CONVERTING STRAIN TO INTERNAL FORCE IN INSTRUMENTED STATIC LOAD TESTS ON CAST-IN-PLACE GROUTED PILES

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ABSTRACT

Static load tests on cast-in-place grouted piles are often implemented to characterize surrounding geomaterial response to applied loads to further evaluate foundation design parameters. Embedded instrumentation, such as strain gauges, are advantageous for assessing the internal force distribution along an embedded pile's length, and in turn for calculating external resisting forces. Since external resisting forces cannot be measured directly, several pile properties must be determined for appropriate calculation of foundation design values. Critically, pile geometry and composite-section elastic modulus at each strain-gauge level must be reasonably assessed. Pile geometry (in particular total cross-sectional area, A) along the embedded length is not necessarily known, but is often estimated from installation records and/or some quality assurance methods. The grout elastic modulus, E, is very likely not known to a reasonable degree of certainty, being commonly estimated from laboratory tests conducted on grout samples. Therefore, significant shortcomings and a large degree of uncertainty remains in existing estimation methods for these properties for grouted piles. The Incremental Rigidity method uses applied test loads and measured strains to determine the relationship between axial rigidity, EA, and measured strain at individual interpretable strain-gauge levels. This in turn determines a direct relationship between measured strains and internal forces. This method provides significant improvement in calculating axial rigidity directly from static load test measurements through an internal calibration sequence and engineering justification. Shortcomings in existing methods to determine axial rigidity in grouted piles are discussed. Several case histories are presented to demonstrate critical details and significant benefits in applying the Incremental Rigidity method for converting measured strain to calculated internal force on cast-in-place grouted piles. Recommendations for improving industry standards in implementing instrumented static load tests on cast-in-place grouted piles are presented.

INTRODUCTION

Drilled deep foundations involve soil/rock removal using various drilling tools, and subsequent placement of concrete or grout which are cast in place, and oftentimes reinforced with steel. There are many drilling methods practiced around the world. Some methods are more commonly used in specific regions depending on the subsurface conditions, local contractor experience, and foundation loading demands. Recent advances in continuous flight augers, drilling rigs, grout mixes, and measurements while drilling make grouted deep foundations particularly advantageous. Some grouted deep foundations include augered cast-in-place ("ACIP") piles, drilled displacement piles ("DDP"), micropiles, and rigid inclusions ("RI").

Most grouted cast-in-place piles involve soil removal with a hollow-stem, continuous-flight auger, and added displacement segments for DDPs. Grout is then pumped to the auger base through the hollow stem during auger removal. This allows for soil stabilization without the need for additional casings or stabilizing drilling fluid. As with many drilled deep foundations, non-uniformities in the geometry and foundation material properties may arise due to the potential for bulging and soil inclusion during the installation process. Variability of grout modulus can, and does, also vary by location within a pile (i.e., grout is not a uniform material). Additionally, new grout mix designs are continuously developed for improved workability and greater compressive strengths. As technological advancements proceed, and grouted cast-in-place piles are capable of being installed quicker, in more complex subsurface conditions, and to higher structural and geotechnical capacities, quality assurance remains a critical aspect of installation and design.

Quality assurance methods during installation of grouted cast-in-place piles are limited, particularly due to the grout placement methodology and limitations owing to smaller pile sizes compared to larger drilled shafts. Measurements while drilling such as grout pressures, rotation, and auger torque are valuable, but may not provide adequate information regarding intrinsic foundation strength properties or accurate depiction of geometry versus depth. To some degree, low-strain dynamic pile integrity testing can assess major anomalies after the pile is installed, but is often not the sole means of integrity assessment due to several limitations. Thermal Integrity Profiling ("TIP™") incorporates embedded thermal sensors along steel reinforcement, which is then advanced into the grout-filled hole. As the grout cures, an exothermic reaction occurs between water and the cementitious materials which generates heat. Non-uniformities in the temperature-depth profile are then semi-empirically correlated to the pile's geometry versus depth. When used in conjunction with foundation installation records and additional proper engineering justification, TIP provides an effective means of assessing grout quality and potential geometric changes versus depth (Belardo et al., 2021). Piscsalko (2014) presents other non-destructive testing methods for various pile types. However, integrity testing methods do not confirm required bearing capacity, nor do they provide any direct measurement of the size and magnitude of potential anomalous zones or localized grout strength or modulus properties.

