15.0	2.0	6.58	6.33	26.2	443.6	V-30
135.000	126.6	111.6	15.0	2.1	6.56	6.28	26.0	446.9	V-30
140.000	134.9	119.9	15.0	2.3	6.37	6.06	25.5	446.3	V-30
145.000	163.1	133.1	29.9	2.9	6.19	5.26	24.6	450.6	V-30
146.000	321.6	148.6	173.0	69.4	7.50	7.87	20.0	451.0	V-30

Total Driving Time: 4 minutes

Figure 12. Example GRLWEAP drivability summary for vibratory hammer with estimated installation time.

4.5 Thermal Integrity Profiling (TIP) is a method of integrity testing for concrete or grout filled deep foundations. For drilled shafts, barrettes, and diaphragm wall panels, this method requires that Thermal Wire® cables be attached to the reinforcing cage (Figure 13) prior to cage and concrete placement. For augured cast-in-place or drilled displacement piles, a cage or center bar with Thermal Wire attached is inserted into the grout filled hole immediately after auger removal. On circular foundations, one thermal wire cable is typically used for every one foot of foundation diameter so that the concrete or grout integrity both inside and outside of the reinfocing cage can be evaluated.

As the concrete or grout cures, the heat of hydration allows the interpretation of necks or inclusions (regions colder than average), bulges (regions warmer than average), variations in concrete cover, shape of the foundation, or cage alignment. TAG and TAP - EDGE units (Figure 14) collect temperature readings at 15 minute intervals from each wire during the curing process. The data is pushed to the Cloud for review and processing. TIP results are typically evaluated between ½ peak and peak temperature. For common foundation types and sizes, this test window generally occurs within 12 to 48 hours of casting.

Figure 13. TIP wire attachment to a drilled shaft cage.

Figure 14. TAG and TAP Edge units on wires.

Final TIP results include plots of the effective shaft radius and concrete cover versus depth (Figure 15). These results may be evaluated for foundation shape and integrity, concrete or grout quality, and for location of the reinforcing cage. The overall average temperature for all Thermal Wire readings over the embedded depths can be directly related to the overall volume of concrete or grout installed.

Foundation integrity is assessed based on the average temperature measurements from each Thermal Wire at each depth increment. If the measured average temperature versus depth is consistent, the foundation is considered uniform in shape and quality. Bulges can be identified as localized increases in average temperature, while reduced concrete quality or cross section reductions can be identified as localized decreases in average temperature. Anomalies present over more than ten percent of the effective cross-sectional area are normally seen in multiple Thermal Wires at the same depth. Because soil and/or slurry pockets produce no heat, areas of soil intrusion or inclusion are indicated by lower local temperatures.

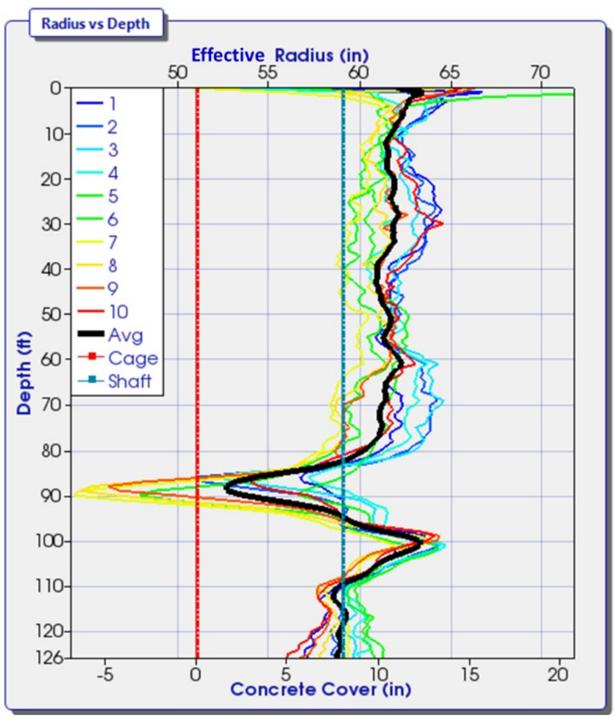


Figure 15. TIP Results: Effective Radius vs depth.

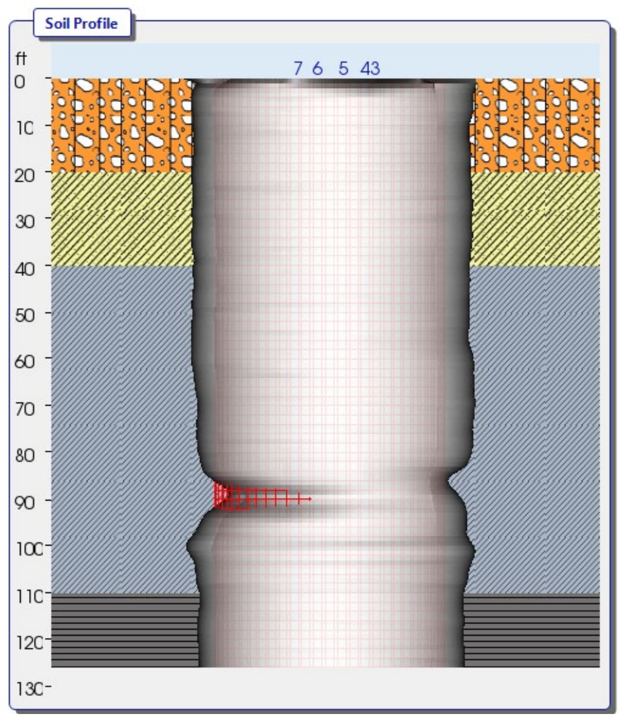


Figure 16. TIP Results: 3D shaft interpretation.

Reinforcement cage location is estimated based on the relative temperature difference between an individual Thermal Wire and the average of all wires. Higher individual Thermal Wire temperatures indicate the wire is closer to the center of the foundation, or near a local bulge, while lower individual Thermal Wire temperatures indicate the wire is closer to the soil interface, or a local defect. By viewing diametrically opposite Thermal Wire results, instances where a lateral shift of the reinforcing cage has occurred can be determined, if one wire temperature is higher than average and the diametrically opposite wire temperature is lower than average. For drilled shafts and piles, a three-dimensional depiction (Figure 16) of the foundation shape is also reported.

Plots of the temperature generated versus time is another tool available to further assess potential anomalies. Temperature versus time plots from the lowest node in two project shafts (Figure 17), illustrate minimal temperature generation occurred at the base of Shaft 2 compared to Shaft 1. This clearly indicates a concrete quality problem or reduced cement content at the base of Shaft 2. This concrete issue was subsequently confirmed by coring.

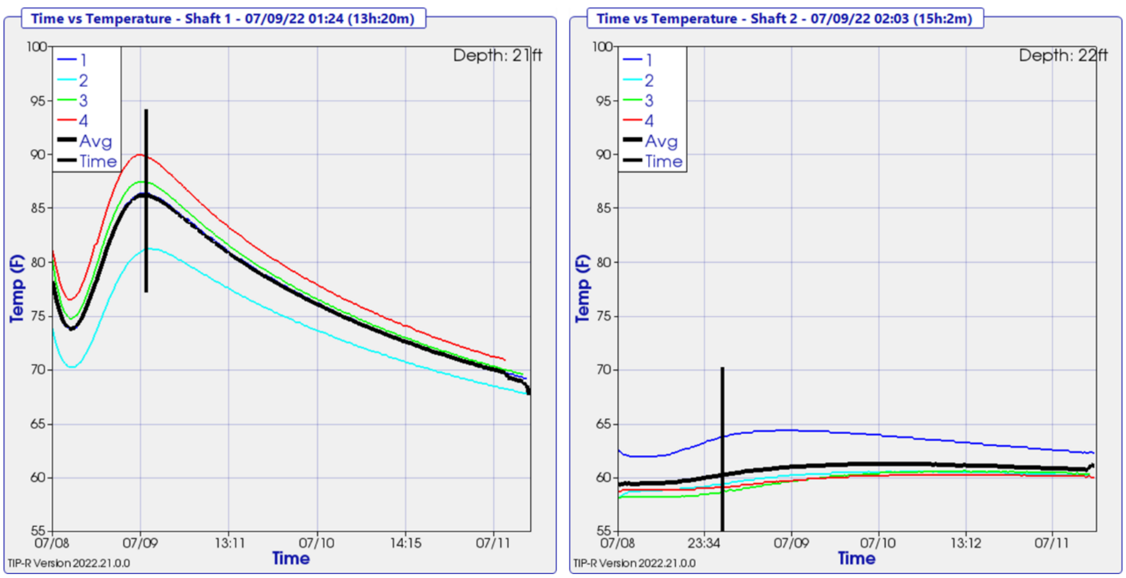


Figure 17. TIP Results: Temperature vs Time Comparison of Lowest Node in Two Project Shafts

For more information - https://www.grlengineers.com/services/tip/

4.6 Crosshole Sonic Logging (CSL) is an integrity testing method commonly used for drilled shafts, barrettes, and diaphragm wall panels. It requires that access tubes, typically one per foot of shaft diameter in a drilled shafts, be attached to the reinforcing cage prior to cage installation into the foundation excavation and subsequent concrete placement. After concrete curing, high frequency acoustic waves are generated from a transceiver in one of the tubes and received by transceivers in other tubes as all probes are pulled upward (Figure 18) from the bottom of the access tubes. The arrival time and magnitude of the received signals (Figure 19) identify the quality of the concrete between tube pairs. Anomalous areas are identified by a delay in the first arrival time or a decrease in the signal energy. CSL tests are typically performed five to seven days after concrete placement with large shafts often necessitating longer wait times.

