Forum Paper

Application of the Concrete Stressmeter for Augered Cast-in-Place (ACIP) Deep Foundation Testing

Jon Sinnreich[1]* and William G. Ryan[2]

Abstract: The conventional method of computing forces from strain gage data during deep foundation load testing relies on knowing the cross-sectional area and Young's Modulus of the pile's concrete or grout. Errors in estimating these parameters directly affect the computed force distribution of the foundation element being tested. Since the standard formulas were derived for concrete with coarse aggregates, the problem of estimating Young's Modulus for augered-cast-in-place (ACIP) piles or other piles constructed with grout is compounded by the lack of mathematical relationships for converting grout strength into modulus of elasticity. Concrete Stressmeters (CSMs) are instruments designed to overcome these difficulties and directly measure unidirectional stress in cementitious materials. The instrument design creates a load cell out of the in-place cementitious material itself, with the same elastic properties as the surrounding material. This study discusses the installation and data analysis of two ACIP bi-directional static load test (BDSLT) piles instrumented with CSMs, to validate the use of these instruments as an alternative to strain gages. The first test pile had a nominal diameter of 610 mm and a length of 26 m; the second test pile had a diameter of 760 mm diameter and a length of 35 m. Both piles were installed in Dade County, Florida, in alternating layers of sand and limestone. CSMs installed using the self-filling method yielded excellent comparison to force values derived from strain gages. An error analysis indicated a potential order of magnitude improvement in the accuracy of computed forces using the stressmeters as opposed to the strain gages, due to minimal reliance on an estimated Young's Modulus. The two case histories yielded comparable and reasonable force distributions with considerably less effort and fewer assumptions. The paper aims to stimulate the discussion and development of reliable alternatives to traditional strain-gage based analyses.

Keywords: stressmeter, pile load testing, force distribution, Augered-Cast piles

Introduction

The conventional method of computing internal pile reactions from strain gage data in deep foundation load tests relies on accurately estimating the cross-sectional area and Young's Modulus of the concrete or grout (E_c). Any error in this estimate directly translates into discrepancies within the force distribution of the deep foundation elements. Since curing conditions affect the strength development of concrete, the strength and modulus of sample cylinders tested in the laboratory may be different than the strength and modulus of the corresponding in-situ material. For augered cast-in-place (ACIP) piles or other piles constructed with grout as opposed to concrete, the problem of correctly estimating Young's Modulus is further compounded by the lack of analytical guidance to confidently convert grout strength into modulus. Empirical constitutive model formulas for estimating concrete modulus are formulated for mix designs with coarse aggregate and have limited application to grout fluids with only fine aggregate sizes. For instance, ACI 318 (2019) allows the concrete modulus to be calculated according to Eq. 1:

$$E_c = 0.043 w_c^{1.5} \sqrt{f_c'} \quad (1)$$

where f_c' is the concrete strength (MPa) and w_c is the unit density (kg/m^3). Eurocode 2 suggests the concrete modulus to be calculated according to Eq. 2:

$$E_c = 22(f'/10)^{0.3} \quad (2)$$

To the best of the authors' knowledge, no similar equations exist to estimate the modulus of grout in a similar manner. Back-calculation techniques such as the "incremental rigidi-

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ty" method (Komurka and Moghaddam, 2020; Komurka and Robertson, 2020) can result in a better estimate of pile rigidity, but require significant mobilization of the test pile to converge on an asymptotic solution. These methods are based on the assumption that cementitious materials' stress-strain curve is non-linear at strains often observed during load tests (several hundred microstrain or more), and that this non-linear relationship can be approximated by a 2nd-order polynomial function. The constants of this function are the slope and offset of a line curve-fit to a plot of back-calculated rigidity versus strain (see Sinnreich, 2022 for a thorough treatment of these methods). Although the incremental rigidity method was employed in both the field experiments described hereafter, in the authors' experience it is not always applicable due to insufficiently high mobilized strains and/or an inadequately developed mobilization curve, and often requires a degree of subjective judgement to implement.