Static load testing is often implemented to assess the load-bearing capacity of grouted cast-in-place piles. Conventional compressive or tensile load tests typically involve applied test load, Q, at the pile head via a hydraulic jack, and the load reacts against a series of steel beams affixed to reaction piles or cribbing. Bi-directional static load testing ("BDSLT") is a cost- and time-saving alternative where the hydraulic jack is embedded within the deep foundation, and load is applied in both an upward and downward direction (i.e., the foundation itself acts as reaction to test load). Displacement transducers, telltale assemblies, and strain gauges are sometimes embedded in the foundation to determine additional test parameters, including resistance distribution in side-shear and end-bearing resistance.

Strain gauges can be installed within the reinforcing cage at the estimated locations of major strata changes, spaced equally along the embedded pile length, or in some other pattern. The measured internal pile strain, ε, is then converted to internal force, F, using the relationship $F = \varepsilon E_{PILE} A_{PILE}$. The term $E_{PILE} A_{PILE}$ is defined by classical mechanics of materials as axial rigidity (herein simply referred to as rigidity). The pile's composite-section elastic modulus, E_{PILE}, and total cross-sectional area, A_{PILE}, at each strain-gauge location must be reasonably estimated. Pile geometry along the embedded length is not necessarily known, but estimated from installation records and/or some quality assurance methods. The grout elastic modulus, E_{GROUT}, is very likely not known to a reasonable degree of certainty, being commonly estimated from laboratory tests conducted on grout samples (i.e., semi-empirical correlations to test cylinder or cube compressive strength, f'_c, using relationships established in ACI, 2014). Therefore, significant shortcomings and a large degree of uncertainty remain in existing estimation methods for these properties of grouted piles.

The Incremental Rigidity ("I.R.") method uses applied test loads and measured strains to determine the relationship between rigidity and measured strain at individual interpretable strain-gauge levels (Komurka and Moghaddam, 2020). This in turn determines a direct relationship between measured strains and internal forces. This method provides significant improvement in calculating rigidity directly from static load test measurements through an internal calibration sequence and engineering justification. A database developed from several case histories will be presented where strain measurements on various grouted cast-in-place piles were determined appropriate to apply the I.R. method. Considerations in the method application, and appropriate engineering justification will be discussed. Comparisons to the ACI-determined grout elastic modulus and recommendations for improving industry standards in implementing instrumented static load tests on cast-in-place grouted piles are presented.

CONVERTING MEASURED STRAIN TO CALCULATED INTERNAL FORCE IN INSTRUMENTED STATIC LOAD TESTS

Determining internal pile force at strain-gauge levels under static loading is essential for computing soil resistance distributions. Internal force, F, cannot be easily (and is therefore not commonly) measured directly, engineering practitioners must therefore rely on reasonable estimation of a pile's properties to compute force from measured strain. The most common approach of determining internal force is to assume a constant pile rigidity (constant both in terms of location within the pile, and independent of strain magnitude), considering a fixed nominal area and simplified estimation of elastic modulus. This approach often results in unreasonable internal force profiles, for example internal forces exceeding test loads, or "downstream" (further from the load source) internal forces exceeding "upstream" (closer to the load source) internal forces (a physical impossibility). Assuming the strain gauges were properly calibrated and installed, unreasonable internal forces are likely a result of unreasonable estimation of rigidity.