Figure 18. Typical field set-up of multiple transceiver CSL test.

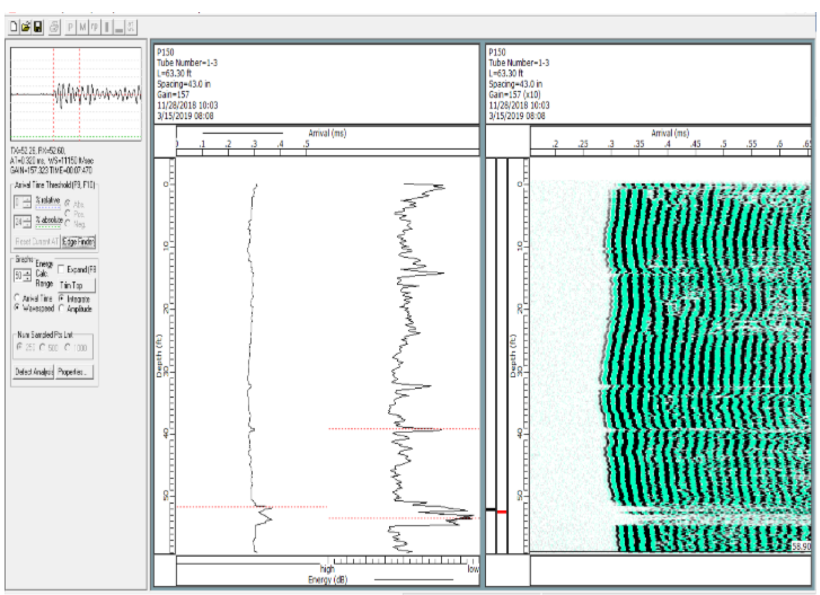


Figure 19. Analysis software showing first arrival time (FAT), energy, and waterfall diagram (right).

The CSL profiles in a four tube (Figure 20) and an eight tube (Figure 21) shaft delinate the approximate shaft area tested by the CSL signals recognizing that the fastest signal transmission can deviate slightly from the depicted straight line path.

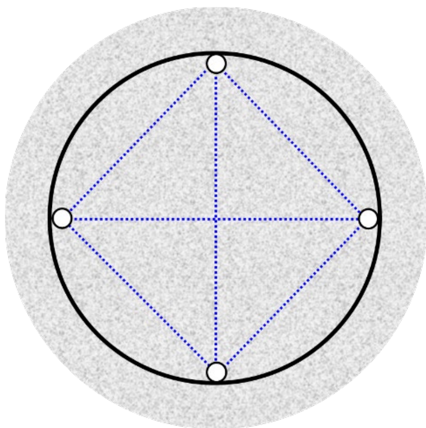


Figure 20. CSL profiles in a four tube shaft.

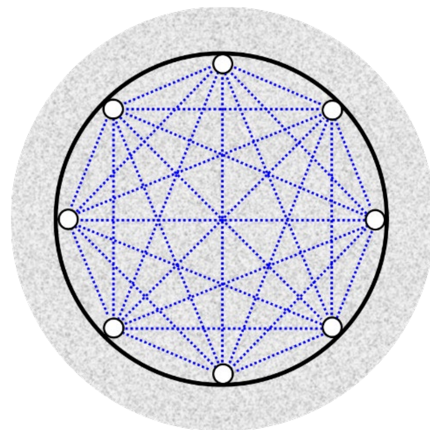


Figure 21. CSL profiles in an eight tube shaft

Tomography analyses using the PDI-TOMO software can be used to further evaluate zones with delayed first arrival times. Selected slices (Figure 22) through the shaft display the effective shaft area having a concrete wave speed greater than the user selected threshold for lower concrete quality.

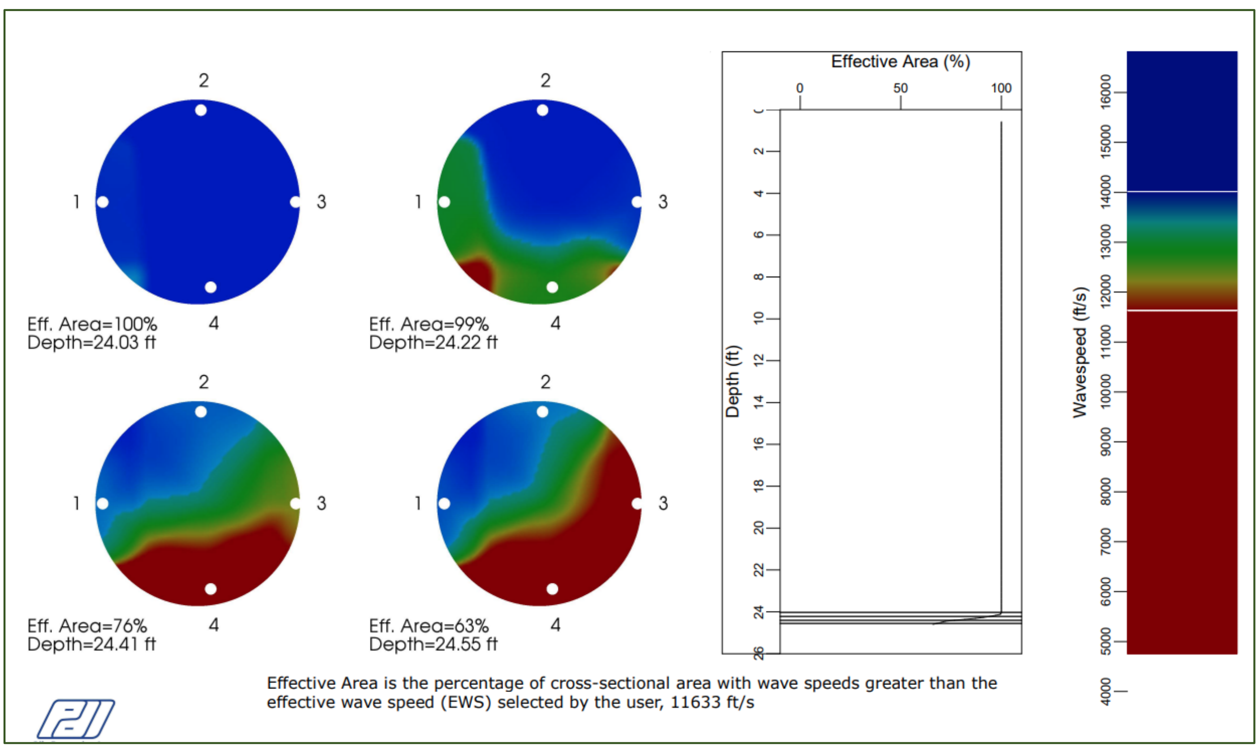


Figure 22. PDI Tomo analysis results

For more information – https://www.grlengineers.com/services/csl/

4.7 Gamma Gamma Logging (GGL) is a non-destructive test method specified to assess the concrete cover and integrity of drilled shafts. GGL provides highly repeatable test results, while objectively evaluating integrity and relative concrete quality. The range of gamma radiation into concrete is limited to approximately the 3 to 4-inch zone surrounding the access tube. GGL is a relatively quick test with no depth restrictions and is typically performed three to seven days or more after concrete placement.

Drilled shafts are prepared for GGL testing by attaching 2-inch O.D., Schedule 40, PVC access tubes to the steel reinforcing cage (Figure 23) prior to cage insertion into the shaft excavation and concrete placement. GGL identifies locations of potential shaft anomalies through statistical analysis using a gamma-density correlation. In cases where GGL testing was not initially planned, it can be performed in core holes drilled through the concrete.

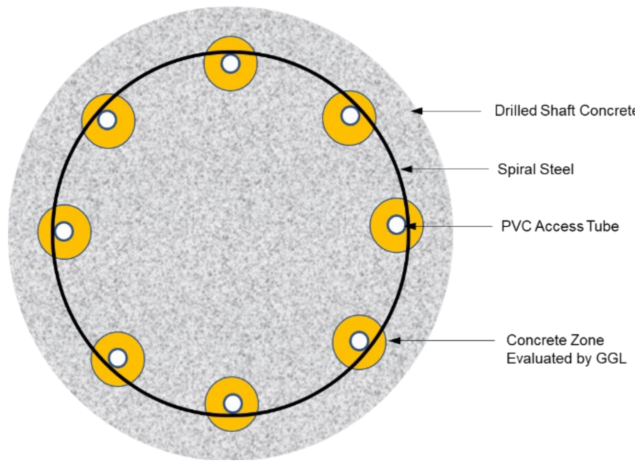


Figure 23. GGL evaluation area.

GGL results (Figure 24) are presented in a density vs depth plot per the CALTRANS CT-233 test standard. An anomalous zone is apparent in all tubes at 160 feet and in tubes 9 and 10 near the shaft base.