To overcome the above-mentioned limitations, the Concrete Stressmeter (CSM) provides a unique alternative to conventional stress analyses by attaching the CSM to the pile's rebar cage and measuring in-situ concrete stresses directly. This method is particularly suitable for pile installation procedures similar to ACIP piles, where sensor instrumentation can be lowered together with the reinforcing cage into fluid grout. To demonstrate the effectiveness and accuracy of the CSM instrumentation, and to spark the discussion and development of this alternative approach, two bi-directional static load test (BDSLT) results of two ACIP piles are presented herein. The CSMs were installed using the self-filling method and provided an excellent opportunity to compare CSM measured forces with force values derived from strain gages. An error analysis indicated a potential order of magnitude improvement in the accuracy of computed forces using the stressmeter as opposed to the back-analysis of forces from strain gages. This reduction in error can be largely attributed to the minimal reliance on an empirical estimate of Young's Modulus.

Bi-directional Static Load Testing

Bi-directional static load testing is a common technique for testing deep foundation elements (piles, drilled shafts, etc.) without the use of an external reaction system (Osterberg, 1989). A sacrificial hydraulic jack is embedded at the balance point of the test element (the depth where the shear resistance above is approximately equal to the shear plus bearing resistance below). The jack is pressurized in a step-and-hold sequence similar to a top-down static load test (ASTM, 2018). Force distribution in the foundation element is typically assessed using strain gages to estimate forces at various depths above and below the jack. Measured strain at various depths is multiplied by the foundation element's composite rigidity to determine the axial force P:

$$P = \varepsilon(EA) = \varepsilon(E_c A_c + E_s A_s) \tag{3}$$

where A_c and A_s are the cross-sectional areas of the cementitious and steel portions of the composite pile, respectively, and E_s is the Young's Modulus of steel (assumed 200 GPa). The most common method of determining the rigidity used in traditional top-down testing is to locate one set of strain gages above the zero-shear (ground level) elevation and back-calculate rigidity from this data directly. This method, known as the secant rigidity method, is not available for bi-directional tests, because significant load is shed via shear immediately above and below the jack. Thus, other methods must be employed. Often, an empirical constitutive relationship (such as Eq. 1 or Eq. 2) is used to convert reported test specimen strength f'_c to modulus, then multiplying by the net concrete or grout cross-sectional area and adding reinforcing steel properties to arrive at a rigidity. However, these relationships are formulated for mix designs with coarse aggregate (Tibbetts *et al*., 2018) and tend to have significant scatter from actual modulus values (Pacheco *et al*., 2019). An error analysis indicates a potential order of magnitude improvement in the accuracy of computed forces using CSMs as opposed to strain gages using the ACI 318 or Eurocode 2 formula method (which is always available because it is independent of measured strain), due to the CSM's minimal reliance on an estimate of Young's Modulus.

Description and Modification of Concrete Stressmeters

The "Toyoko-Elmes"-type Concrete Stressmeter (CSM) comprises a short load cell in series with a longer cylinder of concrete (Geokon, 2015) as shown in Figure 1. This concrete cylinder has the same properties as the surrounding concrete but is de-bonded from it by means of a smooth-walled, porous plastic tube. It is coupled at its ends to the surrounding concrete by means of two flanges equipped with short threaded bars (anchor bolts) to provide a mechanical bond. Typically, the stressmeter installation procedure calls for pre-filling the instrument tube with the same mix as the surrounding material, then attaching the stressmeter to steel reinforcement prior to casting. The load cell measures the normal force imposed on the inner concrete cylinder by stresses in the concrete outside the CSM. This force, when divided by the cross-sectional area of the inner cylinder, gives the unidirectional stresses aligned on the axis of the tube in the surrounding concrete (Laube and Rusack, 2002). The physical dimensions of the tube and load cell ensure that typical concrete (with normal-sized coarse aggregate) will produce a uniform stress on the load cell (Kawaguchi and Nakane, 1996).

The CSM is positioned in line with the direction in which the force is to be measured and is tied to the rebar cage using iron wire or nylon tie-wraps. The traditional installation method, as described in the manufacturer's user manual, calls for the CSM to be filled with the same concrete or grout mix as the surrounding structure. Ideally, this is accomplished by using material from the same truck(s) delivering concrete to the site. This method presents some logistical difficulties in a deep foundation test installation, when the instruments positioned in a rebar cage may be inaccessible (e.g., suspended in the air, or already lowered into the excavation) by the time any concrete is delivered to site. Therefore, a modification

