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Installation, Measurement and Interpretation of "Sister Bar" Strain Gauges in Micropiles

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INSTALLATION, MEASUREMENT, AND INTERPRETATION OF "SISTER BAR" STRAIN GAUGES IN MICROPILES

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Abstract

"Sister bar" strain gauges provide a cost effective and practical means of verifying the location of load transfer in micropiles. This paper provides a general overview regarding the use of strain gauges for interpretation of micropile performance. Topics covered include: pertinent applications, comparison to tell-tales, available equipment, installation, measurement, and interpretation. Emphasis is placed on illustrating the use of strain measurements to determine actual load transfer within the pile, including reconciliation with pile head measurements of displacement and load. Specific examples are used to highlight key points in the interpretation process, including transitions in ground strata and pile cross-sections, and in identifying poor data.

Introduction

It is generally desirable to understand the distribution of load transfer between pile and ground during a load test in order to assess the performance of the designed foundation system. Load transfer has historically been inferred by use of telltales, or through the use of strain gauges. In the case of micropiles, "sister bar" strain gauges have several advantages including accuracy, low cost, and relative ease of use. This paper provides a broad overview of their use and provides details on a specific application.

Pertinent Applications

The primary objective when installing strain gauges is to understand how the load is being distributed to the ground along the length of the pile. A few specific cases when this information is relevant include:

1. Confirmation that design load is carried in targeted bond zone,
2. Measure the depth of load transfer within the bond zone in order to assess of bond lengths can be shortened.
3. Measuring the true load on piles after construction
4. Understanding the differences in short term (undrained) and long term (drained) load transfer characteristics,
5. Accurate estimation of deformation under load.

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Comparison to Tell-tales

Historically, load transfer interpretations where made with the use of "telltales," where a telltale is a small diameter stiff bar that is encased in a tube and attached to the pile at a strategic location. Vertical movement of the bar is an indication of load transfer at the point of attachment. The magnitude of load transfer can be inferred from differences in relative movements of the pile head and individual telltales, by making idealized assumptions regarding the load transfer (or strain) distribution. Telltales can be an effective tool provided that they are installed properly, that they are not damaged during pile construction/installation, and that the subsurface profile can be sufficiently idealized to allow reliable interpretation of the data. In general, many installed telltales do not function properly such that the data available for load transfer interpretation is limited.

Unlike telltales where the average strain is measured between the pile head and the telltale or between two telltales, a strain gauge measures strain locally. Accordingly, the load in the pile at the location of the strain gauge can be estimated directly, provided the composite modulus of the pile is known accurately. For some pile types, including micropiles, the pile modulus can not be calculated accurately based on geometry and assumed material properties; it must be measured. This is true because of natural variability of grout modulus due to: changes with time, non-linearity with stress level, and variation with degree of confinement.

Available Equipment

Until recent years the strain gauges employed were typically thin electrical resistance based gauges that were glued onto a pile component at the desired location. The gauges function by noting small changes in resistance that occur with gauge elongation and the correlation with strain. The challenge was to install the gauges so that they would not be damaged as part of the installation/construction process. Also, the gauges and wires do have to be kept dry because moisture changes the electrical resistance and thus the measured resistance and interpreted strain. In the case of micropiles, which are drilled in elements, there is limited chance of success for strain gauges that are glued to the casing. Furthermore, gluing the strain gauges to the reinforcement bars is not straight forward requiring grinding a flat surface on the threaded rods and significant risk of damage during installation.

A sister bar strain gauge is a robust embedded instrument that consists of a vibrating wire strain gauge mounted on a length of steel rebar as shown in Figure 1. The basis for strain measurement is a wire under tension is clamped at both ends so that it can vibrate freely. Similar to a guitar string, the higher the tension in the wire, the higher the natural frequency of vibration. Strain in compression reduces the distance between the clamps and thereby reduces the natural frequency of the wire. Readings are taken by plucking the wire magnetically with an electric coil. The same coil (or another one) also measures the vibrating frequency. Through calibration there is a linear relationship between wire frequency and transducer strain. As with resistance strain gauges, a wire is used to transmit an electric current to the gauge and to return a signal, which is delivered to a readout box or data logger (see Figure 2). However, since the measurement is frequency of vibration of a wire, it is not affected by moisture or wire length. This is most evident when the gauge is read in the air and then placed in water and read again.