Assuming a fixed nominal area for grouted cast-in-place piles leads to mischaracterization of their geometry, particularly where larger grout volume is placed in comparison to the pile's theoretical volume. Additionally, subsurface conditions such as vuggy materials, loose/soft soils, or fractured rock may lead to localized bulging or external grout take along a pile's length. Various measurements while drilling in conjunction with some quality assurance methods (e.g., TIP) therefore provide improved means of estimating non-uniform geometry versus depth. Where the necessary information is made available, subsurface investigation and pile installation records must always be assessed alongside non-destructive quality assurance test results to best differentiate between material quality and geometric variations along an embedded foundation's length.

The elastic modulus characterizes the stress-strain relationship for a particular material. For some materials, such as steel, the elastic modulus is reasonably estimated based on existing information, independent of the fabrication method or loading conditions. Alternatively, E_{GROUT} is dependent on numerous factors, such as uni-axial compressive strength, curing conditions, and percent fraction of aggregate/water/cement and other admixtures. Grout has smaller and lighter aggregate than concrete, which improves workability but affects its elastic properties. E_{GROUT} is also understood to be strain-dependent, and thus ascribing a uniform value over its strain history is not valid for many loading conditions.

The American Concrete Institute ("ACI") presents a semi-empirical correlation of concrete uni-axial compressive strength to elastic modulus (ACI, 2014). Equation 1 is presented as a function of the concrete unit weight, w_c, typically taken as between 90 and 160 pcf. For example, a reduction from 145 pcf to 135 pcf in Equation 1 results in a 10% overall reduction in the computed elastic modulus. The formula for normal-weight concrete ($w_c \approx 145$ pcf) takes the form of Equation 2, defined as the ACI approach:

$$E\ (\text{psi}) = a(f'_c)^b = w_c^{1.5} \times 33 \times (f'_c\ (\text{psi}))^{0.5} \quad \text{(Eq. 1)}$$

$$E\ (\text{psi}) = \lambda \times 57{,}000 \times (f'_c\ (\text{psi}))^{0.5} \quad \text{(Eq. 2)}$$

Measured values of E may range between 80 to 120 percent of empirically calculated values. Additionally, the elastic modulus is sensitive to aggregate inclusion. Light-weight aggregate, such as sand typically used in grout mixes, can result in a lower elastic modulus for an equivalent uni-axial compressive strength for larger aggregate concrete (Brown et al., 2007; Hassan et al., 1998). However, if concrete/grout samples are not retrieved during foundation installation, nor density measurements obtained, the form of Equation 1 cannot be reasonably applied. A modification factor, λ, is introduced in ACI (2014) to reduce E up to 25% (i.e., λ is taken as ranging from 0.75 to unity for light-weight concrete mixes). Further uncertainty arises due to uncertainty of the in-place grout unit weight, and standard practice of obtaining cube samples for grout, as opposed to cylindrical samples (e.g., 6-inch-diameter cylinders). Cube samples have been shown to have 10 to 20% higher compressive strength compared to equivalent samples in cylindrical form (Elwell and Fu, 1995). There remain limited studies available for reliably correlating f'_c to E_{GROUT}.

Owing to the potential for large variation in E determined from the ACI approach, and the strain-dependency of E_{GROUT}, alternative methods of calculating elastic modulus are required. Initially proposed by Fellenius (1989) as the Tangent Modulus method, embedded strain measurements can be internally calibrated based on static load test measurements to determine elastic modulus, applied in conjunction with the pile's estimated total cross-sectional area. Komurka and Moghaddam (2020) adapted the definition and methodology of the Tangent Modulus method for improved determination of internal force without requiring estimation of either E or A independently, defined as the Incremental Rigidity method. Through assessing increments of applied test load (ΔQ) divided by increments of measured strain (Δε) over the strain history during a static load test, the strain-dependent rigidity can be determined directly at a particular interpretable strain-gauge level. Critical elements of interpreting the I.R. relationship at each strain-gauge level are discussed by Komurka and Robertson (2020). Fig. 1 presents a generalized plot for determining the I.R. relationships.