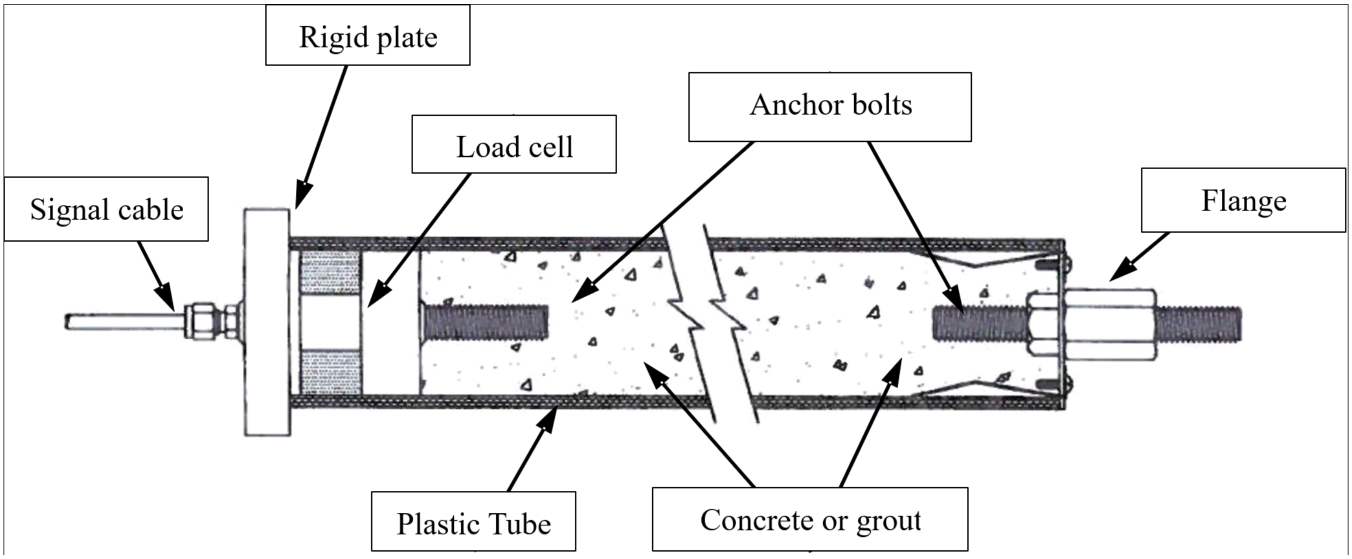

Figure 1. Concrete Stressmeter (after Geokon Inc.)