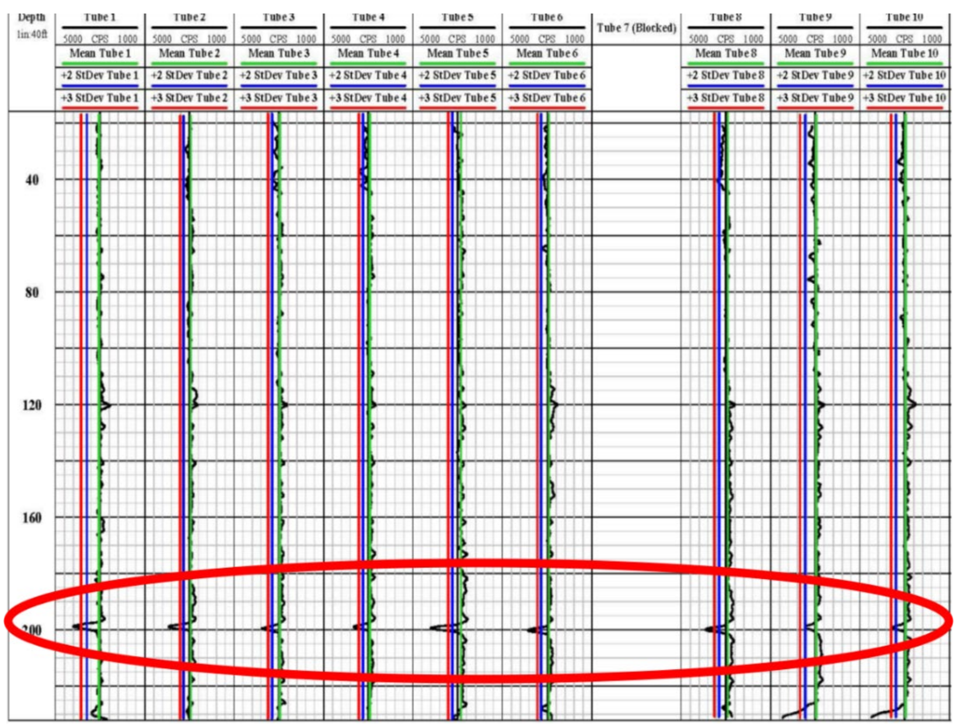


Figure 24. GGL results on a density vs depth plot.

4.8 Pile Integrity Testing (PIT) on drilled shafts, augured cast-in-place piles, and drilled displacement piles as well as on driven concrete and timber piles, is performed by impacting the surface of the deep foundation with a hand-held hammer and measuring the foundation response with a surface mounted accelerometer (Figure 25). The test results can be analyzed using either the pulse echo method or the transient response method. In a pulse-echo test result (Figure 26), significant positive reflections occurring prior to the time of the toe reflection are indicative of significant defects. Pile integrity testing is very economical. Many piles can be tested in a day to provide an assessment of the structural integrity of a deep foundation.

Figure 25. Low strain pile integrity test

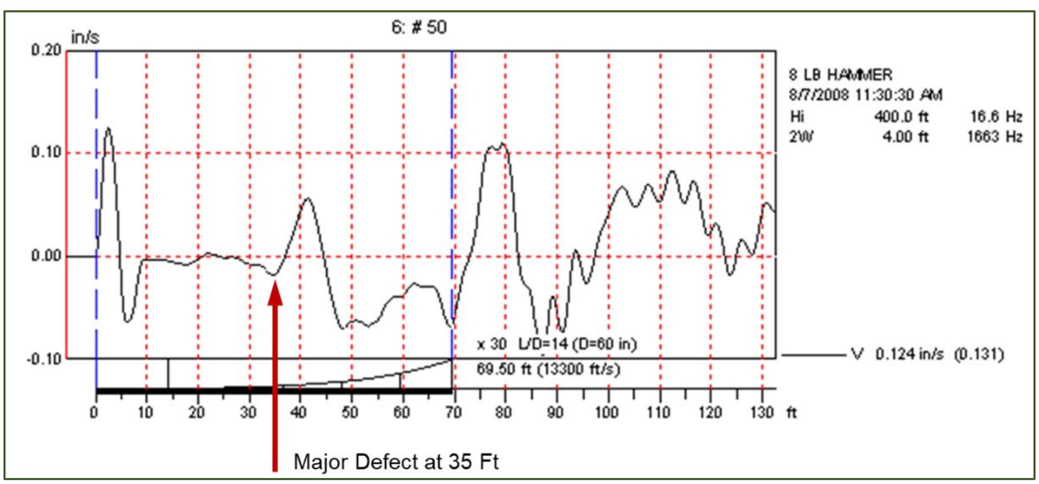


Figure 26. Representative pulse echo low strain integrity test record with reflection from a major deflect.

For more information – https://www.grlengineers.com/services/pit/

4.9 Static Load Testing (SLT) is frequently performed to assess foundation design assumptions. Axial compression load tests (Figure 27) or axial tension load tests can be performed to determine the resistance provided by a deep foundation element. Lateral load tests can be performed to evaluate a foundation's deflected shape under lateral load. GRL performs both highly instrumented static load tests to meet the need of design stage load tests, as well as basic load tests, for construction quality assurance. GRL can provide surface mounted and embedded instrumentation, hydraulic jacks, and loading beams for axial compression, tension, or lateral load tests as part of our testing services.

Figure 27. Reaction pile load frame for an axial compression load test.

A load-movement plot (Figure 28) of the applied load determined from the jack pressure gage and load cell versus the deep foundation head movement determined by LVDTs, digital dial gages, or mechanical dial gages is used to assess the capacity of the deep foundation under axial compression, axial tension, or lateral load.

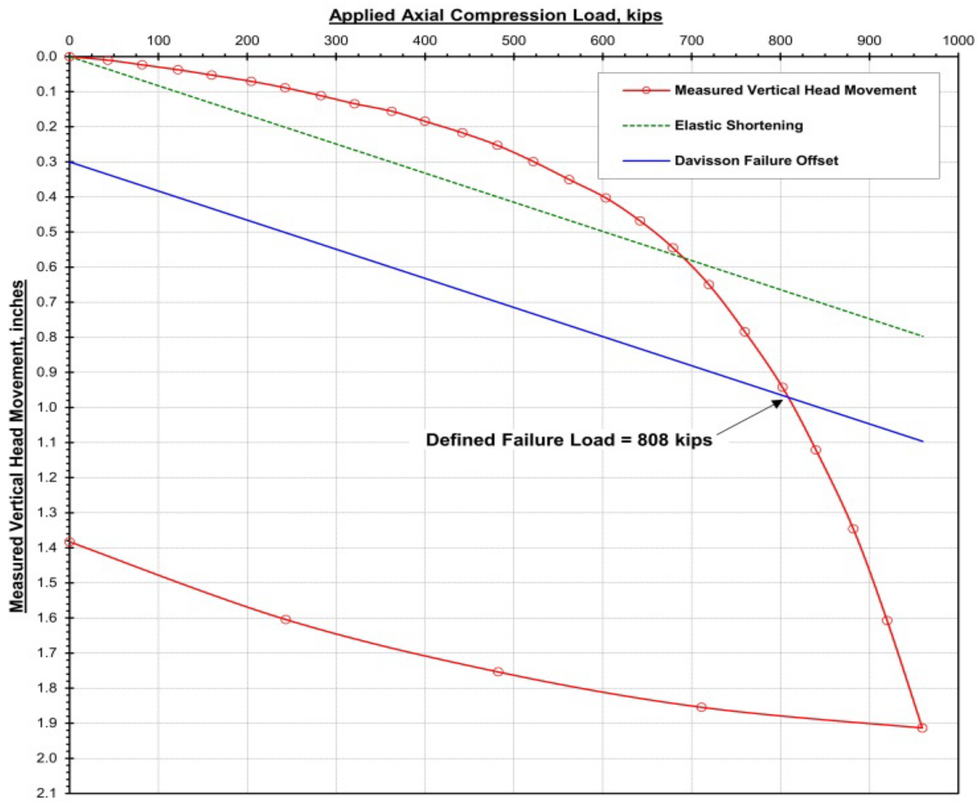


Figure 28. Load-movement plot from axial compression load test.

GRL can furnish and analyze external (Figure 29) or embedded (Figure 30) strain gage instrumentation so that the load-transfer profile (Figure 31) from a static load test can be obtained. Load-transfer information can be used to optimize the required penetration depth for the foundation loads.

Figure 29. External surface-mounted VW strain gauges mounted on H-pile web.

Figure 30. Sister-bar strain gauges attached to drilled shaft cage prior to embedment.

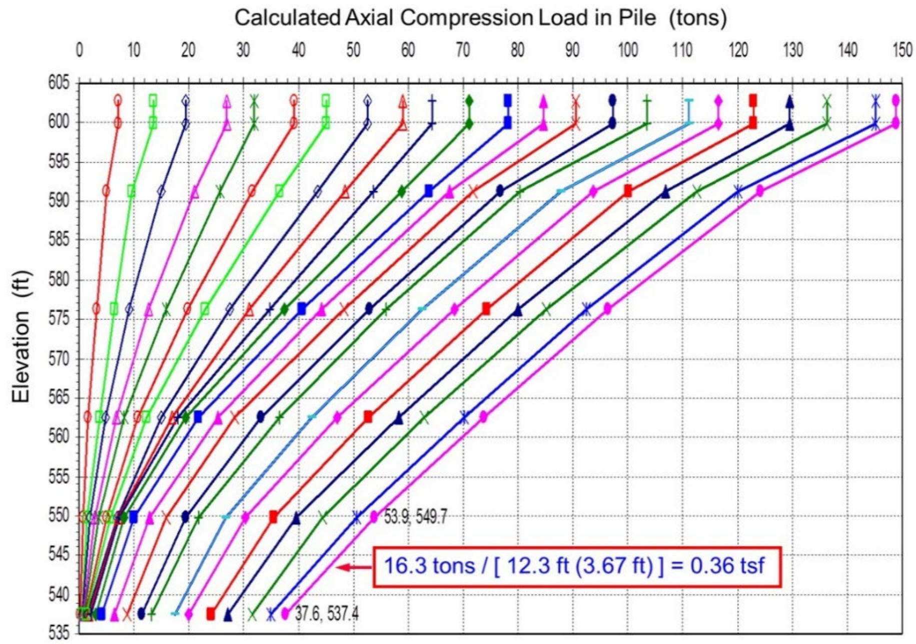


Figure 31. Load-transfer profile from strain gage instrumentation in an axial compression test.

