Independent assessment of toe and skin capacities in near real-time using top and toe instrumentation

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ABSTRACT

The conventional practice of estimating the capacity of deep foundations using dynamic load testing is done by obtaining data from external sensors that are bolted near the top of the pile. The toe and skin components are extracted from the total estimated capacity using signal matching analysis with several assumptions. The results of signal matching analysis are highly dependent on the user performing the analysis and the program utilized. Therefore, the estimated toe and skin capacities are not known with certainty. Also, in top only instrumentation the actual condition of pile toe is only approximately deduced from the top instrumentation data. To overcome these uncertainties, Florida Department of Transportation sponsored research with University of Florida led to the development of EDC (Embedded Data Collector) with sensors embedded at the pile top and pile toe. Using state-of-the-art FDOT (Florida Department of Transportation) method of analysis of the top and toe instrumentation data collected, it is now possible to independently determine the toe and skin capacity accurately in near real-time. In the FDOT method Toe capacity is calculated using 'Energy Conservation' principle with toe gauge data and, Skin capacity is calculated using 'Segmental Skin Friction' approach with top and toe gauge data as boundary condition. The benefits of FDOT method analysis using top and toe EDC instrumentations includes a more efficient design, improved quality, faster construction process. FDOT method of analysis results along with superposition principle to determine the optimum capacity of piles were demonstrated for a bascule bridge built over the Miami River on state road 968, Florida, USA where uplift was a critical design aspect of the bridge.

Keywords: DLT, FDOT method, EDC, Embedded Sensors, Driven Pile, Capacity Superposition

1 INTRODUCTION

Dynamic Load Testing is the conventional practice for determining the capacity and integrity of piles. Dynamic load testing option is very practical because it is non-destructive testing, and it takes less time and effort as compared to conventional Static Load Testing (SLT). The exponential growth in computational power and new disruptive innovations in sensor technology led the way to more advanced dynamic testing options.

2 EVOLUTION OF FOUNDATION DYNAMIC TESTING

Dynamic Load Testing (DLT), also known as High Strain Dynamic Testing (HSDT) has evolved over the last few decades from top only external bolt-on gauges to more sophisticated top and toe embedded gauges. Top external bolt-on gauges are generally referred as External Gauges; Top and toe embedded gauges as Embedded Data Collectors (EDC). The evolution of dynamic testing instrumentation and respective methods of analyses is shown in Fig. 1.

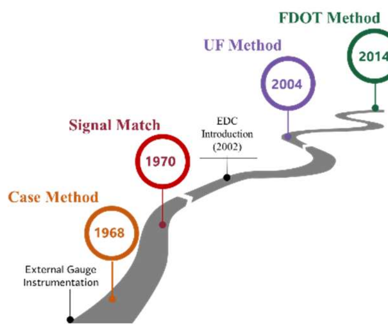

Fig. 1. Evolution of HSDT instrumentation and, methods of analyses (Putcha et al., 2018).

2.1 External gauges

The External Gauge system generally consists of strain gauges and accelerometers attached near the top of the pile, generally 180 degrees apart (opposite faces). The sensors are bolted into the pile for testing as shown in Fig. 2. For data collection sensors are typically connected through cable to the data acquisition system. Case Method of analysis along with signal matching is used to estimate pile capacity using this approach.

Fig. 2. Typical external gauges installed on concrete piles.

2.1.1 Case method

The Case equation was developed for external bolt on gauges under the assumption that the damping acts only at the toe of the pile. But this is not true since considerable damping occurs also on the pile skin. Case method is generally used in the field to estimate total capacity with an approximate damping value in the case equation.

The assumption limiting damping response to the toe and completely ignoring inertial component during dynamic testing makes case method results less reliable. In some scenarios such as very long piles with small toe movement during dynamic testing, case method might produce inaccurate results.

2.1.2 Signal matching

Signal Matching combines measured field data (top gauges) with pile wave equation solution to estimate the pile's static bearing capacity. This approach requires several soil parameters to be changed arbitrarily until measured and calculated pile top variables reach a reasonable match. Therefore, the results of signal matching analysis are highly dependent on the user performing the analysis and the program utilized. Consequently, the separation of toe and skin capacities are not known with certainty.

Several limitations of top external gauge methods including the lack of data at the pile toe and the consequent flawed methods of providing the pile capacity and pile integrity led to the development of Embedded Sensors.