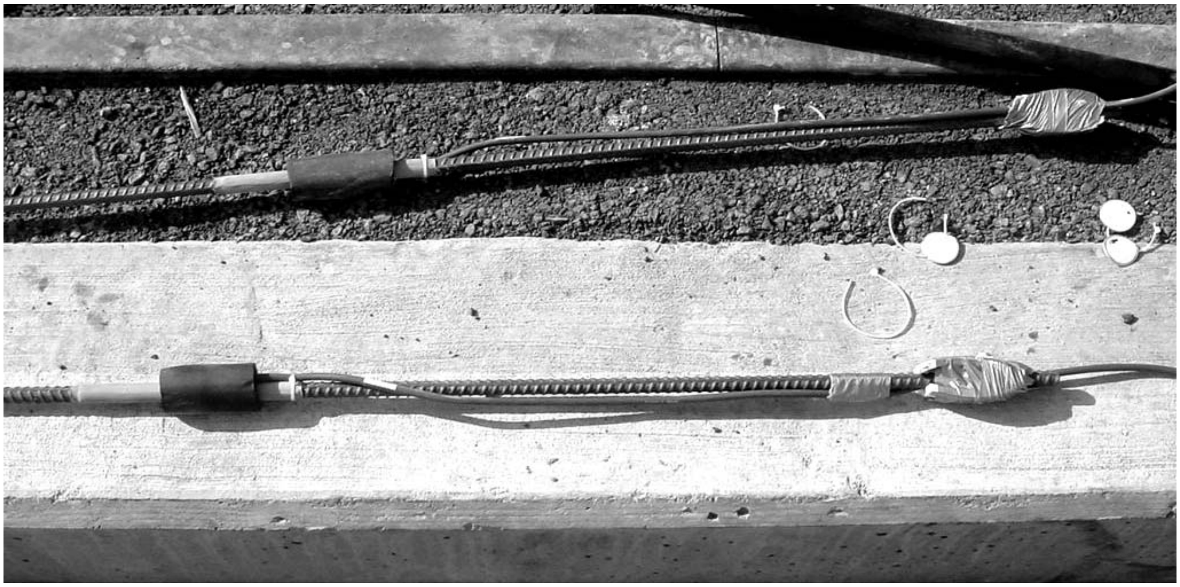

Figure 1 Sister Bar Strain Gauges

Figure 2 Datalogger and Multiplexer

Planning and Location of Gauges

Cost and pragmatics limit the number of strain gauges that can be used. Accordingly, it is necessary to position the instruments strategically in order to obtain the desired data. Generally, the instruments are used to assess the applicability of the model employed in the design analysis. In most micropile applications the objectives are to demonstrate that the load is being transmitted to the bond zone and to verify the reduction in load within the bond zone. Accordingly, it is common to concentrate the strain gauges in this zone. However, it is important to place additional gauges at the pile head to measure the composite modulus of the pile.

Typical layout of the gauges is shown in Figure 3 and described as follows:

1. Two gauges 3 to 5 feet below the top of the pile to measure composite modulus and two average out bending,
2. Just above the bond zone to record the load that is getting to the bond zone,
3. Within the upper few feet of the bond zone and below the typical change in reinforcement (often no casing in bond zone),
4. Midway in the bond zone to assess load distribution and to assess actual bond stresses for possible redesign of the pile if desired,
5. Near the bottom of the pile to determine how much (if any) load is being transferred in end bearing.

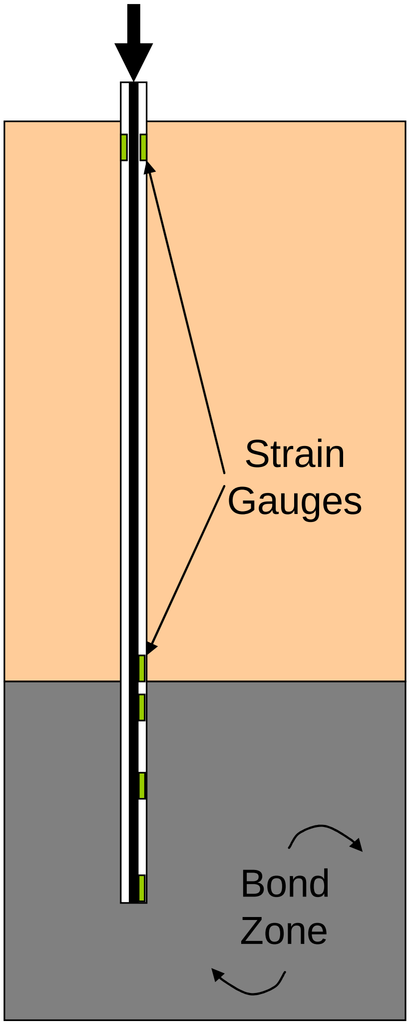

Figure 3. Typical strain gauge layout.