For lateral load tests, ShapeArrays (Figure 32) or in-place inclinometer strings can be used to determine the deflected shape versus length (Figure 33). Head rotation can also be determined by attaching a tilt meter at the foundation head.

Figure 32. ShapeArrays installed in two pipe piles during a lateral load test.

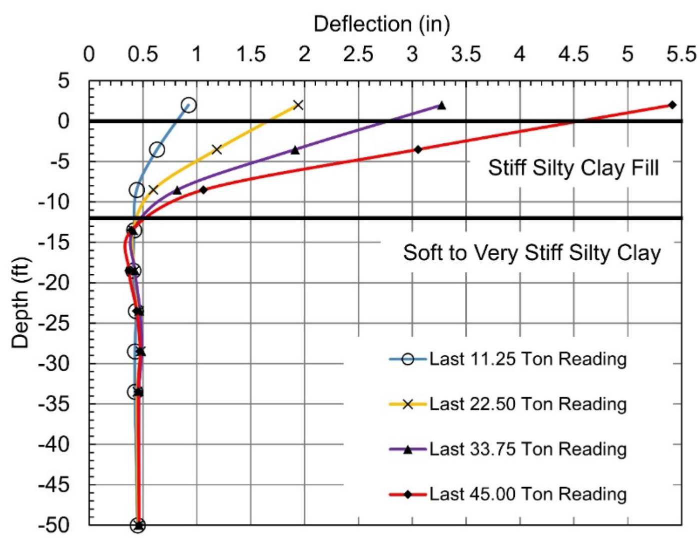


Figure 33. Deflected shape versus depth from instrumented lateral load lest.

For more information https://www.grlengineers.com/services/slt/

4.10 Bi-Directional Static Load Testing (BDSLT) is a method used to statically load test cast-in-place deep foundation elements including drilled shafts, augured cast-in-place piles, drilled displacement piles, barrettes, and diaphragm wall panels. The GRL-Cells and jack assembly are attached to reinforcing cage (Figure 34), lowered into the foundation excavation, and cast into the foundation during concrete placement. For augured cast-in-place and drilled displacement piles, the GRL-Cell is attached to the jack assembly and reinforcing element and then lowered into the grout filled pile excavation immediately folowing auger removal.

The GRL-Cell is a piston type jack that statically loads the deep foundation in two directions, upwards and downwards, from the cell location. Depending on the shaft diameter and required load, one or more GRL-Cells may be used to configure the jack assembly. When located at the soil/rock resistance balance point in the soil profile, a maximum test load of up to twice the capacity of the jack assembly can be achieved.

Test results (Figure 35) include upper and lower bearing plate movement versus load at the jack assembly location. Bi-directional static load testing is the most economical methods to perform a high capacity static load test.

Figure 34. Multi-cell jack assembly in cage at base of drilled shaft.

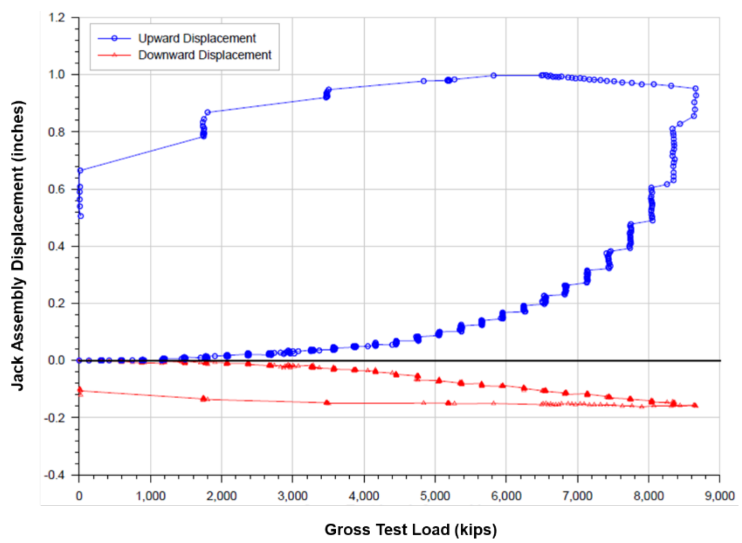


Figure 35. Upper and lower bearing plate displacements.

A bi-directional test shaft or pile is typically heavily instrumented. Strain gages are attached to the reinforcing cage or center bar at multiple levels in the deep foundation. Movements of the shaft head, top bearing plate, lower bearing plate, and shaft toe are measured during the test. From these measurements, a calculated axial internal compression force profile (Figure 36) indicative of the load-transfer behavior and soil / resistances is obtained. Derived t-z, q-z behavior from the test is used to develop an equivalent top loading curve (Figure 37).

For more information https://www.grlengineers.com/services/bdslt/

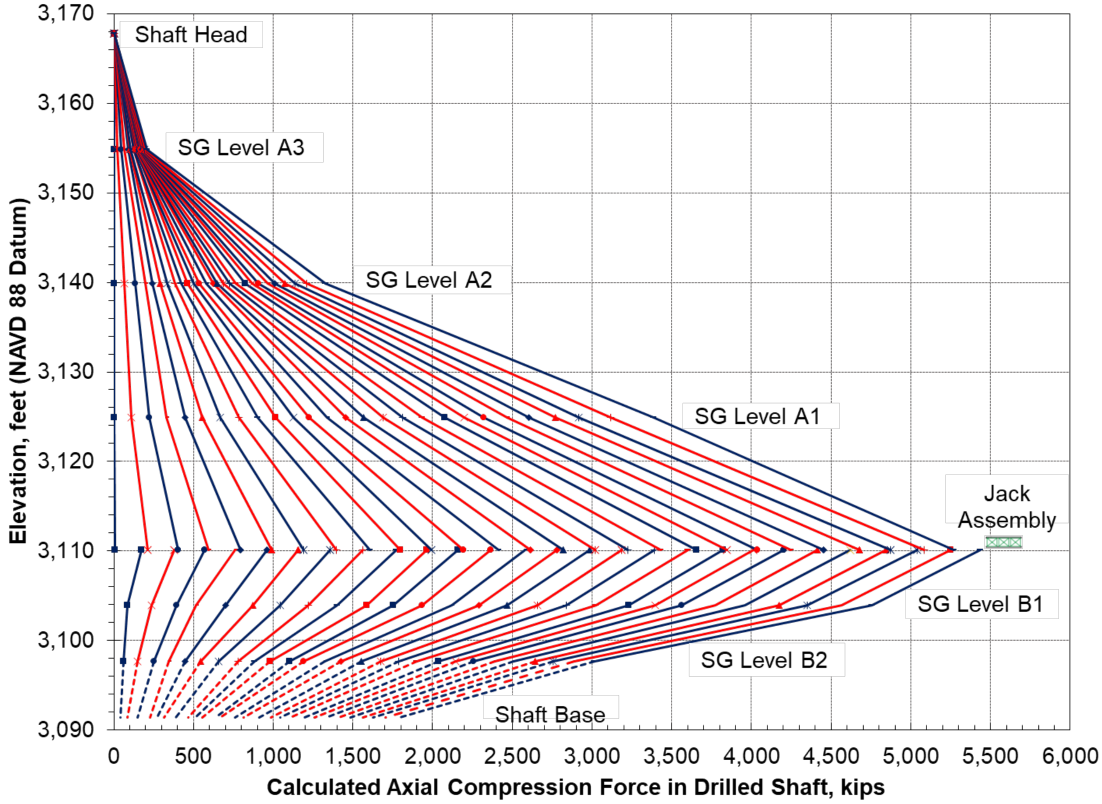


Figure 36. Calculated axial internal compression force profiles.