2.2 Embedded data collectors (EDCs)

The EDC system includes strain gauges, accelerometers, and temperature sensors embedded at the top and toe of the pile. The sensors are mounted on a frame that is placed inside the pile reinforcement prior to casting. Strain gauges are aligned to the center of pile cross section such that it is in line with the central longitudinal axis of the pile and accelerometer is offset by couple of inches from the strain gauge as shown in Fig. 3.

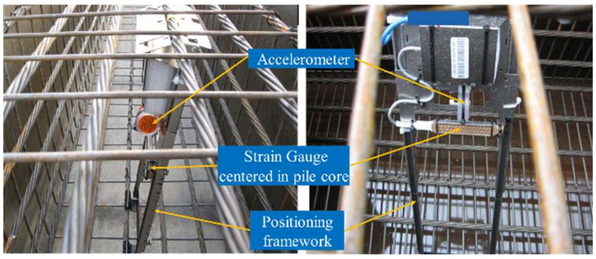

Fig. 3. EDC sensor pack installed prior to casting.

Data collection is done with a wireless radio transmitter, a receiver and laptop software to analyze the data in real time (Fig. 4).

Fig. 4. EDC sensor pack radio transmitter, acquisition system.

There are no external wires involved in EDC system of dynamic testing and the need for climbing the lead to install instrumentation is eliminated. This enhances safety and speeds up construction. Data measured from the top and toe sensors are analyzed to measure the driving stresses and to provide independent toe and skin capacities in real-time for every hammer blow. With the introduction of EDCs more advanced dynamic test data analysis methods i.e., UF method and FDOT method were developed.

2.2.1 UF Method

UF Method is an advancement over the Signal Matching method used in the HSDT process. The UF method uses both top and toe instrumentation data and calculates total static capacity using dynamic damping factor for every blow, and toe capacity using unloading point method in real-time.

2.2.2 FDOT method

This state-of-the-art dynamic testing method developed recently determines independently toe and skin capacities for each hammer blow based on the EDC - top and toe gauge data. Total capacity in FDOT method is determined as sum of independently calculated toe and skin capacities. Embedded sensors data collected from the toe gauge is analyzed using 'Energy Conservation' principle for toe capacity calculation and 'Segmental Skin Friction' approach is used with top and toe gauge data as boundary conditions for skin capacity calculation (Tran et al., 2012).

<u>Independent toe capacity</u>

The pile segment beneath the toe gauges and the soil mass moving along the segment (pile-soil mass) is modelled as a single degree of freedom (SDOF) system. The dynamic force and energy measured at toe gauge during hammer blow is equal to sum of inertial, damping, and static responses at the toe of the pile (force, energy equilibrium). The SDOF system models a nonlinear static capacity mobilization at toe and viscous damping dissipation to the surrounding soil.

By solving the energy equilibrium over the time domain using Genetic Algorithm Inversion, which is a global optimization method, the unknown parameters (mass, damping, and nonlinear stiffness) and the static toe capacity of the pile for that blow are estimated.

Independent skin capacity

The soil–pile system is modeled as a combination of nonlinear skin friction mobilization at several pile segments and different damping factors acting on each of those segments. Monitored strains and accelerations at the top and toe of the pile were used to find the unknowns in each segment by solving the wave equation. The segments were modelled with nonlinear skin friction and radiation damping dissipation with the surrounding soil mass.

The Genetic Algorithm Inversion is used to solve for unknown parameters in the skin model by matching the estimated and measured particle velocities at the top and toe of the pile. The sum of all the segment's static component is the FDOT skin capacity of the pile for that blow.

3 BENEFITS OF FDOT METHOD

Embedded instrumentation at the pile toe and pile top for the dynamic testing successfully addresses the many limitations of conventional top only instrumented methods. Toe instrumentation has its own set of advantages which monitors the toe in real-time, and it includes measuring actual stresses, displacements and monitoring physical parameters such as prestress change at the toe.

3.1 Optimum capacity by superposition

The need for separating toe and skin capacity is due to the dichotomy of optimum toe and skin mobilizations occurring at different times and for different hammer blows of pile driving operations (NCHRP Synthesis 418, 2011). The optimum toe mobilization is achieved during End of Initial Driving (EOID) and optimum skin mobilization occurs during Beginning of Restrike (BOR) due to pile-soil freeze or relaxation, Fig. 5. illustrates this process.