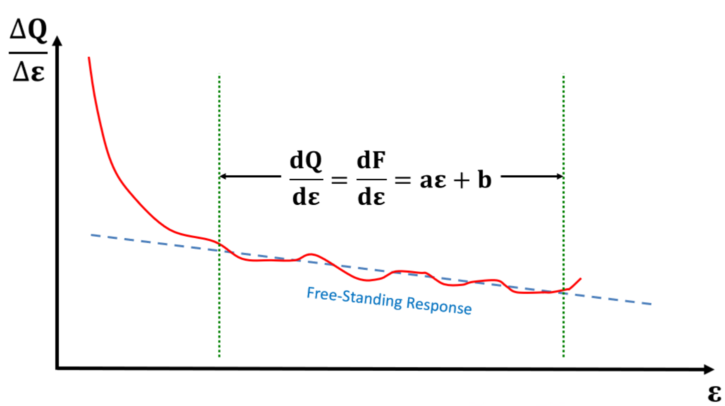

Fig. 1. Generalized Incremental Rigidity relationship at a strain-gauge location.

Generally, where the I.R. plot becomes linear, it is assumed that the soil resistance between the test load and the strain-gauge location has been essentially fully mobilized. Any additional test load increment is then equal to the internal force increment at that location (i.e., becomes equivalent to a free-standing response with no external resisting forces, such as soil resistance). Assuming rigidity is a linear function of strain, the differential equation in Equation 3 is derived. Following the steps outlined in Equations 4, 5, and 6, the strain-dependent rigidity is determined as ($0.5a\varepsilon + b$), where a and b are the slope and intercept shown in Figure 1, respectively.

$$\frac{dF}{d\varepsilon} = a\varepsilon + b \quad \text{Eq. 3}$$

$$F = \int (a\varepsilon + b)\, d\varepsilon \quad \text{Eq. 4}$$

$$F = 0.5a\varepsilon^2 + b\varepsilon + c \quad \text{(where } c \text{ is assumed to be 0)} \quad \text{Eq. 5}$$

$$F = (0.5a\varepsilon + b)\varepsilon \quad \text{Eq. 6}$$

Based on the I.R. derivation, the internal force at a strain-gauge location can be determined without knowledge of either elastic modulus or area independently. Komurka and Robertson (2020) present critical requirements for defining *interpretable* strain measurements in I.R. application, which are effectively strain measurements deemed appropriate for back-calculating grout moduli. E_{GROUT} can then be predicted at interpretable strain-gauge levels, and applied to levels deemed *non-interpretable*, using reasonable estimates of constituent materials' (e.g., steel and grout) cross-sectional areas. These in-situ-determined responses to test loads, and the resulting rigidity relationships and back-calculated grout moduli, provide improved internal force calculations compared to using estimated areas and empirical modulus relationships based on laboratory testing. For instance, Robertson et al. (2021) presents a case history where strain-dependent grout moduli were deduced using the I.R. method from BDSLT results on an ACIP pile and DDP.

CORRELATIONS OF CALCULATED GROUT MODULI FROM INSTRUMENTED STATIC LOAD TESTS

A database was compiled from instrumented static load tests on grouted cast-in-place piles. The tests were conducted mainly on DDPs and ACIP piles, using top-down compressive or bi-directional static load tests. The pile sizes ranged from 16- to 36-inch-diameter. Each case history was reviewed for adequate installation records (including compressive strength test results, reinforcing cage design, and non-destructive test results) and applicability of implementing the I.R. method. It was found in most cases presented that the ACI method yielded unreasonable calculated internal forces. Table 1 presents a summary of the case histories and pertinent project information. Thermal Integrity Profiling was implemented for each case history. Grout moduli were back-calculated from the I.R. relationship at 50% of the maximum measured strain, using the total cross-sectional area interpreted from TIP and accounting for the contribution of the steel components in the total composite area. For each pile, at least one or more strain-gauge level was found to have interpretable I.R. results. The results presented from the ACI method were determined using relationships established for normal-weight concrete, and were calculated without any modification factor, λ. Fig. 2 is a graphical presentation of the grout moduli correlations. Each datapoint in Fig. 2 is the correlation of calculated E_{GROUT} at a particular strain gauge level. Some piles yielded interpretable I.R. results at multiple (two or three) strain-gauge levels.

