NON-LINEAR PILE RIGIDITY DETERMINED FROM EMBEDDED STRESSMETERS IN INSTRUMENTED BI-DIRECTIONAL STATIC LOAD TEST PILES

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ABSTRACT

Instrumented static load testing can be implemented for assessing load-transfer characteristics of augered cast-in-place piles under static axial load. Strain gauges are typically instrumented on the steel reinforcement at specific locations along the pile's embedded length for determining side-shear and end-bearing geotechnical resisting forces. Conversion of strain to internal force at each gauge level can be complicated, requiring critical assessment of the pile properties and potential strain-dependent response to applied load. Current design codes and standards provide recommendations for approximating these necessary pile properties. However, these commonly employed methods may not routinely yield realistic conversion of measured strains to internal force. Non-linear rigidity may be exhibited over a static load test duration, and there remains limited published methods for determining load-distribution characteristics under these conditions. Through measuring embedded strain and uniaxial stress simultaneously, the pile's strain-dependent rigidity can be directly determined, thus minimizing uncertainty in the analytical process. A case study is presented where stressmeters were specially adapted for installation on augered cast-in-place piles on a bi-directional static load test program. Based solely on the measured strains, it was realized that a non-linear rigidity would be required for properly converting strains to internal forces. The uniaxial stresses determined from stressmeter measurements provided valuable insight in the pile material response to applied loads, ultimately reducing to a piecewise-linear function of rigidity versus strain. Derivation of this piecewise-linear function and methodology for computing internal forces are addressed. Comparisons of various rigidity (linear and non-linear) determination methods are presented to delineate practical versus impractical methods for computed internal forces. Recommendations for improving instrumented static load tests are summarized, primarily focusing on prospects and interpretation of embedded stressmeter measurements in top-down and bi-directional static load tests.

INTRODUCTION

An augered cast-in-place ("ACIP") pile is a drilled deep foundation where soil/rock is removed using a continuous flight auger, and the excavated hole is grouted through the hollow stem auger. Steel reinforcement is subsequently advanced in the wet grout after auger removal. ACIP piles are particularly advantageous for relatively fast installation, with consistent improvement in drilling tools/rigs accommodating installation in very dense and potentially problematic soils. Quality assurance methods are often necessitated for assessing the grout quality below grade, possible geometric deviations from nominally designed, and load-bearing resistances of the final constructed element. Axial load bearing resistance can be determined, for example, from conventional top-down static load tests, bi-directional static load tests, or dynamic load testing. Embedded instrumentation (e.g., strain gauges) help facilitate determining load-transfer characteristics in side-shear and end-bearing resistances under applied axial load. Internal pile forces at discrete locations of each strain gauge level can then be estimated. The differences in the computed internal forces, and known boundary forces, are then used to determine the load shedding characteristics over the representative pile segments. Robertson and Komurka (2023) describe various methods of strain gauge data reduction, particularly for grouted drilled deep foundations.

In current practice, there remains no methodology for directly *measuring* internal pile forces. Practitioners therefore rely on *computing* internal force from measured axial strain and a series of broad assumptions/estimations of the pile's geometry and intrinsic material properties. The measured strain, ε, is

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converted to internal force, P, using the relationship $P = \varepsilon(AE)_{Pile}$, where $(AE)_{Pile}$ is the axial rigidity at the particular strain-gauge level. While strain is measured, it is a common misconception that the pile's axial rigidity is readily known. Drilled deep foundations oftentimes are non-uniform in geometry, and therefore the total cross-sectional area, A, may vary over the embedded length. Additionally, the grout elastic modulus, E_{grout}, must be estimated in some way. Area may be assumed/estimated based on the pile installation records or via incorporating integrity testing, such as Thermal Integrity Profiling ("TIP") (Robertson and Komurka, 2023; Belardo et al., 2021).