The reason for two gauges at the top are to average out bending strain caused by imperfect loading. These gauges need to be placed equidistantly from the centerline of the pile and preferably on the sides of the pile perpendicular to the axis of the test beam, which is the most likely direction of bending. The gauges at the top of the pile should be far enough from the end of the pile to minimize non uniform strain distribution, while being close enough to measure the applied load. Pairs of gauges at depth are often not used because the bending at depth is minimal.

The reason for a gauge near the top of bond zone is that the pile section, especially the area of steel, often changes in the bond zone. When planning the location of the strain gauge, the length of the sister bar must be considered to keep the bar length in the same section of pile and avoid casing joints.

When ordering the gauges, inform the gauge manufacturer whether you intend to load the pile and gauges in compression or tension and the estimated strains for each case. This will allow the proper selection of gauge with a more appropriate vibration range for the test being conducted.

Installation

For micropiles, the rebar and mounted gauges are typically tied to the threaded reinforcing bar(s) and lowered into position. Care must be exercised not to damage the wires during or after installation and arrangements must be made to pass the wiring through the casing or bearing plate.

Precautions that should be taken during installation include:

- Label all wires (most instrument manufacturers assign a serial number to each gauge and provide a label of the serial number on the wire)
- Do not proceed without the special vibrating wire gauge measurement unit (typically the readout box) and be sure to have the readout box in the proper setting,
- Read the gauges as delivered and compare readings to factory zero readings,
- Layout the gauges on the bar at the desired location,
- Modify the gauge locations as necessary with the as-built pile. Try to place the bar in the same cross section of the pile and avoid alignment with casing joints.
- Note the gauge serial number and as-built location ,
- Zip tie or duct tape the reading wires to the sister bar with a little slack in the cable using care to not cut the wire. This will avoid pulling on at the wire/gauge connection.
- Tiewire the gauges to the pile reinforcing bar and read again and compare to factory zero,
- Modify centralizer locations near the gauge (do not let centralizer location change the target location of the gauge),
- While placing the pile reinforcing bar down the pile, zip tie or duct tape the reading wires to the bar using care to not cut the wire and not allow bulges in the wires that could get cut at pinch points (bar couplers or casing threads),
- Use plenty of bar centralizers and run the wires through the centralizers, not on the outer edge of the centralizers
- Do not cut the wires without relabelling which gauge serial number on the wire,
- Obtain readings initially after gauge placement and grouting, during grout hydration, and after grout is hard,
- Prior to testing, put a nut on the bar with the upper face in the plane of the casing edge, fill the entire annulus with grout and place the bearing plate on top. This will improve the even loading of the inner rod, the grout and the casing and the evaluation of composite modulus. This is discussed further below regarding Figure 7.

Most manufacturers' literature recommend against hanging the sister bars from the electrical wire. However, in piles without a central bar, we have successfully inserted the gauges after neat cement grouting by duct-taping the wire to the sister bars (to avoid tension at the connection), then lowering with the wire (See Figure 1) and hanging the sister bar from the wire.

Most gauges also have a temperature sensor. It is interesting to see how hot the grout gets. On one project, the grout inside 7 inch casing reached a temperature of over 100 deg C and gauges appeared to have functioned fairly well during the load test.

Measurement

The strain gauges arrive factory calibrated. Strain readings can be recorded manually using a digital readout unit or automatically with a data logger. The strain gauges are typically connected to a junction box. For manual readings, a switch box can be used to read each gauge sequentially using the digital readout unit. Alternatively, the data logger cycles through each of the strain gauges and takes readings at preset time intervals or with computer keystrokes after some datalogger programming. These time intervals are synchronized with the pile loading sequence. These components are shown in Figure 2.