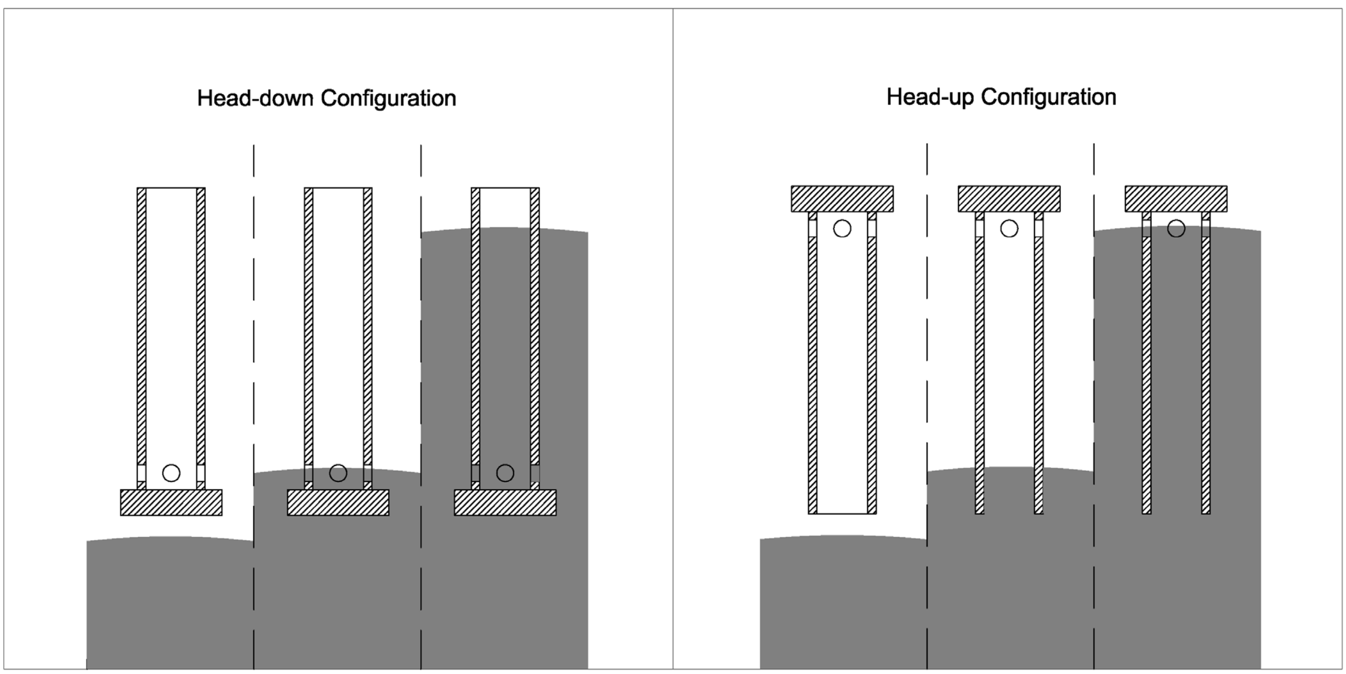

Figure 2. Modified self-filling CSMs being submerged in grout

was made to the CSM so that when installed into wet grout of an ACIP pile, the CSMs are self-filling. The modification consists of drilling vent holes at the base of the tube, immediately above the face of the load cell, and either removing the end flange and bolt assembly completely, or modifying it to allow grout flow. This allows the CSM to passively fill with grout and vent air in the tube as the rebar cage is lowered into the wet grout, regardless of whether the instrument is positioned head-up or head-down, as indicated in Figure 2. Because all CSMs in a bi-directional test are stressed in compression, the open-end flange and threaded bar may be removed completely to facilitate grout flow.

Force Calculation Methods

The CSM produces axial stress data in cementitious material (concrete or grout). Typically, in a deep foundation test application CSMs would be installed in pairs or fours, and the average of these measurements is used to estimate the stress σ_{CSM} at a given depth. To compute axial force in a composite (steel-reinforced grout or concrete) pile, the following methods to analyze this data are available:

(1) Multiply the average stress by the cross-sectional area of the pile A_{pile} as given by Eq. 4:

$$P = \sigma_{CSM} A_{pile} \tag{4}$$

where $A_{pile} = A_c + A_s$ is simply the full cross-sectional area and σ_{CSM} is the average stress in the plane obtained by the CSM. This is the simplest method but will incur a significant error since the plane-strain assumption implies an equal strain in the reinforcement steel. However, a given amount of strain results in a much higher stress in steel than in cementitious material, typically an order of magnitude more. This additional stress is neglected in Eq. 4 because only the cementitious material's stress is multiplied by the total cross-sectional area.

(2) First, estimate or assume a grout modulus E_c, and back-calculate strain ε_{calc} using Eq. 5. Next, calculate stress in the rebar based on this strain and the known Young's modulus for steel E_s. Multiply the steel stress by the steel cross-sectional area A_s, and CSM stress by the cementitious cross-sectional area A_c. Finally, by adding the two force components resulting from concrete and steel, the total axial force P can be calculated (Eq. 6):

$$\varepsilon_{calc} = \sigma_{CSM}/E_c \tag{5}$$

$$P = \sigma_{CSM} A_c + \varepsilon_{calc} E_s A_s \tag{6}$$

This method will have less error than Method 1 but requires a reasonable estimate of the cementitious material modulus.

(3) Use tandem strain gages embedded at the same plane as the CSMs to directly measure strain (ε_{SG}). Use this measured strain to calculate stress in the steel reinforcement. Next, multiply steel stress by the steel cross-sectional area, as well as multiply CSM stress by net grout cross-sectional area, and add the two force components together to calculate the total force in the pile:

$$P = \sigma_{CSM} A_c + \varepsilon_{SG} E_s A_s \tag{7}$$

Note that pile cross-sectional area is assumed to be known in the analyses presented herein. For ACIP piles, rig instrumentation logs, pump stroke counts and thermal integrity profiling data (Johnson, 2016), if available, should be analyzed to determine actual diameter vs. depth.