The majority of the I.R. cases yielded back-calculated E_{GROUT} values within 70 to 90% of the ACI approach. Some cases where the I.R. / ACI ratio was much less than 0.7 were potential outliers, for example, Cases 17 and 18 were DDPs and there were indications that potential modulus reduction resulted from the installation methodology. There was no major indication that grout cubes versus cylinders generated a larger reduction in the I.R. / ACI ratio, and the spread of correlations from grout cubes was similar to that obtained from grout cylinders. However, grout samples (whether cubes or cylinders) taken above ground, and cured and tested in a controlled environment, are not accurately representative of grout cast-in-place and cured in-situ. Therefore, the I.R. method is further justified since it provides a means of assessing in-place grout properties and load response.

Ultimately, a direct modification factor to the ACI method was not realized from the comparison results. Additionally, the ACI method does not account for a strain-dependent modulus, which can significantly affect calculated internal forces. Most cases evaluated were found to fall within the recommended range of the modification factor, λ, for light-weight concrete. It should be noted that the I.R. method may not apply to all cases, and while load-test practitioners can use the ACI method with a modification / reduction factor, it is best to recommend elastic modulus tests in conjunction with compressive strength tests on grout samples. Komurka and Moghaddam (2020) offer several recommended static load testing and data reduction protocols which aid in improving I.R. analyses. Local knowledge of anticipated geotechnical resistance, careful review of pile installation records, and additional non-destructive testing methods are recommended for best practice.

Table 1. Database summary of Incremental Rigidity results on grouted cast-in-place piles

Case No.	Test Type[A]	Test Pile No.	Pile Type[B]	Pile O.D., inches	f'_c[C], psi	Strain-Gauge Level[D]	I.R. Rigidity Relationship[E]		Grout Modulus[F], ksi		I.R. / ACI Ratio
							Slope	Inter-cept	I.R.	ACI	
1	CSLT	TP-1	ACIP	16	8,405*	1	-1.26E-03	0.92	2,662	5,226	0.51
						2	-1.83E-03	1.23	3,739	5,226	0.72
2	BDSLT	TP-1	ACIP	24	8,032	A1	-3.44E-04	2.18	3,458	5,108	0.68
						B1	-2.60E-05	2.50	4,311	5,108	0.84
3	BDSLT	TP-2	ACIP	24	7,308	A1	-2.34E-05	2.45	4,251	4,873	0.87
4	CSLT	TP-1	ACIP	16	6,562*	1	-7.47E-04	1.25	3,701	4,617	0.80
5	BDSLT	TP-1	ACIP	24	9,540	A1	-9.59E-04	2.95	4,308	5,567	0.51
						B1	-7.17E-05	2.95	4,439	5,567	0.80
6	BDSLT	TP-2	ACIP	24	6,730	A1	-3.35E-04	2.80	4,119	4,676	0.88
						B1	-1.91E-04	2.66	3,936	4,676	0.84
7	BDSLT	TP-1	ACIP	24	8,781	B1	-3.88E-04	2.90	4,565	5,341	0.85
8	BDSLT	TP-1	ACIP	24	5,878*	A1	-5.46E-05	2.61	4,325	4,370	0.99
						B1	-1.71E-04	2.32	3,711	4,370	0.85
9	BDSLT	TP-1	ACIP	18	5,025*	B1	-8.01E-04	1.18	2,668	4,041	0.66
10	BDSLT	TP-1	ACIP	18	5,121*	B1	-1.16E-03	1.71	4,175	4,079	1.02
11	BDSLT	TP-1	ACIP	24	7,080	B1	-8.41E-05	2.80	5,084	4,796	1.06
12	BDSLT	TP-1	ACIP	24	7,650	A1	-3.01E-04	2.00	3,459	4,985	0.69
13						B1	-8.51E-05	2.10	3,798	4,985	0.76
14	BDSLT	TP-2	ACIP	24	7,480	A1	-5.51E-05	2.20	3,958	4,930	0.80
15	BDSLT	TP-1	ACIP	24	6,075	B1	-1.31E-05	2.31	4,012	4,443	0.90
16	BDSLT	TP-2	ACIP	36	5,930	B1	-1.92E-04	4.50	3,385	4,389	0.77
17	BDSLT	TP-1	DDP	18	6,640	A3	-1.09E-04	0.96	2,321	4,645	0.50
						A2	-3.79E-05	0.99	2,494	4,645	0.54
						A1	-3.06E-04	1.11	2,912	4,645	0.63
18	BDSLT	TP-2	DDP	24	5,785	A1	-9.85E-05	2.00	2,853	4,335	0.66
						B1	-1.28E-03	1.86	2,525	4,335	0.58
19	BDSLT	TP-1	ACIP	20	6,890	A1	-3.59E-04	1.50	3,637	4,731	0.77
20	BDSLT	TP-2	ACIP	20	7,000	B1	-2.60E-04	1.50	3,480	4,769	0.73
21	BDSLT	TP-3	ACIP	20	7,040	A1	-3.31E-04	1.50	3,554	4,783	0.74
22	BDSLT	TP-1	ACIP	18	8,807	A1	-9.59E-05	1.40	4,024	5,349	0.75