The gauges measure strain relative to some arbitrary "zero" strain condition. Usually, the zero condition is taken to be the readings just prior to the application of load on the pile, after the gauge has acclimated to the stress and temperature conditions for the as constructed condition. All strains, and therefore loads, are assumed to be relative to this base condition. However, it is important to obtain background readings and evaluate the change in strain between installation and testing.

Interpretation

Strain measurements are obtained at the location of each gauge at specific loads and times. In general, the objective is to acquire loads in the piles at these locations. The relationship used to estimate local load in the pile is as follows:

$$\varepsilon_a = \frac{\Delta L}{L} = \frac{\sigma_a}{E} = \frac{P}{AE} \qquad (1)$$

Where:

ε_a	=	Axial strain
ΔL	=	Change in length
L	=	Length
σ_a	=	Axial Stress (average)
E	=	Young's Modulus (average)
P	=	Force in pile
A	=	Cross-sectional area

Rearranging Eqn. (1)

$$P = AE\varepsilon_a \qquad (2)$$

Accordingly, it is necessary to estimate the average Young's modulus in order to estimate the pile load from strain measurements. One approach is to obtain the weighted average from the grout and steel components, such that:

$$AE = A_g E_g + A_s E_s \qquad (3)$$

The drawback of this approach is that the modulus of the grout is not known accurately, and varies with axial and confining stress, and with strain levels. A better approach is to include strain gauges at a location where the pile load (Gauges 1 and 2 in the above list) is reliably known such as just below the pile head, and use this information to back calculate the average pile modulus versus strain. Gauges a few feet above and below any change in cross section can be used to estimate AE versus strain. The measured AE should always be compared to the theoretical AE and differences understood and explained. Due to the grout, the AE should decrease with strain.

Example Data from a Real Load Test

An example problem is used to illustrate interpretation of sister bar strain gauges. The ground conditions were silts, clays and loose sands to a depth of approximately 100 feet underlain by very dense till which served as the bond zone. Five strain gauges were installed (Fig. 4): a set of parallel strain gauges at the pile head to calculate the average pile modulus; one gauge approximately midway through the overburden; one gauge just above the bond zone; and one gauge near the base of the bond zone.

Figure 5 shows the measurements of strain versus normalized time for each gauge. Superimposed on this figure is the load applied to the pile head. Strains are measured from the left y-axis, while load is measured from the right.

The measured strain versus pile head load is shown in Figure 6.

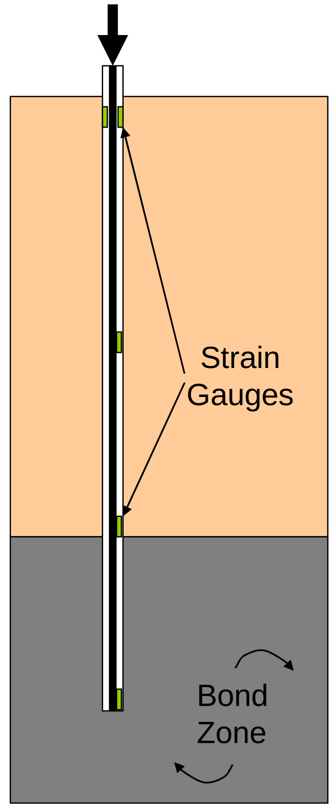

Figure 4. Layout of strain gauges in example case.