Several commonly applied methods for estimating concrete/grout elastic modulus are as follows:

1. Assume a constant, non strain-dependent elastic modulus.
2. Assume a strain-dependent elastic modulus relationship.
3. Compute a strain-dependent elastic modulus based on internal calibration sequence over a load test duration.
4. Measure stress and strain at discrete locations along the embedded pile length.

There exists some degree of uncertainty for each of these methods. Proper engineering justification and correlations between multiple methods are required. An assumed constant elastic modulus is generally based on semi-empirical correlations with uni-axial compressive strength test results performed on concrete/grout samples (e.g., American Concrete Institute, 2019). However, semi-empirical methods may not yield reasonable computed internal forces, and it is generally understood that the elastic modulus of cementitious materials is not necessarily constant but strain dependent.

A strain-dependent elastic modulus can be assumed, and in some cases this is required, such as conditions where tension cracks have formed or there is potentially fractured grout. Since the cross-sectional area at a particular strain gauge level does not change to any significant extent over a static load test duration, the combined function for rigidity can be assessed (i.e., there is no need to determine A and E independently). A strain-dependent rigidity model was developed by Sinnreich (2011). Figure 1 presents simplified representations of various rigidity relations, including both linear (strain-independent) and non-linear (strain-dependent) models. Figure 1a is directly adapted from Sinnreich (2011) based on rigidity relationships exhibited from instrumented bi-directional static load test results. The tangential rigidity relationships presented in Fig. 1b are the slopes of the of the various plots in Fig. 1, and allow for further interpretation of the various methods of estimating axial rigidity of composite steel/cementitious materials.

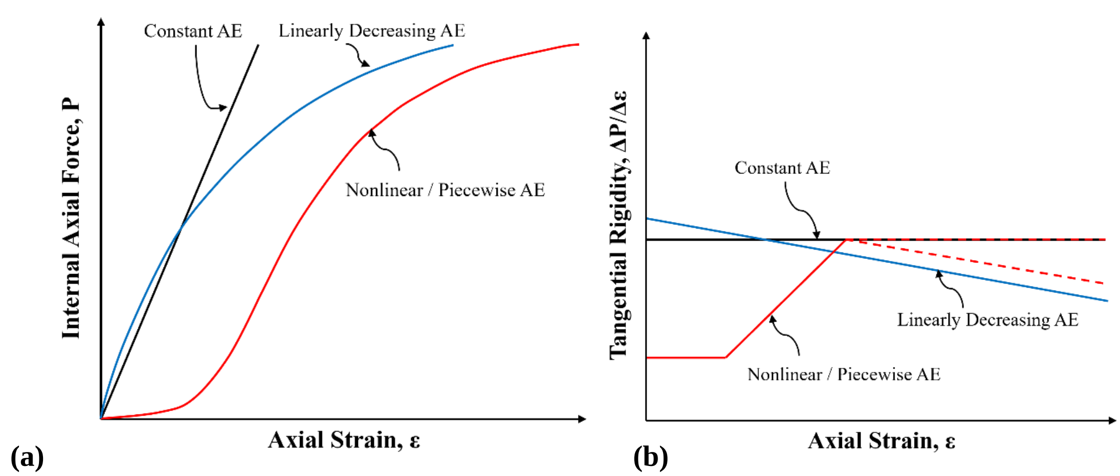

Fig. 1. Stress-Strain Relationships for Composite Pile Material

The constant AE function essentially describes the ACI method, while the linearly decreasing AE function can be determined using the Incremental Rigidity (I.R.) method outlined by Komurka and Moghaddam (2020) based on Fellenius' tangent modulus approach (Fellenius, 1989). The non-linear AE can be simplified as a piecewise-linear function, whereas the three linear components are defined in Fig. 2.