Total pile capacity is the sum of the optimum toe and optimum skin capacities which are mobilized at different phase of driving and sum of these two independent mobilized capacities is the optimum pile total capacity. FDOT method results thus addresses the dichotomy in HSDT.

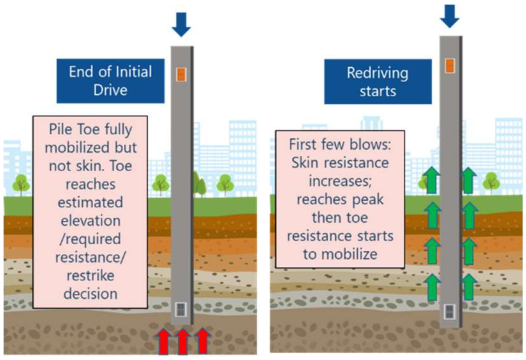

Fig. 5. End of Initial Drive (EOID) vs Beginning of Restrike (BOR) capacity mobilization in pile.

3.2 Freeze, relaxation analysis for toe and skin

The time dependent capacity gains or loss due to soil pore water dissipation, settlements and consolidation after the pile installation can be ascertained accurately with FDOT method of analysis. Such change in capacity can be measured and studied for toe and skin separately due to the separate determination of pile toe and skin mobilizations during EOID and BOR phases of pile driving.

3.3 Predrill / Preform zone skin contribution

By comparing EOID and BOR skin capacity distribution along the pile one can estimate predrilled/preform zone skin component mobilization occurring during BOR in addition to total skin freeze. This is possible due to the segmented calculation approach for skin capacity in FDOT method that calculates skin capacity mobilized in each segment modeled along the pile.

3.4 Use of different resistance factors for toe and skin

Since the toe and skin capacity components are calculated independently, the pile can be designed for each of the two components separately with different Resistance Factors (safety factor). One example where this approach leads to more efficient design is in the scour prone areas. Independent assessment of toe and skin capacities enable one to efficiently address the skin component variability without underestimating the toe.

3.5 Uplift design

Accurately determining skin capacity mobilized is crucial in the case of uplift piles because only the skin capacity will resist the uplift forces and ensure the serviceability of structures built on those piles. FDOT method calculates skin capacity parameters for every pile segment modelled and improves the confidence in uplift designs.

3.6 SLT comparison

FDOT method analysis calculated T-Z (skin friction vs settlement) and Q-Z (toe friction vs settlement) data independently for each blow. By combining T-Z curve for side friction and Q-Z curve for toe response when each mobilizes optimally, one can plot total pile load vs displacement curve. These results can be compared with SLT toe and skin loads and settlements with reliability.

The benefits of independent assessment of toe and skin capacities in FDOT method using top and toe EDC instrumentations include efficient design, improved quality, and faster construction process. It has been implemented in many projects across USA. One such project was a bascule bridge built over the Miami River on state road 968, FL. FDOT method analysis results and few advantages of it were discussed next as a case study.

4 CASE STUDY

A Bascule Bridge (also referred to as a drawbridge or a lifting bridge) is constructed across the Miami River at SW 1st street, State Road 968, Florida state, USA. The bridge has two piers (pier 2 and pier 3) constructed on the riverbed and two end bents on either side of the piers. Adjacent to pier 2 a freestanding foundation is constructed to support a control house for the bridge operating machinery.

Soil below riverbed consists of sand, silty sand with trace limestone fragments in them. The bearing layer is sandy limestone encountered at 30 to 40 ft below riverbed. All the piles were 24-inch square precast prestressed concrete piles except for end bent 1 which was built with micro piles. A total of 182, 24-inch piles were driven as part of this project and each one was instrumented with top and toe EDC. Pier 2 and Pier 3 has an uplift capacity requirement of 150 kips/pile as per design and has 72 and 73 piles respectively.

Fig. 6. SR968 bascule bridge over Miami river project site.

Few days after initial drive of pile, a restrike (approx. 10 blows for each pile) were performed on several selected piles from each pier (17 piles from pier 2, 18 piles from pier 3). On Average there was 12 days' time interval between the initial drive and restrike. FDOT analysis is performed on these piles for last five Initial Drive blows and first five Restrike blows. The Independent Skin Capacity calculated are presented in Table 1.