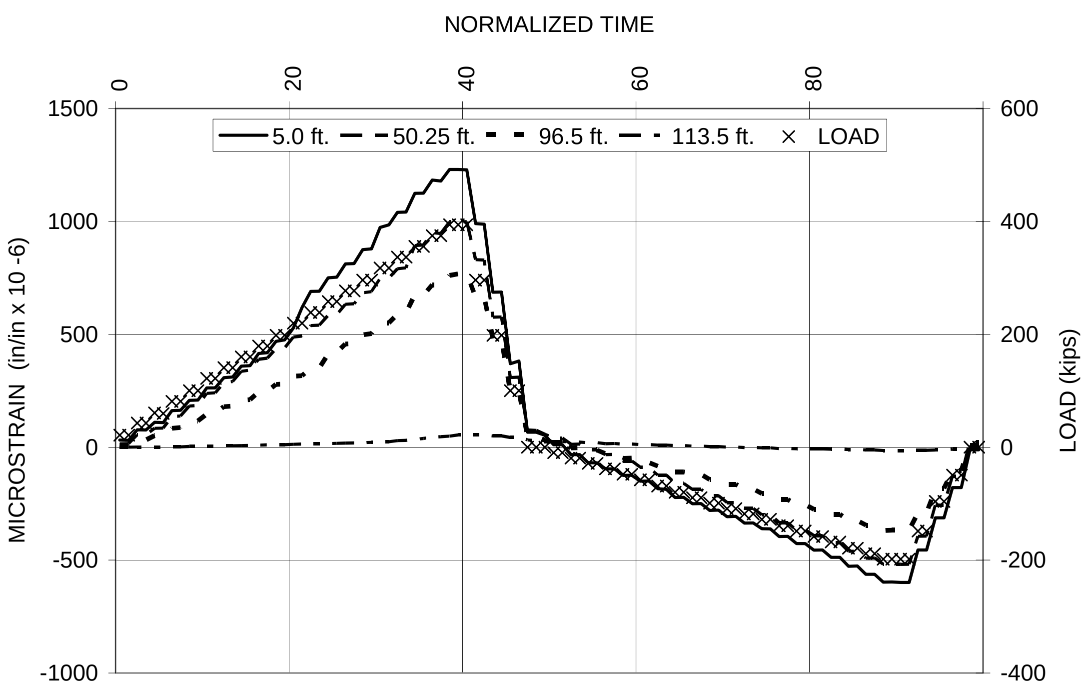

Figure 5. Measurements of strain at each gauge versus normalized time.

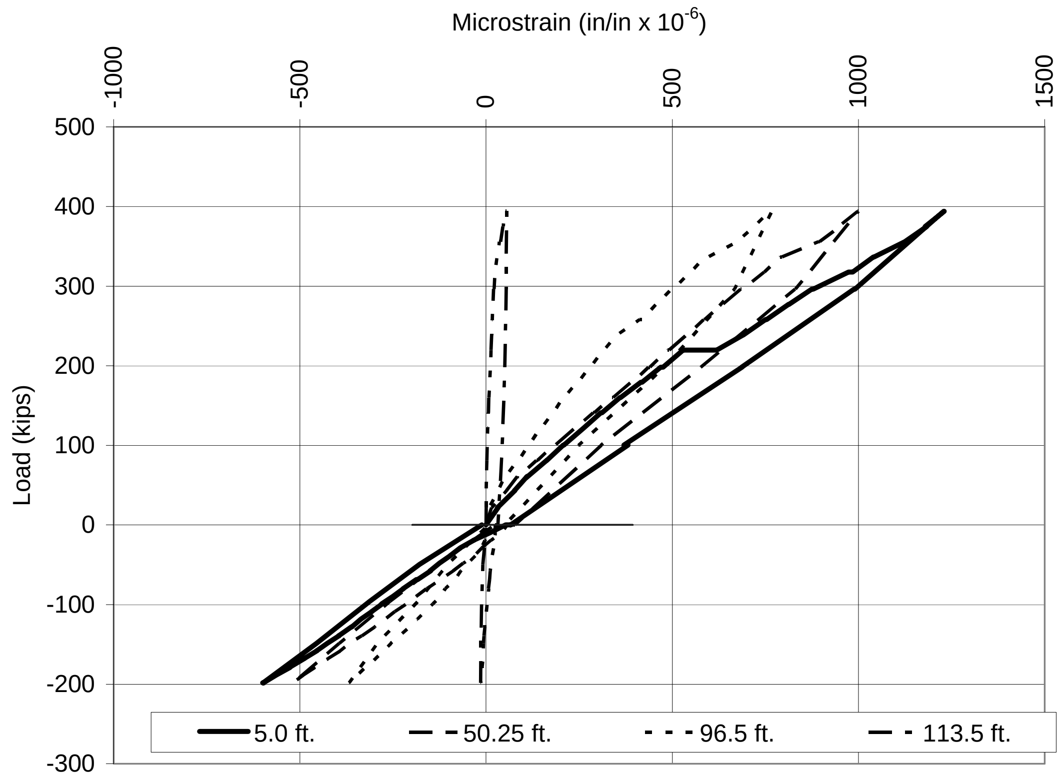

Figure 6. Measured strain versus pile head load.