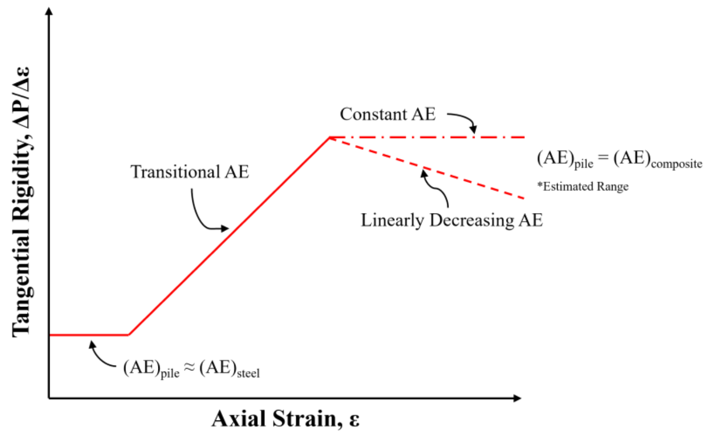

Fig. 2. Piecewise-Linear Tangential Rigidity Relationship

The piecewise-linear AE describes the scenario where initial stresses are predominantly concentrated on the steel reinforcement. Over the progression of increased applied load, the stress-strain relationship becomes better defined by full grout/steel composite section. This may occur where tension cracks that formed during the curing process gradually close over the load test duration. The initial rigidity (at zero strain) can be estimated based on the known cross-sectional area of the steel reinforcement and a rational steel elastic modulus (e.g., E_{steel} = 29,500 ksi). When the load is assumed to be distributed across the full cross-section (i.e., $AE_{Pile} = AE_{Composite}$), the composite elastic modulus can be estimated based on the ACI (constant AE) or I.R. (linearly decreasing AE) methods. The strain at which the individual linear functions are defined can be assessed from the incremental strains measured over the load test duration (Sinnreich, 2011).

The methods outlined in Figs 1 and 2 require broad assumptions which may not fully reflect the structural response under applied axial load for either top-down or bi-directional static load testing. Sinnreich and Ryan (2022) present an alternative method of directly measuring the stress-strain relationship of grout using Concrete Stressmeters ("CSMs") adapted for ACIP pile instrumentation. The adapted CSM consists of a load cell affixed to an open-ended plastic tube. The CSM is attached parallel to the longitudinal steel reinforcement, and preferably adjacent to a strain gauge. Upon installation of the instrumented steel reinforcing cage, the tube fills with grout which becomes de-bonded along a smooth inner wall. The stress of the de-bonded grout cylinder is then measured from the calibrated load cell. Under the assumption of strain compatibility, the grout stress-strain relationship can be directly determined. Additionally, internal force can be computed at the instrumented level considering the stress in the grout and computed stresses in the steel reinforcement. A case history is presented herein where Geokon Model 4370 vibrating wire CSMs were installed on two ACIP load test piles.

CASE HISTORY – CSM INSTALLATION

Two 36-inch-diameter ACIP piles were instrumented with strain gauges and CSMs as part of a bi-directional static load test program. The CSMs were incorporated strictly for experimental means, and therefore the data reduction methodology for the load test program did not directly rely on these stress measurements. For each pile, a jack assembly comprised of a single 17-inch-diameter hydraulic jack was installed at the pile base. Designated minimum-required test loads were 1,600 kips in each direction, equating to a 3,200-kip combined bi-directional test load. The 17-inch-diameter hydraulic jacks could apply upward of 1,925 kips in each direction. Test Pile TP-A was approximately 85 feet long, and TP-B was approximately 92 feet long. Figure 3 presents elevation views of the test piles with the respective subsurface and strain gauge instrumentation details.