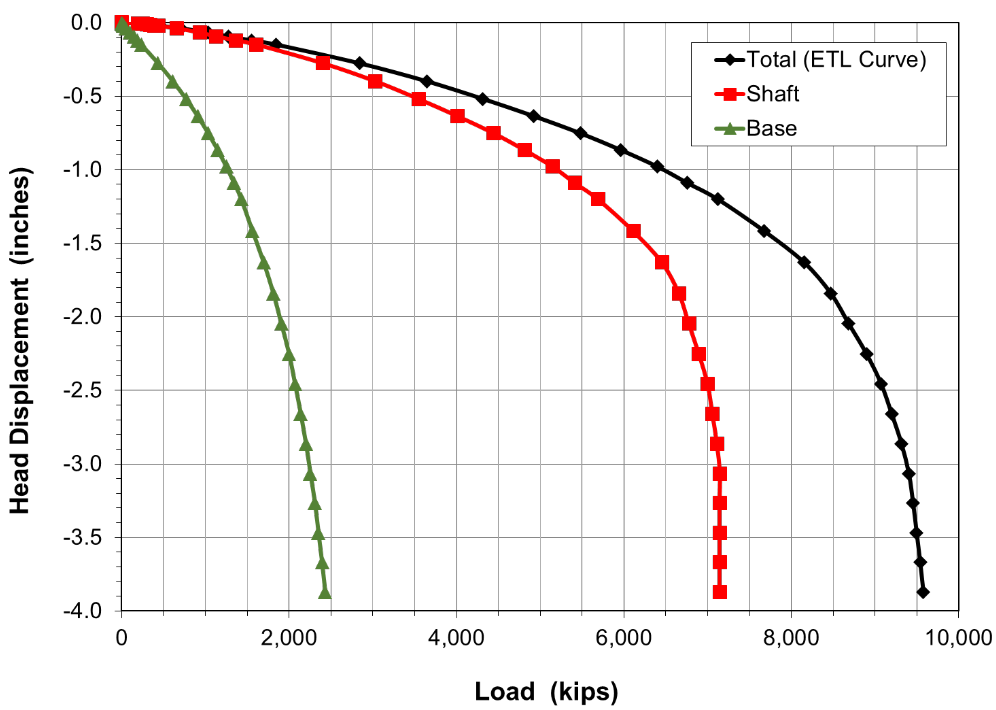


Figure 37. Calculated equivalent top loading curve with shaft and base resistances.

4.11 Top Loaded Bi-Directional Test (TLBT) is a method to perform a bi-directional static load test without embedding a sacrificial jack in the foundation element. GRL provides a reusable above grade hydraulic jack and load assembly to apply bi-directional loads to embedded bearing plates through shaft mobilizer and base mobilizer bars (Figure 38). Test instrumentation for determining bearing plate movements (Figure 39) and load transfer behavior is similar to a conventional bi-directional static load test. The test is particularly well suited to moderatly loaded foundations with nominal diameters, lengths, and loads. A TLBT can offer significant cost savings when when multiple foundation elements need to be load tested on a given project site.

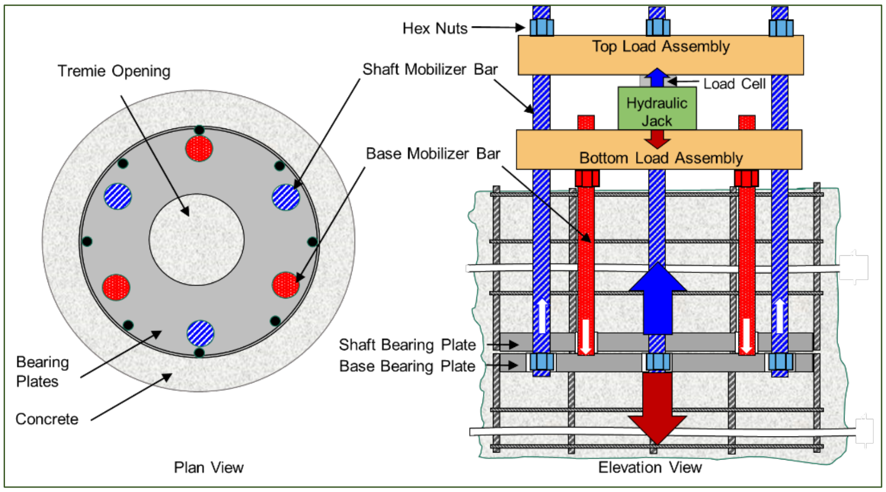


Figure 38. General schemtic of a Top-Loaded Bi-Directional Test.

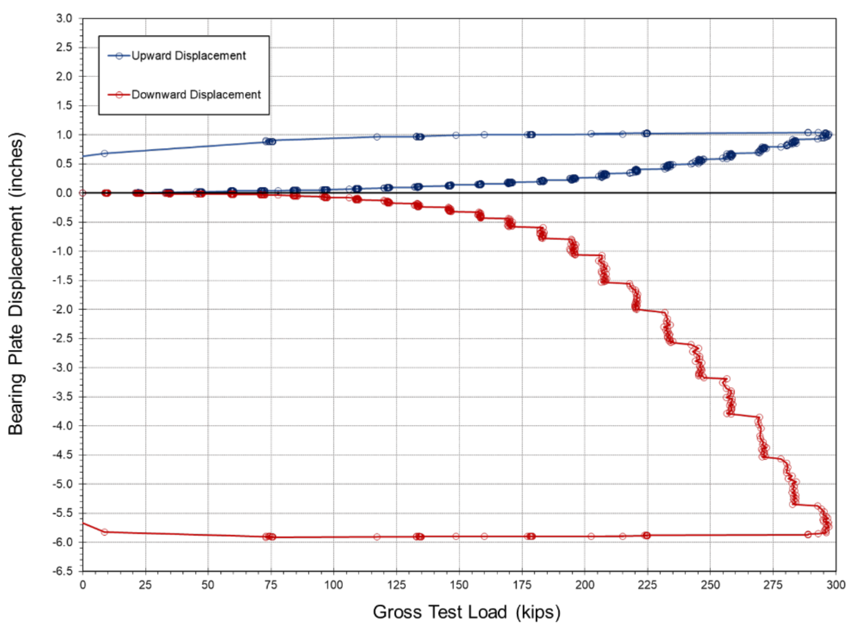


Figure 39. Upper and lower bearing plate displacements from TLBT.

For more information – https://www.grlengineers.com/services/tlbt/

4.12 Drilled Shaft Verticality, Radii, Profile, and Excavation Volume tests are performed by GRL to determine the characteristics of a wet pour or dry, drilled shaft excavation. GRL uses the appropriate **SH**aft **A**rea **P**rofile **E**valuator (SHAPE), which can be quickly attached to the drill rig Kelly bar or winch system, and then lowered into the shaft excavation. The SHAPE device for wet pours (Figure 40) uses eight ultra-sonic signals to scan the sides of the shaft excavation, whereas the SHAPE for dry shafts uses Lidar sensors.

Figure 40. SHAPE moving over shaft excavation.

Scan results (Figure 41) from each of the four profiles, provide a quick check of the drilled shaft verticality, radii, and shape. The combined results are used to calculate the drilled hole volume. During the test, all collected data is stored within the SHAPE device's internal memory allowing for cable free data collection in the shaft excavation. Tests can be performed with a GRL engineer at the site or from the office in real time using the SiteLink capability. Results (Figure 42) include the verticality, maximum eccentricity and encroachment area.

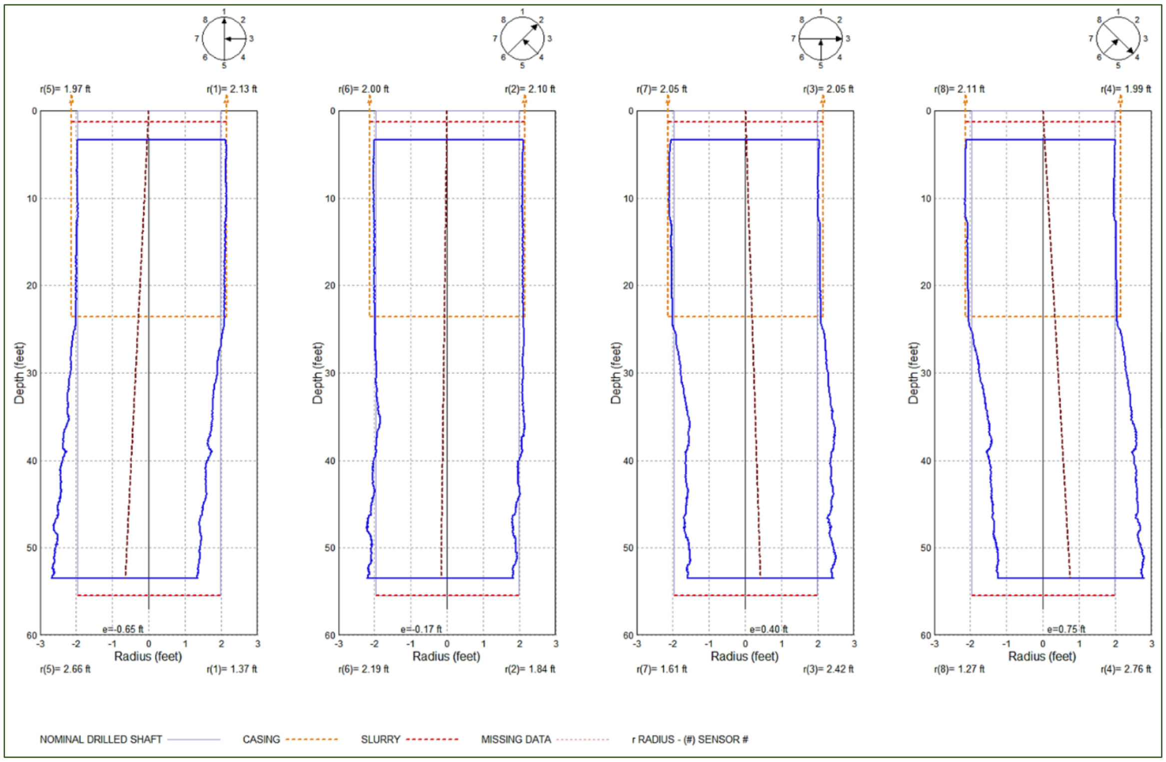


Figure 41. SHAPE profiles of radius vs depth.