Field Studies and Experimental Measurements

Field Trial – Project A

A total of 4 CSMs were first installed in paired configurations inside a 610-mm-diameter test pile at Project A – Hallandale Beach, FL. Figures 3 and 4 are photos from the installation of CSMs in the ACIP test pile. The primary purpose of installing these instruments was to test their performance in an ACIP pile.

The standard method of installation calls for pre-filling the stressmeter tube with the same type of material as the mass grout in which it is embedded. For each installed pair of CSMs, one unit (the "b" side) was pre-filled and sealed, as per manufacturer's instructions. The opposing unit ("a" side) was modified with vent holes drilled in the side of the PVC sleeves as indicated in Figure 3. Although one of the four CSM instruments (pre-filled unit in position 4b) did not function, data from the other three CSMs yielded very comparable force distribution curves (dashed lines) to those generated using strain gage data. Figure 5 presents a comparison of force distribution curves. Considerable analytical effort was expended on ana-

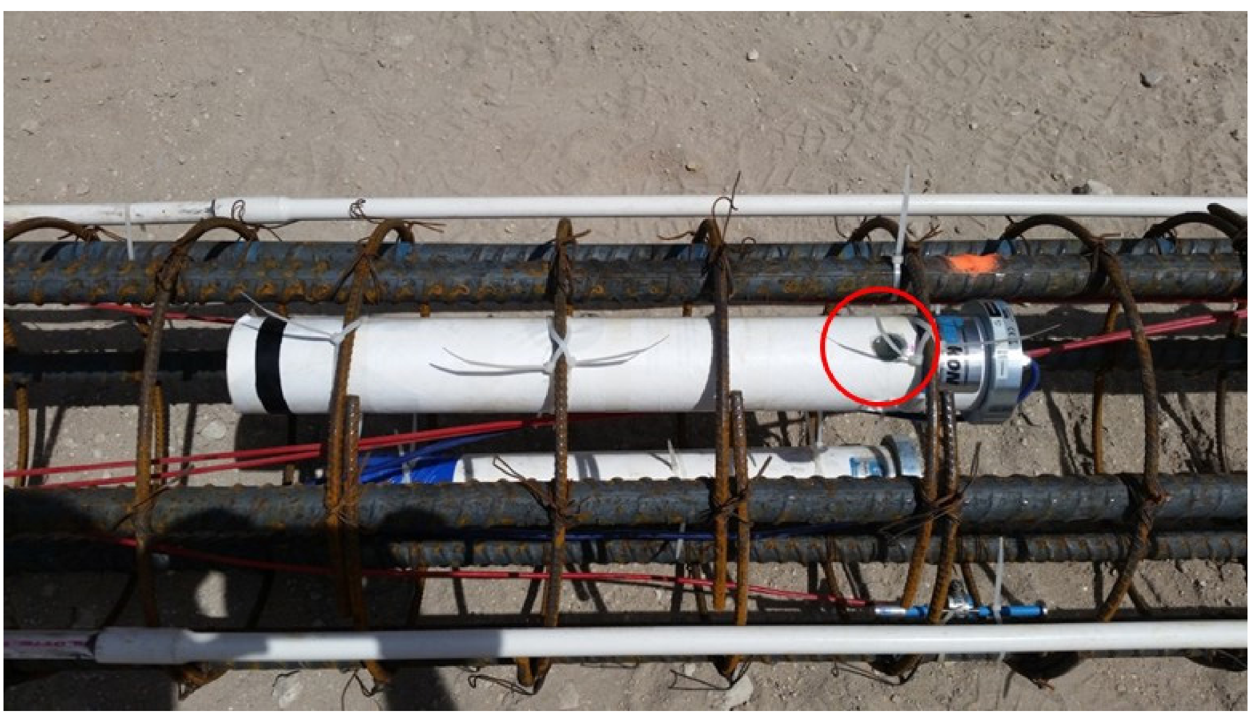

Figure 3. Self-filling ("a", top) and pre-filled ("b", bottom) CSM mounted in rebar cage (vent holes in self-filling tube circled) – Project A

Figure 4. CSM pair in rebar cage (circled) – Project A

lyzing the strain gage data. The conventional (ACI 318 empirical formula) method resulted in computed forces higher than applied jack load and is not plotted. Both the incremental rigidity method and the non-linear rigidity method (Sinnreich, 2012) were utilized instead to obtain sensible results from the strain gage data. The analysis of the CSM data was straightforward, using Method (3) data analysis as described in the Force Calculation Methods section above. The data collected from the CSM's suggest that the self-filling units performed at least as well as the pre-filled units, based on a comparison of the resulting force distribution curve with strain gage data.