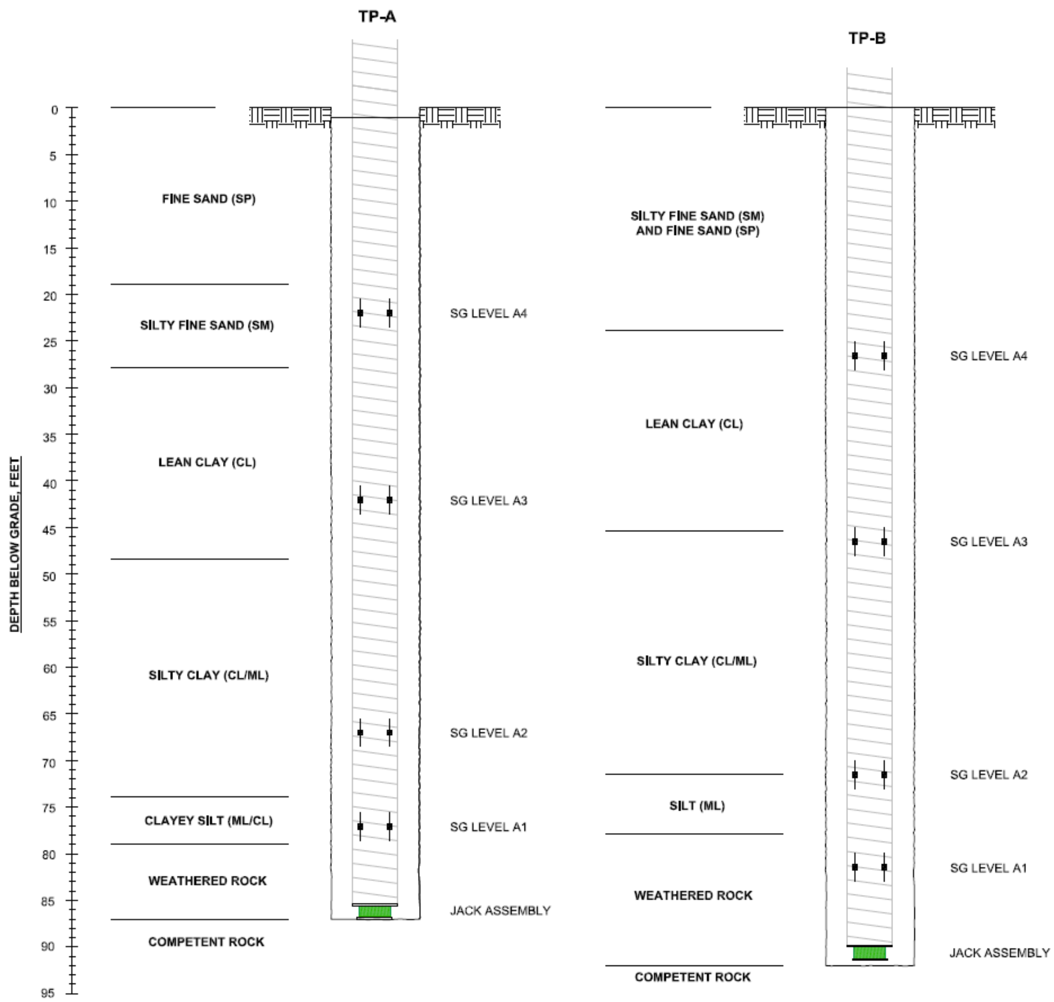

Fig. 3. Test Pile Elevation Views

The subsurface stratigraphy generally consisted of silty fine sands, lean clay, and silty clays to approximately 79-foot depth. Weathered limestone extended below this for another 5 to 12 feet until competent rock was encountered during drilling operations (as indicated by auger refusal).

The jack assembly was welded to the bottom of the steel reinforcement cage. Strain gauges were instrumented at four levels above the jack assembly, with each level consisting of four vibrating-wire sisterbar strainmeters spaced 90 degrees apart. The CSMs were installed adjacent to strain gauges located 8.8 feet above the jack assembly (designated as Strain-Gauge Level A1, “SGL A1”), with two CSMs installed orthogonally along longitudinal bars. Three thermal wires were additionally installed along each reinforcing cage. Figure 4 presents images of the installed CSMs on the reinforcing cages.