The average Young's modulus of the pile can be estimated using the strain data from the gauges located five feet below the pile head assuming that 100% of the jack load is applied to this section. These data are summarized in Figure 7. The solid squares represent the results obtained from the average of two gauges. Two gauges are used in order to compensate for possible eccentric loading conditions. The data show that the modulus at lower pile loads is greater than at larger pile loads. For comparison, "theoretical" average moduli are superimposed on the data considering: i) the composite pile; and ii) only the steel section. Under compression loading the true modulus decreases by approximately 50 percent, while in tension the decrease is approximately 20 percent.

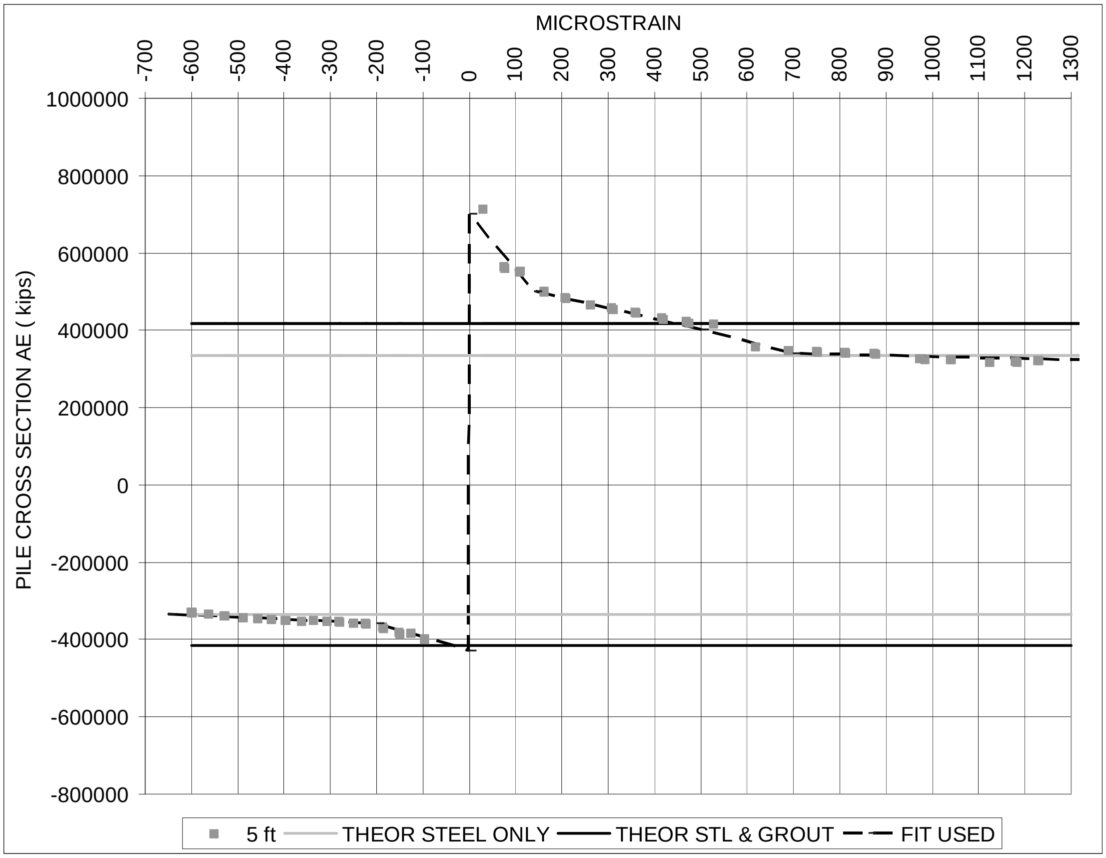

Figure 7 MicroStrain versus Measured AE

The measured AE approached the theoretical line for steel only suggesting that the grout had little contribution. On this particular test, this has been attributed to the bar going through the bearing plate without a nut on the bar below the bearing plate and possibly a low grout level. Therefore, the load was applied to the casing at the top of the pile and had to be transferred through bond and shear to the grout and the bar.

The best fit line in Figure 7 was used to represent the change in pile modulus throughout the tests and was therefore used to interpret the pile loads from strain measurements at depths of 50.3 and 95.0 feet. The gauge at a depth of 113.5 feet is in the bond zone such that the cross-section of the pile is different and the back calculated modulus is not applicable. Accordingly, a theoretical estimate of the modulus was used at this location. Using these interpretations of pile modulus, the distribution of load within the pile is shown in Figure 8 for several specific pile head loads.