The forces computed from strain gage data and the three methods for analyzing CSM data described above are listed in Table 1 for comparison.

Field Trial – Project B

A second experimental evaluation of the CSM instrumentation was performed at Project B, located in Miami, FL on a 760-mm-diameter test pile. In this study, four pairs of CSMs (all self-filling) were installed in opposing pairs, as shown in Figure 6.

To test the effect of the open end anchor bolts, some end cap flanges were modified by cutting away most of the capping plate to permit free grout flow, as shown in Figure 7. Two pairs of CSM's installed (level 1 and level 7) were capped with these modified flanges. Two other pairs (level 3 and level 5) were left open (anchor bolt assembly removed completely). The elevation of the CSMs in this test corresponds to strain gage levels 1, 3, 5 and 7, as shown in Figure 8.

The results of this test were not as clear-cut as Project A. The strain gage and CSM force distribution curves had some significant differences above the bi-directional jack. Based on the soil boring log, the analysis of strain gage data using the incremental rigidity (IR) method produced the most-reasonable force distribution. On the other hand, using the ACI 318 estimate of grout modulus produced the worst results, with level 3 strain gages indicating forces higher than the applied

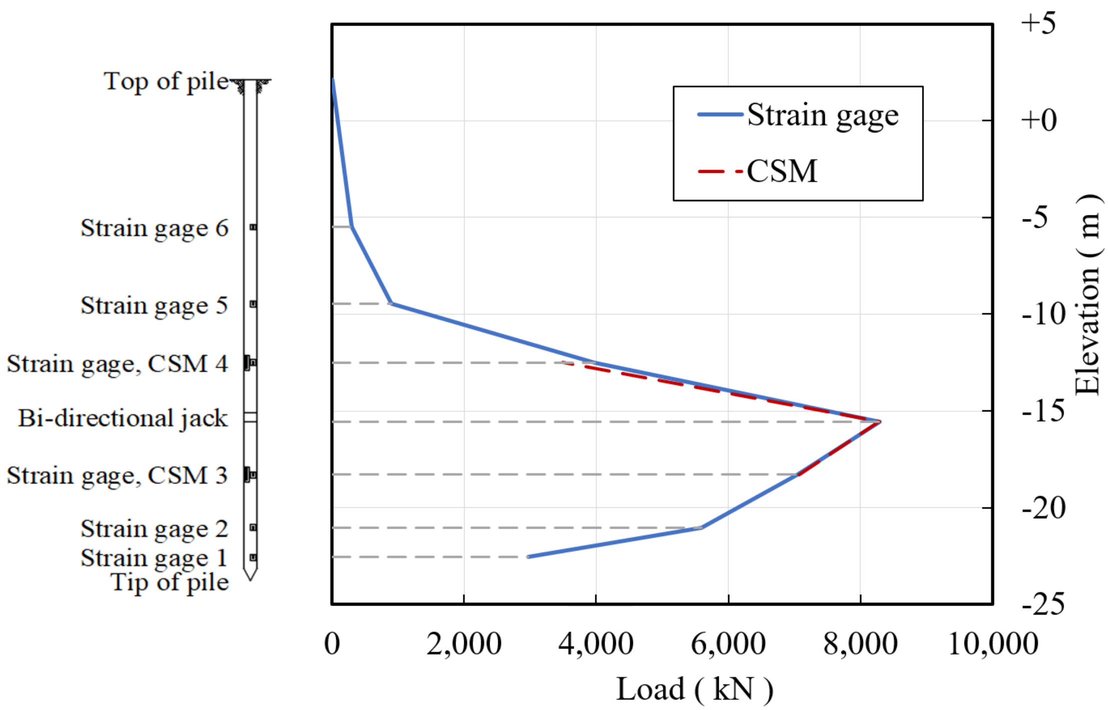

Figure 5. Pile elevation schematic and force distribution curves – Project A

Table 1. Project A Data Analysis Summary

	Strain gage	CSM (Method 1)	CSM (Method 2)	CSM (Method 3)
Elevation –12.5 m (level 4)	3973 kN	2550 kN	3313 kN	3489 kN
Elevation –18.3 m (level 3)	7050 kN	5430 kN	6126 kN	7070 kN