Fig. 4. Photographs of the Instrumented Reinforcing Cage

The CSMs were installed with the open face down to accommodate the self-filling method described by Sinnreich and Ryan (2022). The test piles were installed with 6,000 psi grout mix. The bi-directional tests were conducted 4 and 5 days after installation of TP-A and TP-B, respectively, and were performed in general accordance with ASTM D8169-18. Average grout strength on the days of the tests were approximately 5,800 for TP-A and 6,560 psi for TP-B, which were determined from the average of three 3-inch-diameter grout cylinders (6-inch height). Elastic modulus tests per ASTM C469 were additionally conducted on 4-inch-diameter grout cylinders (8-inch height). However, a relatively broad range of 2,300 to 6,150 ksi was determined, and therefore direct correlations to *in situ* determined elastic moduli could not be established. Real-time strain measurements were not obtained during the laboratory testing procedures, which further complicated the laboratory test data interpretation.

Each bi-directional static load test was conducted by applying load, Q, in 80-kip increments, with each increment held for at least 10 minutes. Instrumentation measurements were digitally measured and stored every 30 seconds throughout the entire load test duration. Applied load was increased until the maximum jack capacity was reached. Maximum upward pile movements ranged from 0.25 to 0.50 inch without any major plunging failure observed, indicating that the nominal geotechnical side-shear resistances were likely not fully mobilized over the test durations.

CSM RESULTS AND COMPARISON

The CSM measured stress versus average measured strains are presented in Fig. 5. The CSM results from TP-A generally resulted in a linear trend while TP-B exhibited non-linearity over the majority of the test duration. The elastic modulus determined from the linear portion for TP-A results with E_{Grout} of 3,250 ksi, which correlates well with the ACI method with a modulus reduction factor of 0.75. This modulus reduction factor falls within the anticipated range presented by Robertson and Komurka (2023). Alternatively, the stress-strain relationship measured from TP-B appeared to follow a similar trend as the non-linear/piecewise-linear function presented in Fig. 1. Further examination of the intrinsic elastic properties for TP-B will therefore be the focus in subsequent discussion since the nonlinearity was exhibited where the CSMs were installed.

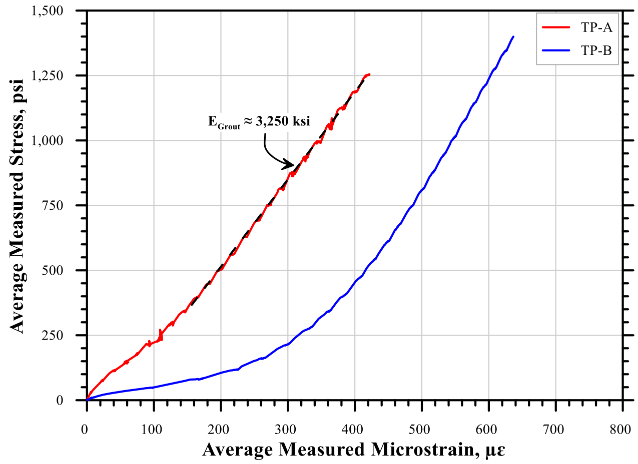

Fig. 5. CSM Stress-Strain Relationships

Figure 6 presents the tangential rigidity relationship from the CSM measurements on TP-B, as well as a comparison to the computed incremental rigidity from SGL A1 strain measurements. The tangential rigidity from the CSM measurements was determined as the difference in the incremental internal forces divided by the incremental strains. Incremental internal forces were calculated from combined stresses in both the grout (i.e., measured from the CSMs) and the steel reinforcement (i.e., calculated from the measured strains and an assumed steel elastic modulus). This calculated tangential rigidity follows a very similar trend as the piecewise-linear function outlined in Fig. 2. The assumed piecewise-linear rigidity function presented in Fig. 6 was therefore derived, and provides a similar trend as that computed from stress/strain measurements.