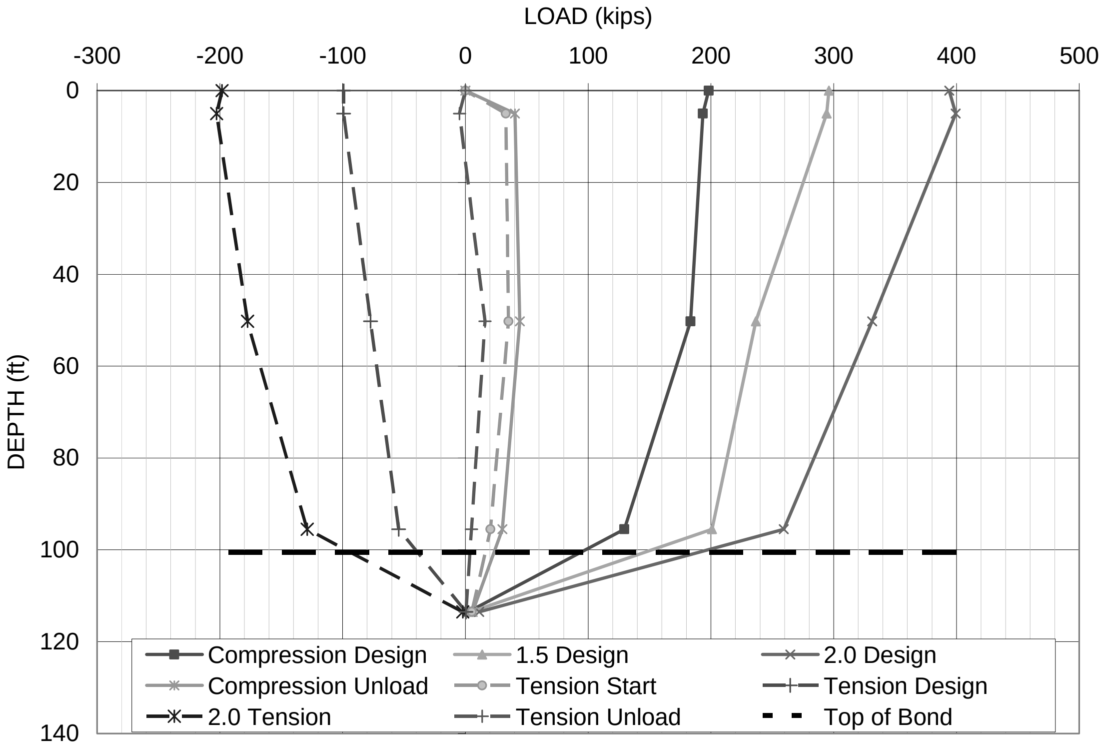

Figure 8. Interpreted load distribution within pile at various applied head loads.

At the design compressive load of 200 kips, approximately 125 kips are transmitted to the bond zone while the remaining 75 kips are transferred to the overburden. At the maximum compressive load of 400 kips, approximately 250 kips are carried in the bond zone. In tension, approximately 75 kips are carried in the bond zone at the design load of 100 kips.

The test pile was first loaded in compression and then tension (Figure 5). Figure 6 and 8 illustrate that the strain gauges did not return to "zero" after unloading the pile in compression. Residual strain is present within the pile because the overburden provides shear resistance during the unload process. Accordingly, the tension portion of the tests is starting from a residual compression condition. For future discussion on this topic, see Richards (2005).

The strain gauge readings can also be used to approximate the elastic movement versus depth by using the following formulas:

$$\delta e = \varepsilon \cdot L$$

and considering versus unit length:

$$\delta e = \int_z^D \varepsilon \cdot dz$$

where:

z = depth of a particular gauge
D = bottom of pile

This requires assumptions of strain distribution between gauges to complete the integration.

Figure 9 depicts the estimated distribution of displacements within the pile based on the strain gauges measurements and assuming a linear distribution of strain between gauges. Accordingly, this distribution is only approximate. Had telltales been used, the displacement would be "known" at one location per telltale and the interpretation of load would require following this process in reverse including the needed underlying assumptions.