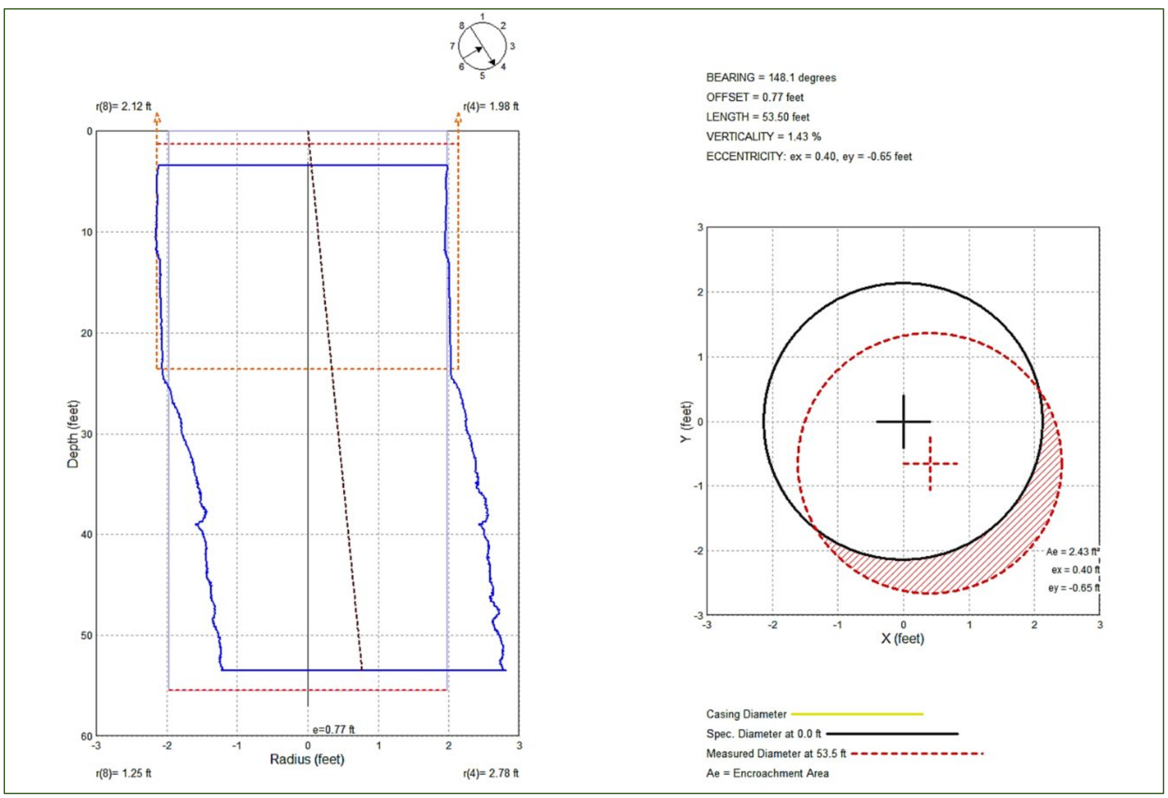


Figure 42. SHAPE results of verticality, eccentricity, and encroachment

For more information – https://www.grlengineers.com/services/shape/

4.13 Drilled Shaft Base Cleanliness Evaluations are an important part of drilled shaft or bored pile construction. The cleanliness of the shaft base is important for shafts that derive a significant amount of their total capacity from base resistance. Base cleanliness is also important to minimize concrete contamination risks from excessive debris material. GRL performs base cleanliness checks prior to placing the reinforcing cage and shaft concrete using the **S**haft **QU**antitative **I**nspection **D**evice or SQUID. This device quickly attaches to the drill rig Kelly bar (Figure 43). The tests provide a quantitative assessment of the drilled shaft base condition using the SQUID's three penetrometers and three displacement plates. For small shafts a single test is typically performed. For shafts greater than five feet in diameter, tests are typically performed in the center of the shaft and in the four perimeter quadrants. When the Kelly bar weight is applied, the device measure penetrometer force as a function of penetrometer depth into the materials at the shaft base (Figure 44). From these measurements the base cleanliness and debris thickness can be evaluated and reported. Tests can be performed with a GRL engineer at the project site or in real time from the office using the SiteLink capability.

Figure 43. SQUID moving over shaft excavation.

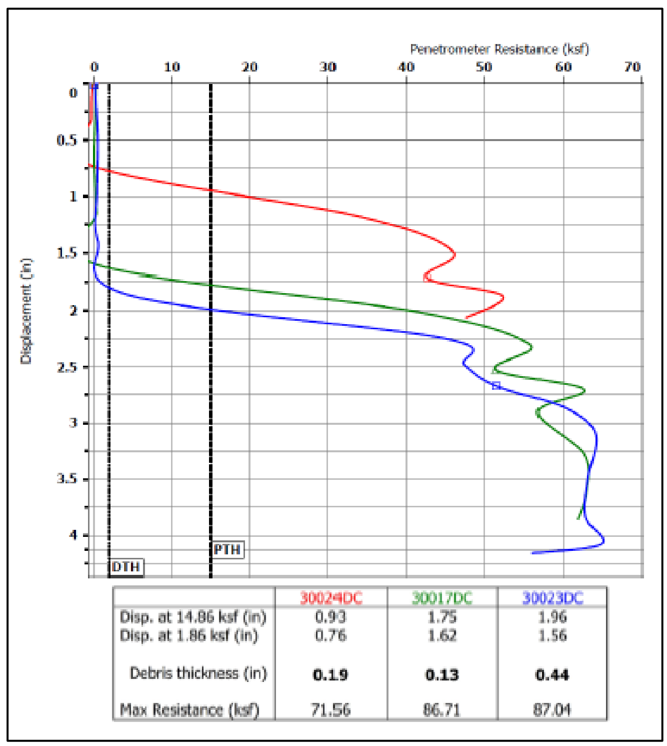


Figure 44. SQUID test resistance vs displacement results from one test location.

For more information – https://www.grlengineers.com/services/squid/

4.14 SPT Energy Measurements are used to calibrate SPT hammers on soil boring rigs. The Standard Penetration Test (SPT) consists of driving a split spoon sampler 18 inches into the soil with a 140 pound weight dropped from 30 inches. The number of blows required to drive the sampler the last 12 inches is termed the SPT N value, which is used to assess the soil strength. There are several types of SPT hammers used in the industry. Depending upon the hammer type, SPT hammers can transfer from 45% to 95% of the rated energy into the drill rod.

Many design procedures require the N value to be based on a standard energy transfer to the drill rod of 60%. An SPT N_{60} value can be obtained by multiplying the recorded N value by the ratio of the measured energy transfer divided by 210 ft-lbs, 60% of the theoretical energy transfer of 350 ft-lbs. GRL provides energy measurement services (Figure 45) on SPT hammers for general drill rig calibration purposes as well as for site specific studies which may use the N_{60} results to identify soil layers subject to liquefaction in seismic events.

Figure 45. Energy measurements being acquired on the drill string during SPT soil sampling.

For more information – https://www.grlengineers.com/services/spt/

4.15 Becker Energy Measurements are made on Becker Penetration Tests (BPT) which are commonly used to characterize the liquefaction characteristics of gravel and cobble materials. The BPT consist of driving a 5-$^1/_2$, 6-$^5/_8$, or 9 inch O.D. drill string into the ground with a small, truck-mounted diesel hammer (Figure 46). GRL performs both convention energy measurements at the top of the Becker drill string as well as an instrumented Becker Penetration Test (iBPT) with energy measurements at both the top and bottom of the drill string. From the top and bottom energy measurements, a normalized Becker blow count, or N_{B30} value, is computed. The N_{B30} can be correlated to the SPT N_{60} value for liquefaction assessment.

Figure 46. Energy measurements being acquired on the drill string during Becker Penetration Testing.

GRL uses PDA Model 8G units with the SPT Analyzer software package when collecting iBPT energy transfer measurements near the top and bottom of the drill string. These iBPT energy measurements can be transferred to the SPT Analyzer via either wired or WiFi technology.

iBPT energy transfer measurements to the top and bottom of the Becker drill string versus depth (Figure 47) as well as an equivalent SPT N_{60} profile versus depth are reported (Figure 48).

For more information – https://www.grlengineers.com/services/becker/

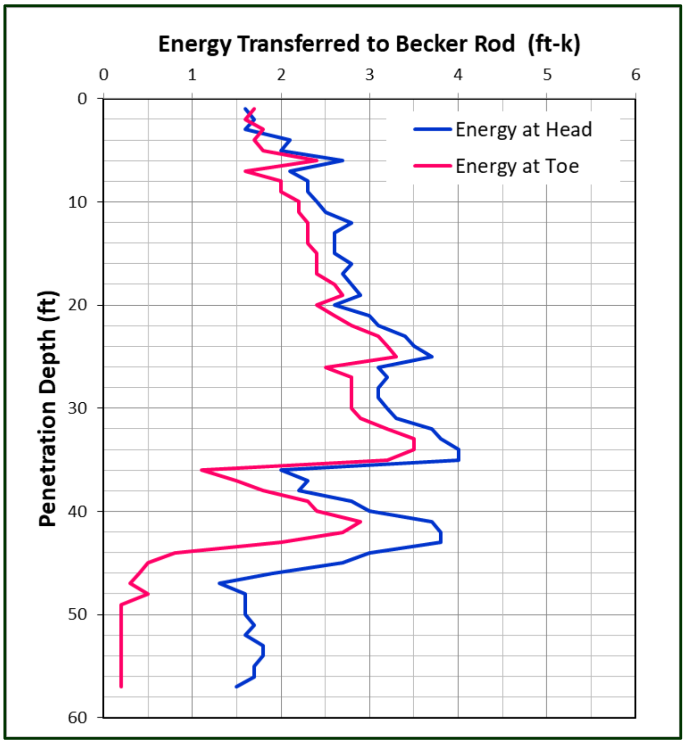


Figure 47. iBPT energy measurements versus depth.