The I.R. relationship from SGL A1 shown in Fig. 6 consistently trended higher than that directly computed tangential rigidity at that location. Since side-shear resistances were likely not fully mobilized, this trend is expected because the incremental stresses at SGL A1 cannot be approximated from the incremental applied loads (which is inherently how the I.R. method is derived). Therefore, the I.R. relationship under these conditions should trend higher than the equivalent free-standing structural response, since measured strains were lower than the condition where ΔQ is realistically equal to ΔP. Komurka and Robertson (2020) discuss several critical aspects for properly applying the I.R. method.

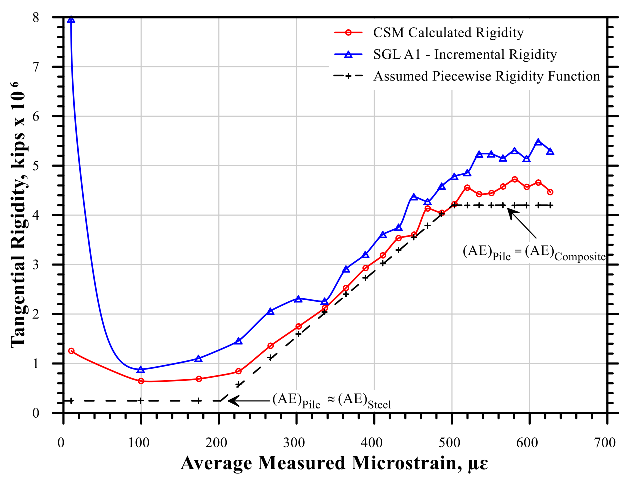

Fig. 6. TP-B Tangential Rigidity Relationships

Figure 7 and Fig. 8 present the piecewise-linear functions for TP-A and TP-B, respectively, based on the methodology described by Sinnreich (2011). Results from TP-A (Fig. 7) display both the measured strain data at SGL A1, where adjacent CSMs were installed, and SGL A2. These results delineate the significantly different strain responses where a constant rigidity (SGL A1) versus non-linear rigidity function (SGL A2) is required for reasonable conversion of strain to internal force. The assumed rigidity function at SGL A1 was assumed a constant 3,525,300 kips, which was equal to the maximum rigidity defined by the rigidity function for SGL A2 only beyond 500 με.