Figure 6. CSM pair in rebar cage below jack – Project B

jack load. For the CSMs, one unit in the level 3 pair was disregarded, because it produced data that indicated a force greater than applied bi-directional load, and one unit in level 7 did not function at all for unknown reasons. The remaining CSMs were analyzed using Method (2) as described in the Analysis of Data section above and used an estimated grout modulus per Eq. (1). Figure 8 plots the various resulting force distributions. Note that both strain gages and one of the paired CSMs at level 3 indicated unreasonably high strain and stress, respectively. This may be a result of being positioned too close to the source of load, within a zone where the plane strain assumption does not hold. The authors' prior experience with strain gages has indicated that optimally, gages are located at least two pile diameters away from the bi-directional jack. In this case, the client specified the level 3 gage locations at 1.6 diameters below the jack, which may have contributed to some of the difficulties in interpreting the strain data. For comparison, the various results of the data analysis at levels 1,3, 5 and 7 are tabulated below.

Figure 7. Original (left) and modified (right) flange-and-bolt assembly

Error Magnitude Analysis and Discussion of Test Results

Assuming a "true" value of force in the pile is known, the following set of calculations will illustrate the relative magnitudes of potential error using the various methods presented above. Typical values of grout modulus (35000 MPa), steel reinforcement (1%), diameter (760 mm) and strain (250 με) encountered in ACIP pile tests are assumed. First, some derived values are computed:

$$A_{pile} = \pi D^2/4 = 0.25\pi(0.76)^2 = 0.454 \text{ m}^2$$

$$A_c = 0.99A_{pile} = 0.449 \text{ m}^2$$

$$A_s = 0.01A_{pile} = 0.005 \text{ m}^2$$

$$\sigma_{CSM} = \varepsilon E_c = 250 \times 10^{-6} \cdot 35000 = 8.75 \text{ Mpa}$$

Next, the true force as well as the value derived from Method (1) (Eq. 4) are computed:

$$P_{TRUE} = \varepsilon(E_c A_c + E_s A_s) = 250 \times 10^{-6} (35000 \cdot 0.449 + 200000 \cdot 0.005) = 4.18 \text{ MN}$$

$$P_{Method\ (1)} = \sigma_{CSM} A_{pile} = 8.75 \cdot 0.454 = 3.97 \text{ MN}$$

As mentioned in the discussion of Equation 4, this method, while straightforward, will not give the correct estimate of force. Methods (2) and (3) will return the true value of force in this example, but only if the grout modulus is correct.

Next, the impact of an incorrect estimate of the true grout modulus is examined. Assuming a 10% error in estimated grout modulus $E'_c = 0.9E_c$, the strain gage analysis (Eq. 3), Method (2) (Eq. 6) and Method (3) (Eq. 7) are all compared:

$$P_{Strain\ Gage} = \varepsilon(E'_c A_c + E_s A_s) = 250 \times 10^{-6} (0.9 \cdot 35000 \cdot 0.449 + 200000 \cdot 0.005) = 3.79 \text{ MN}$$

$$P_{Method(2)} = \sigma_{CSM} A_c + \left(\frac{\sigma_{CSM}}{E'_c}\right) E_s A_s = 8.75 \cdot 0.449 + \left(\frac{8.75}{0.9 \cdot 35000}\right) \cdot 200000 \cdot 0.005 = 4.21 \text{ MN}$$