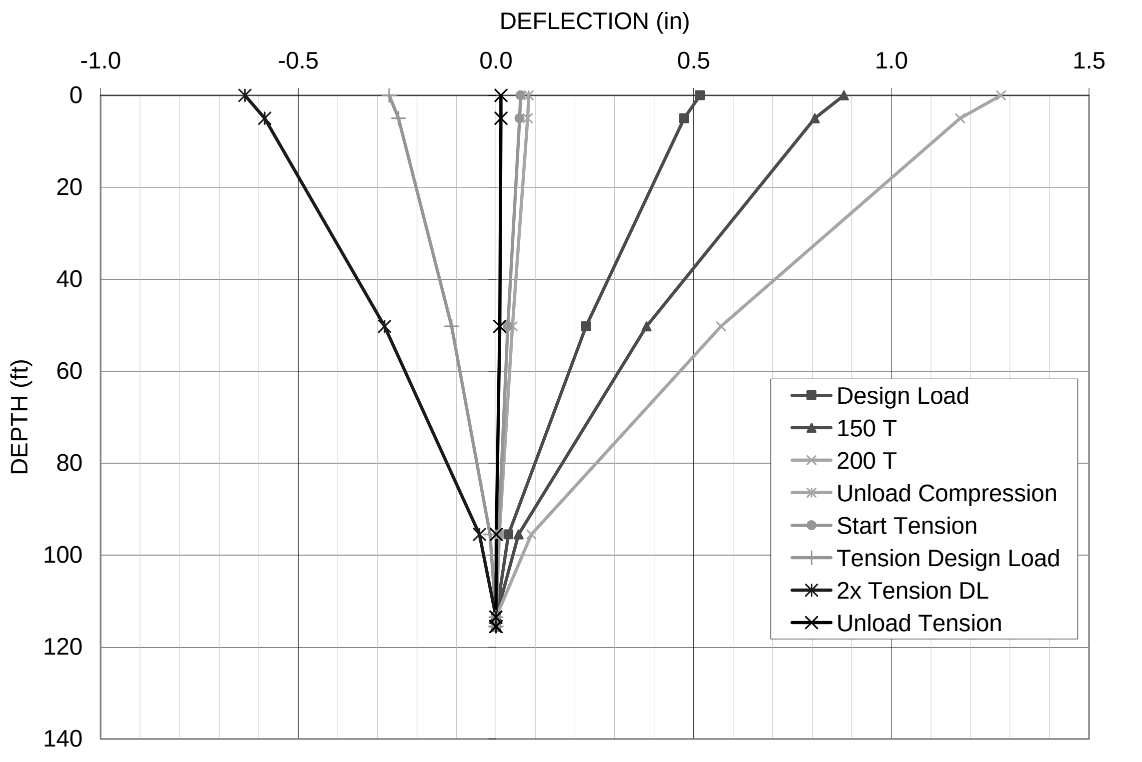

Figure 9. Approximate distribution of vertical pile deflection with depth.

Encountering Anomalies

<u>Increasing Stiffness at High Strains</u>

Sometimes at high strains the apparent measured stiffness (AE) increases. This is not realistic and can be attributed to one or more of the following:

- Reaching a non linear range of the strain gauge or limit of the strain gauge,
- The gauges not obtaining a true average strain,
- Debonding of the sister bar,
- Possibly not really applying the maximum load to the top pair of gauges because of friction in the jack or inconsistent load transfer at bearing plate due to uneven grout level or nut on bar, or gauges are positioned too close to the pile top.

Tension in Upper Gauges after Unloading from a High Load (such as Maximum Test Load)

Often after applying a large maximum test and then unloading, the upper gauges indicate tension even when no tension load is being applied. This may be real in that the grout is now under tension because it reached a high strain, then tried to rebound along an unloading curve, not the initial parabolic stress strain curve. The casing continues to rebound and forces a tension strain in the grout, which shows up in the sister bar since it is bonded to the grout.

Conclusions

Sister bar strain gauges are very useful in evaluating micropile load tests. Installation is fairly simple but must be done with care and reading must be obtained during installation and prior to load testing. The non linear AE versus strain must be considered in evaluation of the measured strains, particularly in compression. Details at the top of pile including nuts on the bar and fully grouting the top of the pile influence the measured AE at the top of the pile and the success of using that measured AE. A very good appreciation of the testing sequence and mechanics of materials is required to account for anomalies.

References

Richards, T.D. (2005). “”Pent Up” Load and Its Effect on Load Test Evaluation.” *Proceedings of the GeoCubed ADSC Conference*, ADSC, November 2005