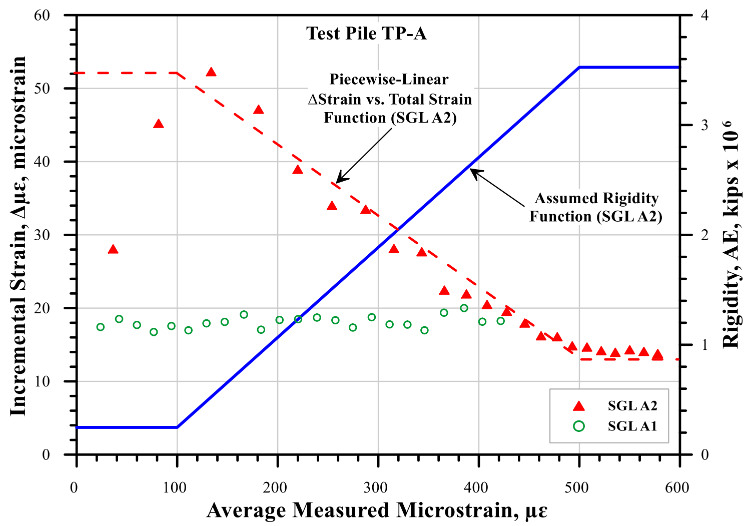

Fig. 7. Piecewise-Linear Rigidity Model for TP-A

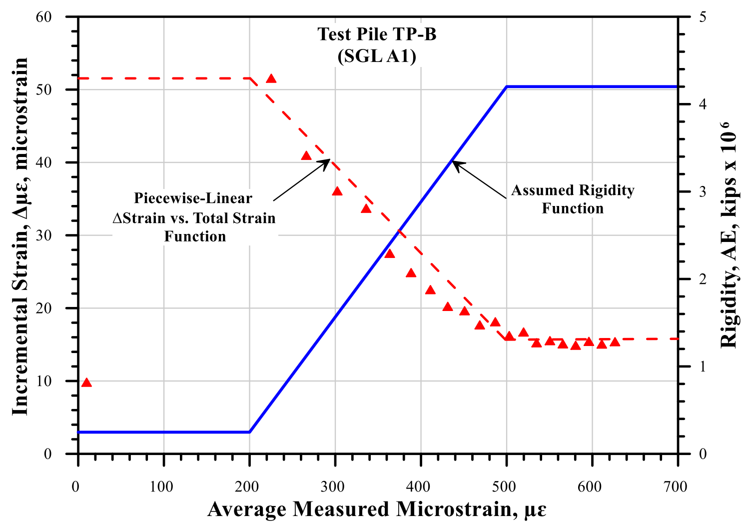

Fig. 8. Piecewise-Linear Rigidity Model for TP-B

Based on the derived piecewise-linear function in Fig. 8 for TP-B, the internal forces were computed from the average measured strains for each loading increment. A similar piecewise-linear function was derived for SGL A2, where there were no CSMs installed. Comparable derivations were considered for strain measurements in SGL A3 and A4, however a constant rigidity based on the ACI method was deemed appropriate for converting strain to internal force at these levels. Figure 9 presents the internal force profiles computed based on the established non-linear rigidity relationships compared to solely utilizing a constant rigidity determined using the ACI method for each test pile.

The ACI method resulted in computed internal forces at SGLs A1 and A2 that exceeded the applied test loads. This is a physical impossibility. The case history therefore demonstrates the importance that a constant rigidity model cannot be directly applied for all cases. Additionally note that the I.R. method could not be applied due to the lack of full resistance mobilization at SGLs A1 and A2. The piecewise-linear functions resulted in much more reasonable internal forces, which correlated better with the stratigraphy along the pile's embedded length. While practitioners may rely on neglecting strain measurements that exhibit abnormal trends, the resulting internal force profiles and computed unit side-shear resistances will certainly differ.