Significant skin capacity gain is observed during restrike as compared to EOID. Restrike skin capacity mobilized is the criteria to evaluate the pier's total uplift capacity. For Pier 2 mean of all the 17 pile's skin capacity mobilized during restrike is 359 kips/pile. For Pier 3 mean of all the 18 pile's skin capacity mobilized during restrike is 414 kips/pile.

Table 1. SR 968 Bascule bridge FDOT skin results Pier 2 and 3.

S No	FDOT Skin Capacity (kips)					
	Pier 2			Pier 3		
	Pile No	EOID	BOR	Pile No	EOID	BOR
1	1	145	301	2	48	333
2	4	91	615*	6	61	411
3	6	212	340	21	28	277
4	9	164	269	25	222	459
5	11	117	308	28	48	527
6	17	87	303	36	27	367
7	21	151	405	37	34	324
8	28	28	504	38	83	383
9	32	79	345	39	34	447
10	36	126	395	41	63	309
11	41	78	297	44	261	553
12	43	172	328	45	219	584
13	44	98	287	46	99	486
14	60	140	296	50	216	370
15	62	157	455	53	62	288
16	63	22	413	57	75	431
17	65	148	493	68	23	499
18	-	-	-	70	62	407
Mean		119	**359**		93	**414**
STD		51	76		78	91
Avg - STD		68	283		14	323

EOID capacity for every pile indicated is average of last 5 blows, BOR capacity for every pile is average of restrike skin friction mobilized, Mean is for all the piles considered in a pier for EOID and BOR instances, STD – Standard Deviation, * - outlier eliminated from the averaging (minimum top movement is observed during restrike in this pile).

In Both Piers the skin capacity mobilized in each pile tested were found to be more than the design requirement of 150 kips/pile. Even if one were to reduce 'one standard deviation of the skin capacity distribution' from the mean for a conservative approach, pier 2 would still offer 283 kips/pile and pier 3 would offer 323 kips/pile uplift capacity which are still considerably more than the design requirement.

An independent analysis for uplift forces at the bottom of the seal mat due to water level difference between the cofferdam and normal river water level was calculated. An uplift force of 194 kips/pile for pier 2 and 165 kips/pile for pier 3 was expected to act at the bottom of the seal mat, considering a conservative 35 ft hydrostatic water head and a safety factor of 1.85 on the uplift force.

Uplift resistance of the pier foundations was of critical significance for this project, and reliable skin capacity determination was important. Unlike conventional DLT methods, only the state-of-the-art FDOT method calculates skin component independently and ensures the accuracy of it. FDOT Method results ensured the proper anchorage for both pier 2 and pier 3 since uplift capacity available (table 1) were considerably higher than the calculated requirement for each pier.

Additionally, second set check was performed on few piles to ensure the consistency in skin capacity gained, and marginal increment in skin friction capacity was noted for these piles as compared to first restrike.

In this project conventional top external signal matching is also performed on few piles. For Pile 24 in pier 3, signal matching resulted in damping constant of 1.09. But the recommended range is 0-1 depending on the pile toe soil layer. The final report was made with reducing the damping constant to 0.9 to fit into the range. This is one of the many practical limitations of top external method analysis.

Another advantage of FDOT Method analysis is the ability to determine optimum pile capacity by superposition of independently calculated Toe and Skin capacity. From the project two pile's analysis results were used to demonstrate this next.

5 CAPACITY SUPERPOSITION

5.1 Pier 2 Pile 43

FDOT method analysis result toe and skin capacities are plotted in Fig. 7. The respective toe and skin settlements and hammer energy imparted to the pile are plotted in Fig. 8. Blow numbers 977 to 986 are the 10 EOID blows, and 987 to 994 are the 8 Restrike blows performed on the pile. Restrike was conducted 11 days after EOID.

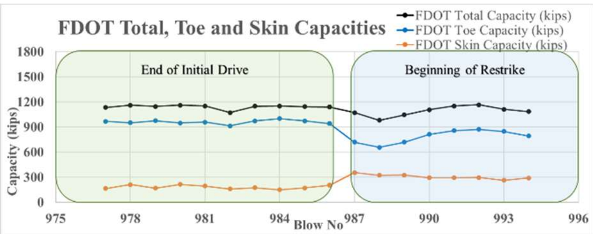

Fig. 7. Pier 2 Pile 43 FDOT capacities at EOID and BOR.