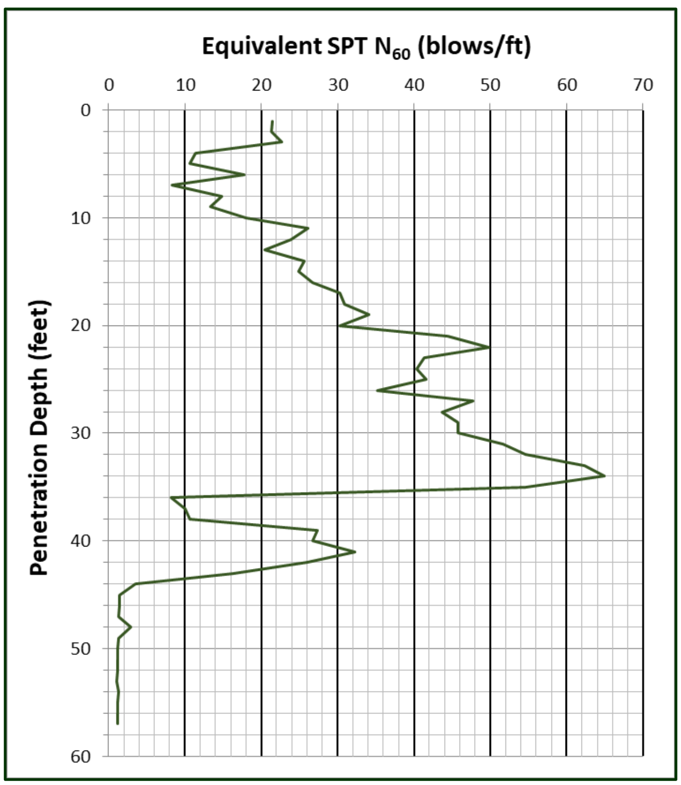


Figure 48. Equivalent SPT N_{60} values versus depth.

4.16 Offshore Oil Platforms and Offshore Wind Turbine Foundations are installed in challenging construction environments where reliability of the test measurements is essential due to project time and cost considerations. While the test method and the analysis procedures are the same as those described in Sections 4.1, 4.3, and 4.4, offshore projects require backup test systems and highly experienced personnel to staff the round the clock construction activity. GRL has performed dynamic pile monitoring on over 250 offshore projects around the world (Figure 49, Figure 50). In the US, these projects have been located in the Gulf of Mexico, the Pacific Ocean offshore California, in Cook Inlet, Alaska as well as on monopile wind turbine foundations in the North Atlantic Ocean. GRL has also performed offshore dynamic pile monitoring services in the Arabian Sea, Bay of Bengal, Bay of Cambay, Bay of Campeche, Black Sea, Bohai Sea, Caribbean Sea, Caspian Sea, East China Sea, Lake Maracaibo, North Sea, Persian Gulf, Red Sea, South Atlantic Ocean, and the South China Sea. Dynamic pile monitoring services have been performed with conventional above water PDA gages as well as up to 600 feet below sea level with our waterproof underwater PDA gages and cables.

Figure 49. Offshore Platform

Figure 50. Platform with Underwater Testing.

For more information – https://www.grlengineers.com/services/oft/

4.17 Parallel Seismic Testing (PST) is performed to evaluate unknown foundation lengths. A minimum two-inch diameter borehole must be drilled within 24 inches of the foundation to be tested. The borehole must also extend well below the expected toe of the deep foundation element. Since the foundation length is unknown, the borehole termination depth must be carefully selected. A PVC pipe is inserted into the borehole. Both the PVC pipe and the surrounding borehole must be filled with water. The pile top is struck with an instrumented hammer while a hydrophone is incrementally lowered down the cased hole (Figure 51). The stress wave travels down the pile and outward through the soil. At each test depth, the wave arrival at the hydrophone is plotted versus time (Figure 52). When the hydrophone is positioned below the foundation termination depth, the wave must travel an increasingly greater distance through soil. The plot of wave arrival time versus depth will have a change in slope corresponding to the termination depth of the foundation element.

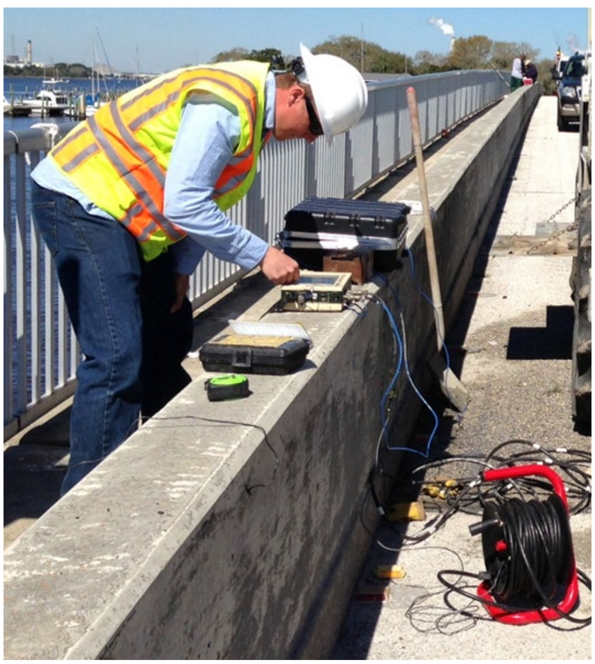


Figure 51. Parallel seismic test equipment.

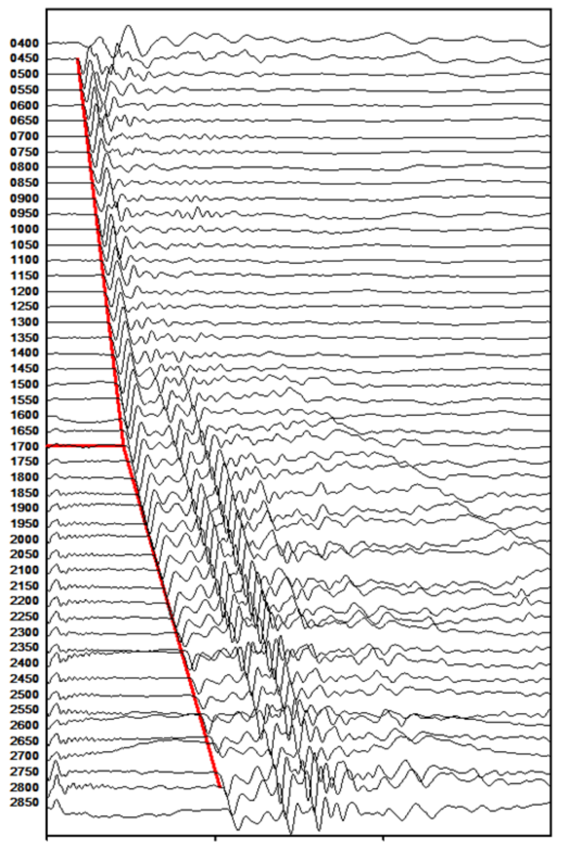


Figure 52. Parallel seismic test results.

For more information – https://www.grlengineers.com/services/eef/

4.18 Length Inductive Test Equipment (LITE) services are provided by GRL to assess the length of unknown steel foundations (Figure 53). The test can be performed on steel sheet piles, H-piles, pipe piles, cased portions of drilled shafts, and in some instances highly reinforced drilled shafts. The LITE probe is lowered into a PVC cased drilled hole located within 18 inches of the foundation (Figure 54). The LITE detects whether metal is present or not present with the effective radius. Data interpretation is straightforward. Provided the probe senses the proximity of metal, it will display a high voltage. Once the LITE probe is below the steel or steel reinforced foundation depth, the absence of detected metal will cause a zero or negative value which can be used to ascertain the foundation length (Figure 55).

Figure 53. LITE System.

Figure 54. LITE probe in PVC borehole.

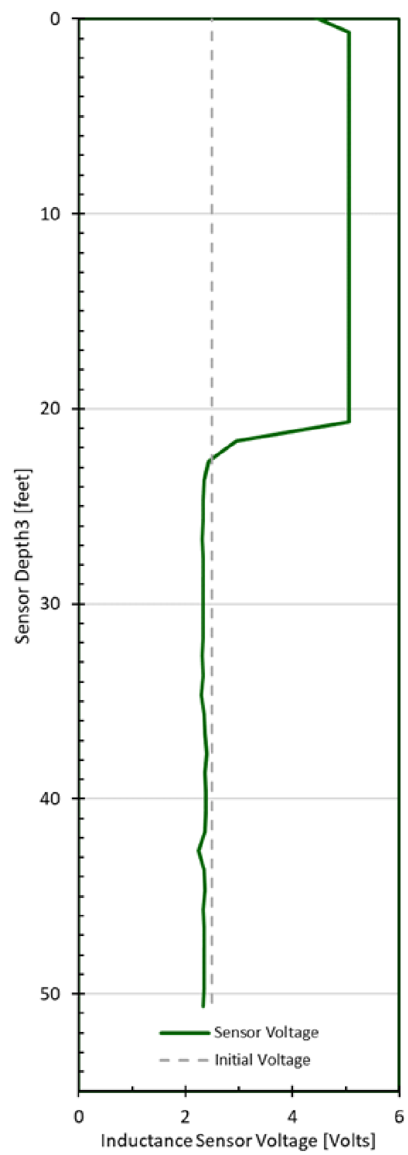


Figure 55. LITE Results.