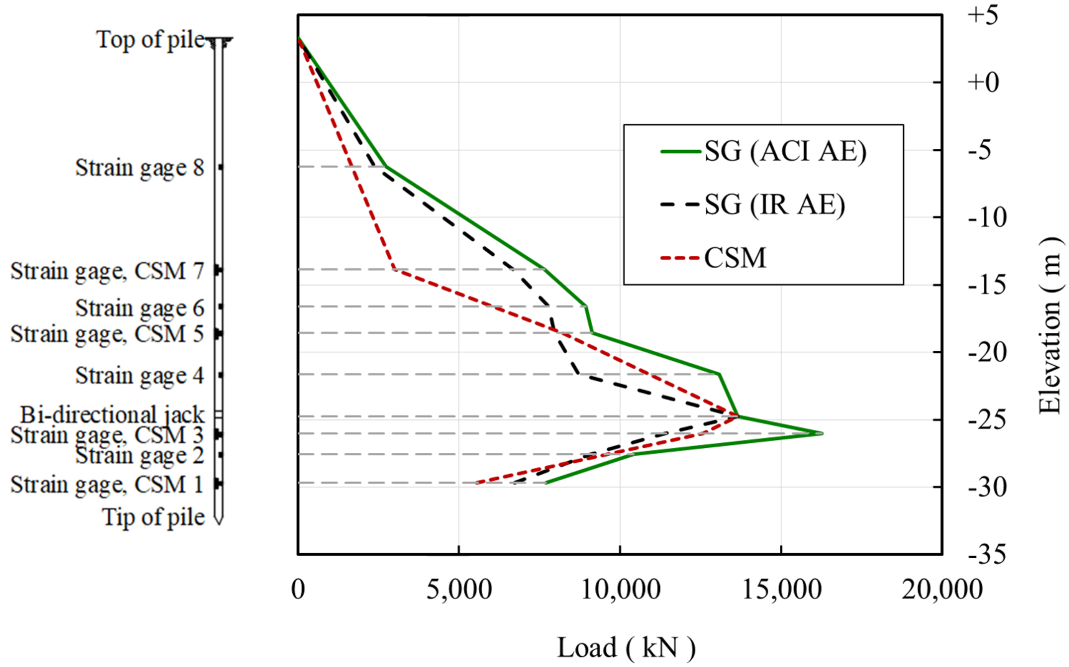

Figure 8. Pile elevation schematic and force distribution curves – Project B

Table 2. Project B Data Analysis Summary

	Strain gage (ACI Method)	Strain gage (IR Method)	CSM (Method 1)	CSM (Method 2)	CSM (Method 3)
Elevation –13.8 m (level 7)	7,639 kN	6,005 kN	2,426 kN	3,003 kN	4,245 kN
Elevation –18.6 m (level 5)	9,123 kN	7,018 kN	7,330 kN	8,202 kN	8,318 kN
Elevation –26.0 m (level 3)	16,258 kN	11,397 kN	11,229 kN	12,564 kN	13,030 kN
Elevation –29.7 m (level 1)	7,702 kN	6,047 kN	4,953 kN	5,542 kN	5,814 kN

$$P_{Method\ (3)} = \sigma_{CSM} A_c + \varepsilon E_s A_s = 8.75 \cdot 0.449 + 250 \times 10^{-6} \cdot 200000 \cdot 0.005 = 4.18 \text{ MN}$$

The sample calculations performed above illustrate the relative resilience of CSM data analysis to incorrect grout modulus estimates. For a 10% error in modulus estimate, the strain gage method returns essentially a 10% error in force calculation. The CSM methods return a closer value. Method (3) will (in theory) yield exact results, but requires use of both strain gages and CSMs, rather than replacing the first with the second. It is utilized in the field trials described herein to validate the CSM data but would not be economical in a typical field application. Method (1) is completely independent of modulus estimates but will give an approximately 5% erroneous force estimate due to neglecting the stress in the reinforcing steel. Method (2) results in a less than 1% error in computed force given a 10% error in modulus estimate and is therefore the best choice for CSM data analysis.

Using best practices to convert strain to stress, the results of the field trials yielded differences in forces computed from strain gages and CSMs ranging from 0% (exact match, project A level 3) to 50% (project B level 3). These discrepancies emphasize the very high sensitivity of the strain-to-force conversion method and the strong dependence on correct assumptions regarding the material modulus. Although the pile cross-sectional area plays a significant role in force calculations in general, in the data analysis presented herein assumes the area to be nominal and constant for both strain gage and CSM data analysis.

Conclusions

The modified concrete stressmeter (CSM) represents an alternative to strain gages for instrumenting ACIP test piles. Although some individual instruments did not function in the field trials presented herein, overall, the self-filling installation method for CSMs in fluid grout was validated, and the resulting data was analyzed with considerably less effort and subjective judgement than the corresponding strain gage data while producing comparable results. Estimating foundation rigidity for strain gage data interpretation includes inherent uncertainties. The use of the CSM with data analysis Method (2) instead of strain gages potentially reduces these by as much as an order of magnitude. More work is needed to establish proper guidelines for installation of self-filling CSMs in test piles, to ensure instrument survival of the construction process and to determine optimal spacing, orientation and minimal distance from load sources.

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