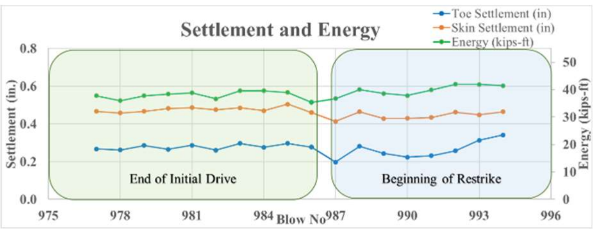

Fig. 8. Pier 2 Pile 43 Settlements and energy at EOID and BOR

If one were to analyze only the Total Capacity of each blow it would seem the pile has lost 52 kips from EOID average of 1141 kips to BOR average of 1089 kips. It is imperative to investigate the mobilized toe and skin components separately along with their respective settlements to understand the true pile behavior. It can be observed that full mobilization of toe and skin capacities does not occur in a single blow or at same phase of driving.

Toe capacity is optimally mobilized during EOID, and does not completely mobilize during BOR. It is evident when EOID toe settlements of 0.28 in. is compared against BOR toe settlement of 0.23 in, toe does not mobilize during initial BOR blows. For the later Restrike blows the toe settlement and toe capacity starts to mobilize gradually as driving continues. At EOID blow 984, toe capacity mobilizes optimally at 1001 kips.

By comparing EOID and BOR skin capacities, significant skin freeze is evident and optimum mobilization of skin occurs during BOR initial blows. BOR blow 987 mobilizes maximum skin friction of 354 kips. Superposition logic for this pile to determine 'Optimum Total Capacity' is given in table 2.

Table 2. Capacity Superposition Pier 2 Pile 43

	Blow no	Toe Capacity (kips)	Skin Capacity (kips)	Total Capacity (kips)
EOID	984	**1001**	150	1151
BOR	987	718	**354**	1072

Optimum Pile Capacity = Toe optimum mobilized at EOID (blow 984) + Skin maximum mobilized at BOR (blow 987), and this is equal to 1001+354 = **1355 kips**.

Total Capacity of each individual blow at EOD and BOR is considerably less than the calculated Optimum Pile Capacity of 1355 kips, and the maximum for an individual blow is 1166 kips (blow 992). If independently calculated toe and skin components were not available to superimpose, the total capacity would have been underestimated as 1166 kips instead of optimum capacity of 1355 kips.

5.2 Pier 3 Pile 25

FDOT method analysis toe and skin capacities are plotted in Fig. 9. The respective toe and skin settlements and hammer energy imparted to the pile are plotted in Fig. 10.

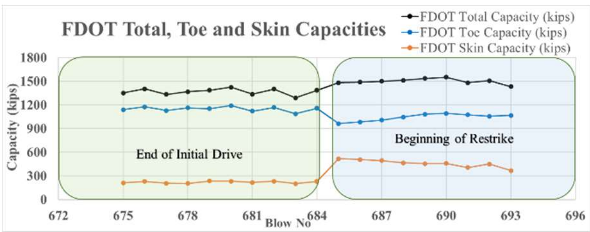

Fig. 9. Pier 3 Pile 25 FDOT capacities at EOID and BOR.

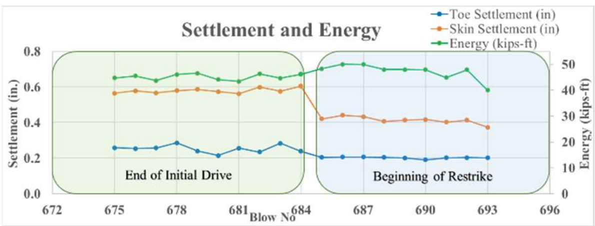

Fig. 10. Pier 3 Pile 25 Settlements and energy at EOID and BOR

Blow numbers 675 to 684 are the 10 EOID blows, and 685 to 693 are the 9 Restrike blows performed on the pile. Restrike was conducted 21 days after EOID. Toe optimally mobilizes at EOID blows and skin optimally mobilizes during BOR initial blows. Superposition logic for this pile to determine 'Optimum Total Capacity' is given in table 3.