Notes:

A. BDSLT: Bi-Directional Static Load Test
CSLT: Compressive Static Load Test (top-loaded)

B. ACIP: Augered Cast-In-Place Pile
DDP: Drilled Displacement Pile

C. Average compressive strength from multiple grout samples conducted on the day of each load test. * Denotes samples were 2x2x2-inch cubes, all others were 4-inch-diameter cylinders (8-inch height).

D. Interpretable strain-gauge level used to determine back-calculated grout moduli. Numerical designations increase with distance from applied test load location. BDSLT denotes "A" for strain-gauge levels above the jack assembly, and "B" below the jack assembly.

E. The Incremental Rigidity relationship intercept is the initial tangent axial rigidity, $(EA)_{INITIAL}$ (kips x 10^6).

F. Grout elastic modulus determined from I.R. at 50% of the maximum measured strain. Elastic modulus determined from ACI assumes normal-weight concrete and does not apply any modification factor, λ.

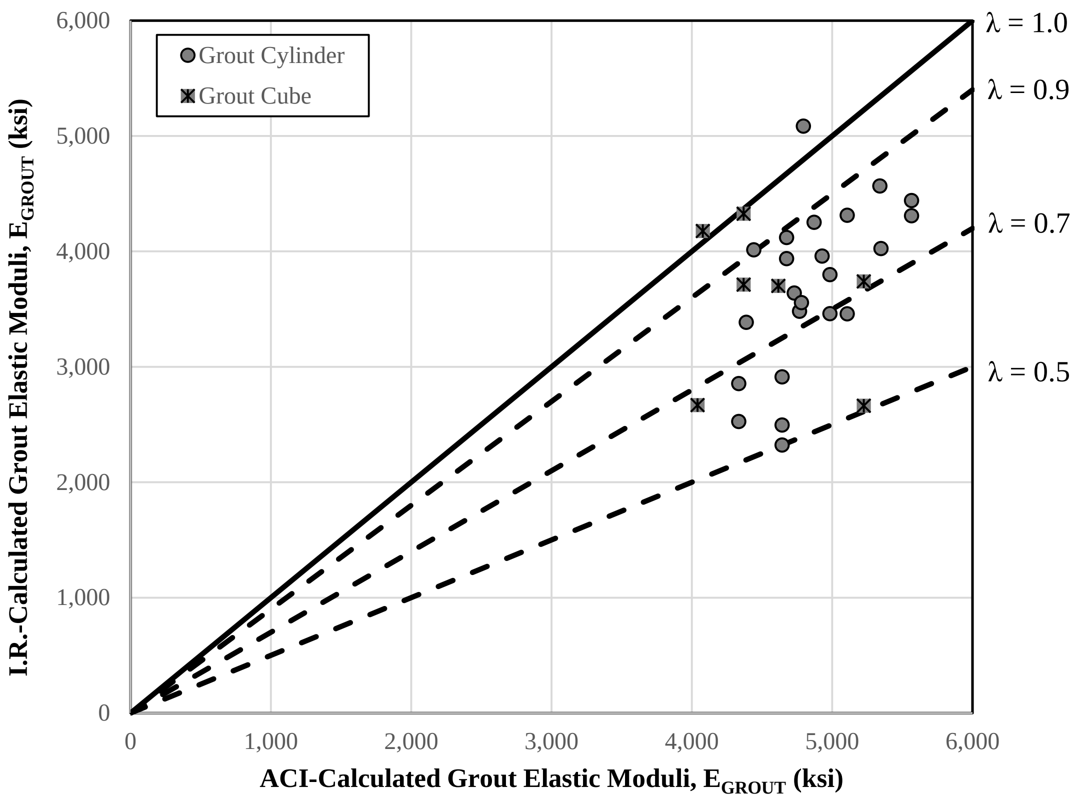

Fig. 2. Comparison of grout elastic moduli calculated from the ACI and I.R. methods.

SUMMARY AND CONCLUSIONS

Static load testing is an effective means for quality assurance and confirmation that the as-built foundation meets design requirements. Embedded instrumentation for measuring strains under applied test loads accommodate assessment of load-transfer characteristics along the embedded foundation length. A critical component of strain-gauge data reduction is converting measured strain to the internal force at a specific strain-gauge level. Difficulty arises due to inadequate or unreasonable internal force profiles resulting from the ACI method. The ACI method is a commonly used approach for determining the elastic modulus of concrete and grout samples from compressive strength test results. This method is a simplified, semi-empirical approach typically implemented as the industry standard. However, significant limitations in the ACI method arise due to uncertainty in the in-place cementitious material properties, and the method's inability to account for cementitious materials' strain-dependent elastic modulus. Additionally, the ACI relationships between compressive strength and elastic modulus were developed from normal-weight, cylindrical concrete samples, and may not reasonably apply to lighter-weight grout samples, especially cubes. Recent advances in cast-in-place grouted foundations were addressed, including improvements in grout placement and mix designs which ultimately require further assessment of their material properties. Additionally, in-place grout may not have the same intrinsic properties as samples obtained above-grade and stored/tested in a controlled environment.