For more information – https://www.grlengineers.com/services/eef/

4.19 Other Consulting Services - GRL also offers other consulting services such as comprehensive training of deep foundation testing methods to engineers worldwide, and review of deep foundation test results obtained from third parties.

5.0 EQUIPMENT

GRL uses state-of-the-art testing equipment for all its service offerings. Our test equipment includes:

Dynamic Pile Monitoring

Pile Driving Analyzer Model 8G (PDA). - For dynamic pile monitoring services, GRL engineers use the Pile Driving Analyzer Model 8G with a selection of WiFi, Bluetooth, or cabled connection between the PDA and the pile top gages. Data from multiple external or embedded gage locations can also be simultaneously acquired.

Dynamic Load Testing

Pile Dynamics Analyzer- Dynamic Load Tester (PDA-DLT) - For dynamic load testing services, GRL uses the Pile Driving Analyzer Model 8G with the DLT software package. For DLT applications, data from multiple external or embedded gage locations can also be simultaneously acquired. This software package also readily accommodates our APPLE drop weight systems and top transducers or APPLE load cells.

APPLE Dynamic Load Test System (APPLE) - APPLE dynamic load test systems include a guide frame, a modular ram and a free release mechanism. The rams of some APPLE systems may be instrumented, or a load cell may be used to simplify force measurements. Available ram weights range from 1 to 80 tons. A dynamic load test capacity of up to 4000 tons in soil and 8000 tons in rock can be mobilized by these systems. ($R_{ultimate}$ = ram weight / 0.02 in soil, and ram weight / 0.01 in rock)

APPLE Load Cells - For dynamic load tests, a top transducer or load cell can facilitate testing speed as well as improve the quality of the collected data. GRL has 12 load cells ranging from 10 to 36 inches in diameter with a corresponding maximum force range from 400 to 14,000 kips. The load cell size and maximum force range is matched to the deep foundation size and capacity.

Bi-Directional Load Testing

GRL-Cells for Conventional Bi-Directional Static Load Tests - GRL Engineers developed and use the GRL-Cell, manufactured in Cleveland, OH. GRL-Cells are available in a multitude of sizes with jack capacities of 180, 400, 650, 750, 850, 1100, 1600, 2000, 2500, and 3500 tons. All cells have a standard stroke of nine inches. Bi-directional cells can be used individually, in groups, or at multiple elevations to satisfy test load requirements.

Top-Loaded Bi-Directional Static Load Tests – GRL has a top load assembly system, an inventory of hydraulic jacks, as well as hi-strength shaft and base mobilizer bars to facilitate performing top loaded bi-directional tests.

Static Load Testing

Static Load Test Beams – As part of our static load testing services, GRL offers load test beams with a maximum beam capacities of 330, 600, and 1200 tons.

Jacks, Pumps, Load Cells and Spherical Bearing Plates - GRL maintains an inventory of jacks, pumps, load cells. and spherical bearing plates to support static load testing projects. Single jack capacities are available from 10 to 1100 tons for solid jacks and from 30 to 300 tons for center hole jacks. Jack capacities of up to 1600 tons can be provided with sufficient advance notice or with multiple jack configurations.

ShapeArray – For lateral load tests, GRL offers ShapeArrays of up to 100 feet in length for monitoring the deflected foundation shape versus depth as a function of the applied lateral load.

Static Load Tester (SLT) - For static and bi-directional load tests, GRL uses the Static Load Tester data acquisition system. This system consists of a SLT tablet and multiple SLT data logger boxes. Each data logger has twelve analog and four digital channels. Multiple data logger boxes can be connected to accommodate greater data acquisition needs. A wired or WiFi connection can be used between the data loggers and the SLT tablet. Real time test data can also be viewed in the Cloud by authorized off-site personnel.

Integrity Testing

Thermal Integrity Profiling (TIP) - For thermal integrity projects, GRL uses Thermal Wire cables connected to a TAG and TAP-EDGE data collectors to evaluate concrete or grout integrity. The TAG unit uses WiFi to collect the data from each TAP-EDGE unit and pushes the collected data to the Cloud. This system significantly reduces GRL's analysis and reporting time as the Cloud data is regularly updated allowing data analysis to begin as soon as the concrete or grout has reached its peak temperature. Real time test data can also be viewed in the Cloud by authorized off-site personnel.

Cross-Hole Analyzer (CHA) - For crosshole sonic logging, GRL engineers use the Cross-Hole Analyzer, Model CHAMP-Q, to evaluate drilled shaft, barrette, or diaphragm wall panel concrete quality and integrity. The CHAMP-Q is a multi-probe system that allows up to four transceiver probes to be pulled simultaneously allowing six profiles to be tested with one pull. The CHAMP-Q can also be deployed using two transceiver probes where access is difficult, or where test setup space or conditions are limiting.

Gamma Gamma Logging (GGL) – For Gamma Gamma Logging tests, a probe containing a low-level radioactive source at the probe tip and a shielded detector located 15 inches away is lowered into a PVC access tube to assess the concrete density surrounding the access tube. Drilled shafts are prepared by attaching 2-inch outer diameter, Schedule 40, PVC access tubes to the steel reinforcing cage prior to cage insertion into the foundation excavation and concrete placement. The access tubes should be located at least 2-inches from longitudinal reinforcement, with several tubes installed for ample coverage.

Pile Integrity Tester (PIT) - Low strain integrity testing projects are performed with the Pile Integrity Tester model PIT-Q, or PIT-QFV. These systems include accelerometers and instrumented hammers. Depending on whether acceleration or acceleration and force data is collected, data can be processed using either the sonic pulse echo method or the transient response method.

Drilled Shaft Services

Shaft Verticality, Radii, Profile, and Excavated Hole Volume - GRL uses the **SH**aft **A**rea **P**rofile **E**valuator or SHAPE device to assess shaft verticality, radii, profile, and excavation volume. The 80 lb SHAPE device can quickly be attached to the drill rig Kelly bar or independently supported via a motorized winch system for testing.

Base Cleanliness – For drilled shaft base cleanliness evaluations, GRL uses the **S**haft **QU**antitative **I**nspection **D**evice or SQUID. This 475 lb device quickly attaches to the drill rig Kelly bar.

Unknown Foundations

Parallel Seismic – For unknown foundation length tests, GRL uses a modified PIT-QFV unit and software package to perform parallel seismic testing. This system includes an instrumented hammer and a hydrophone.

Length Inductive Test Equipment (LITE) – For unknown steel foundation length evaluations, GRL uses the LITE system with its inductive sensor and volt meter.

Pile Integrity Tester (PIT) - For unknown foundation length tests, GRL also uses the Pile Integrity Tester model PIT-Q or PIT-QFV, and its associated hammers and accelerometers.

6.0 CONTACT INFORMATION

Corporate Office
GRL Engineers, Inc.
30725 Aurora Road
Solon, OH 44139
Tel: (216) 831-6131
Fax: 216-831-0916
Email: info@grlengineers.com

California Office (Southern) 516 Crane Blvd Los Angeles, CA 90065 Tel: (213) 200-4956 Email: GRL-CA@grlengineers.com	**California Office (Northern)** 4340 Redwood Highway, Suite F-110 San Rafael, CA 94903 Tel: (213) 200-4956 Email: GRL-CA@grlengineers.com
Colorado Office 14405 West Colfax Ave., Suite 105 Lakewood, CO 80401 Tel: (303) 666-6127 Email: GRL-CO@grlengineers.com	**Florida Office** 8000 South Orange Avenue, Suite 225 Orlando, FL 32809 Tel: (407)-826-9539 Email: GRL-FL@grlengineers.com
Georgia Office 2880 Cobblestone Drive Cumming, GA 30041 Tel: (678) 233-1435 Email: GRL-GA@grlengineers.com	**Hawaii Office** PO Box 11111 Honolulu, HI 968928 Tel: (808) 445-3504 Email: GRL-HI@grlengineers.com
Illinois Office 6677 Lincoln Avenue, Suite 333 Lincolnwood, IL 60712 Tel: (847) 213-0592 Email: GRL-IL@grlengineers.com	**Louisiana Office** 1385 Constance Street New Orleans, LA 70130 Tel: (985)-640-7961 Email: GRL-LA@grlengineers.com
Massachusetts Office PO Box 1285 Haverhill, MA 01831 Tel: (978) 992-7968 Email: GRL-MA@grlengineers.com	**North Carolina Office** 4350 Main Street, Suite 271 Harrisburg, NC 28075 Tel: (704) 456-7215 Email: GRL-NC@grlengineers.com
Ohio Office 30725 Aurora Road Cleveland, OH 44139 Tel: (216)-831-6131 Email: GRL-OH@grlengineers.com	**Pennsylvania Office** 2175 Macdade Boulevard Holmes, PA 19043 Tel: (610) 459-0278 Email: GRL-PA@grlengineers.com
Texas Office 1420A Stonehollow Drive Kingwood, TX 77339 Tel: (281) 706-8202 Email: GRL-TX@grlengineers.com	**Washington Office** 23015 SE 270th Street Maple Valley, WA 98038 Tel: (425)-381-9690 Email: GRL-WA@grlengineers.com