Table 3. Capacity Superposition Pier 3 Pile 25.

	Blow no	Toe Capacity (kips)	Skin Capacity (kips)	Total Capacity (kips)
EOID	680	**1192**	232	1424
BOR	685	963	**517**	1481

Optimum Pile Capacity = Toe optimum mobilized at EOID (blow 680) + Skin maximum mobilized at BOR (blow 685), and this is equal to 1192+517 = **1709 kips**. The maximum Total Capacity of an Individual blow is 1550 kips (blow 690), which is 159 kips less than the pile's optimum capacity calculated using superposition principle.

Thus, independently calculated toe and skin results in FDOT Method Analysis can be used to perform superposition and estimate optimum pile capacity as demonstrated.

6 CONCLUSIONS

Introduction of EDC at the pile top and toe led the way to further advance dynamic testing for deep foundation. By using the top and toe data collected in advanced data analysis methods such as UF Method or FDOT Method addresses many limitations and uncertainties of conventional top external instrumented methods.

FDOT Method of analysis is the state-of-the-art method which independently calculates toe and skin capacities using top and toe EDC sensors data collected. The Total Capacity in FDOT method is determined as sum of independently calculated toe and skin capacities. Due to the independent nature of toe and skin calculation several benefits can be realized using FDOT Method results. These include

i. Optimum Pile Capacity – Optimum pile capacity is estimated using superposition principle on optimum mobilized toe (EOD) and skin components (BOR), thereby addressing the dichotomy in HSDT.
ii. Freeze or Relaxation – Capacity gain or loss due to soil pore water dissipation, settlements and consolidation can be accurately ascertained for both skin and toe components.
iii. Predrill/Preform Contribution – By comparing EOID and BOR skin capacity distribution one can estimate predrilled/preform zone skin component mobilization occurring during BOR in addition to total skin freeze.
iv. Use of Different Resistance Factors – the pile can be designed for each of the two capacity components separately with different factors with confidence.
v. Scour Design – Efficiently address scour instances by applying safety factor only to skin, by doing so not undermining toe capacity.
vi. Efficient Uplift Design – due to increased reliability of independent skin capacity calculated.
vii. Comparability with SLT Results – toe and skin results can be compared readily with SLT toe and skin loads and settlements.

The use of EDC in piles measures stresses at the top and toe of the pile and monitors pile integrity in real-time during pile drive, which enables one to take necessary corrective action while driving before any potential pile damage. The benefits of independent assessment of toe and skin capacities in FDOT Method using top and toe EDC instrumentations are many culminating in efficient design, improved quality, and faster construction process.

REFERENCES

1) ASTM Standard D4945 (2017): Standard Test Method for High-Strain Dynamic Testing of Deep Foundations, *ASTM International*, BOS Vol 04.08, DOI: 10.1520/D4945-17.

2) Khiem T. Tran., Michael McVay., Rodrigo Herrera., and Peter Lai. (2011): A new method for estimating driven pile static skin friction with instrumentation at the top and bottom of the pile; *Soil Dynamics and Earthquake Engineering*, Volume 31, Issue 9, 1285-1295.

3) Khiem T. Tran., Michael McVay., Rodrigo Herrera., and Peter Lai. (2012): Estimating Static Toe Capacity of Driven Piles with Bottom Pile Instrumentation, *Canadian Geotechnical Journal*, vol 49, 381-393.

4) Khiem T. Tran., Michael McVay., Rodrigo Herrera., and Peter Lai. (2012): Estimation of nonlinear static skin friction on multiple pile segments using the measured hammer impact response at the top and bottom of the pile; *Computers and Geotechnics*, vol 41, 79-89.

5) Michael McVay., and Wassman, S.J. (2013): Embedded data collector (EDC) evaluation phase II – comparison with instrumented static load tests - *final report to FDOT*.

6) NCHRP Synthesis 418 (2011): Developing Production Pile Driving Criteria from Test Pile Data. *Transportation Research Board*, *USA*.

7) Sastry Putcha., Aneesh Goly., Kumar Allady., and Vamshi Vemula. (2018): FDOT Method of Independent Separation of Toe and Skin Capacities of Driven Concrete Pile with Embedded Sensors; *Deep Foundation Institute 43rd conference*, publication 1045.