The I.R. method was discussed as a more direct approach for estimating grout elastic moduli directly from embedded strain measurements during static load tests. While the applicability and interpretation of the I.R. method requires engineering review and justification, this method for converting strain to internal force has been found to be highly beneficial compared to other methods relying primarily on semi-empirical correlations.

A database of load test results for 22 grouted cast-in-place piles where the I.R. method was implemented was presented. The grout elastic moduli were calculated using the I.R. method and ACI approach. The I.R. back-calculated grout elastic moduli were typically within 70 to 90% of that determined from the ACI approach for normal-weight concrete/grout samples. This finding is consistent with known reductions in ACI-computed grout moduli considering variation in the sample aggregate inclusion, bulk unit weight, and sample size. Outliers from this typical range cannot solely be attributed to specimen properties (e.g., dimensions and weight), and may be the result of foundation installation methodology or anomalous zones along an embedded foundation's length. However, without additional knowledge of the various affecting factors, the ACI approach cannot be reasonably applied without significant uncertainty, one aspect of which is its inability to account for elastic modulus strain-dependency. The internal calibration sequence following the I.R. method does account for elastic modulus strain-dependency, and cast-in-place intrinsic material properties. When used in conjunction with proper engineering justification (such as correlation to subsurface exploration information, non-destructive quality assurance methods, and measurements taken while drilling), significant improvement is realized from the I.R. method to convert measured strain to internal force in instrumented static load tests on grouted cast-in-place foundations.

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