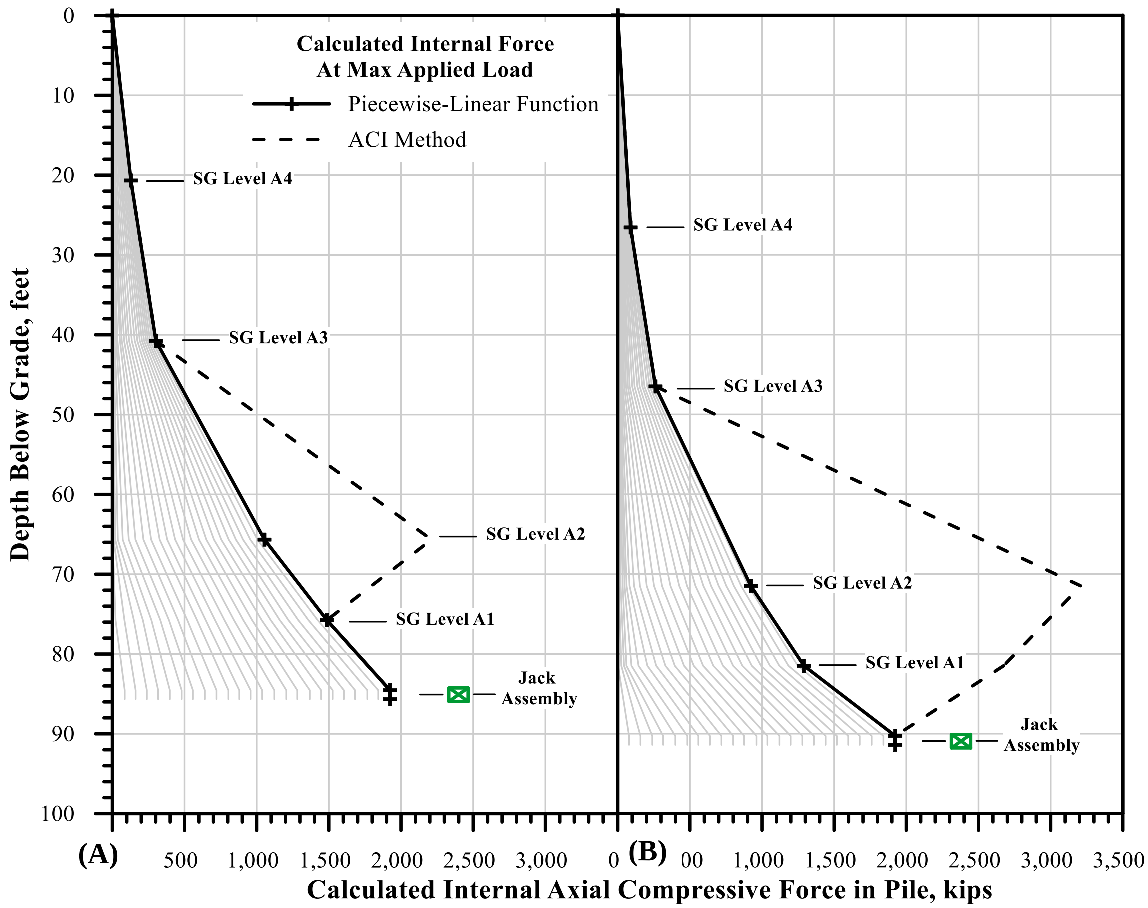

Fig. 9. Calculated Internal Force Profile Comparison for (A) TP-A, and (B) TP-B

The pile's axial rigidity under an assumed piecewise-linear function correlated very well to the computed rigidity based on the CSM measurements. The self-filling method of CSM instrumentation was demonstrated to effectively characterize a relatively complex stress-strain relationship for grouted foundations. While the results and correlations presented herein are very promising, further investigation may be warranted for routine application of CSM installation on load test piles. Calculation of the total axial force in the grout and steel is based on the assumption that strain is compatible across the composite section, and circumstances may arise where this assumption is invalid. Comparisons to multiple methods and existing theories of computing internal forces are therefore required. Additional corrections or measurement adjustments may be realized based on further research and testing, as well as correlations to elastic modulus laboratory test results. Improvement in the industry standard for designating the proper instrumentation and load testing requirements will further advance the interpretation of strain-dependent grout elastic moduli and application of CSMs in instrumented static load tests. Nevertheless, CSMs are viable and very promising for practical *in place* determination of stress-strain relationships on grouted deep foundations.

SUMMARY AND CONCLUSIONS

Instrumented static load tests are valuable for determining the total load bearing capacity for ACIP piles, as well as load distribution characteristics in side-shear and end-bearing resistances. Estimation of the intrinsic elastic properties of cementitious materials is required for proper interpretation of embedded instrumentation, particularly embedded strain measurements. There remains no routine methodology for directly measuring the elastic modulus of in-place grout, instead practitioners often rely on broad assumptions and semi-empirical formulations which may result in large margins of error. A case history was presented where stressmeters (i.e., CSMs) were embedded adjacent to strain gauges on two ACIP piles that were statically load tested. These embedded measurements accommodated assessment of the stress-strain relationship at a particular level in the test piles. While a linear-elastic response to applied loads was anticipated, as accepted in standard practice, a non-linear strain-dependent elastic modulus was actually exhibited at several strain gauge levels. The internal axial forces determined from the CSM measurements were compared to other interpretive methods commonly used. The comparisons demonstrated both that a piecewise-linear function is a reasonable approach for converting strain to internal force under these conditions, and that stressmeters are a viable option for direct determination of the in-place elastic properties of grouted foundations. Where complex stress-strain relationships exist for grouted deep foundations, embedded stressmeters may be the only means for accurately determining load distribution characteristics during static axial loading. Additional development of the stressmeter instruments may be required, in particular for improvement in static load test applications on ACIP piles and advancement to routine practice.

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