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Considerations for Measuring Residual Stresses in Driven Piles with Vibrating Wire Strain Gauges

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**Considerations for Measuring Residual Stresses in Driven Piles with Vibrating
Wire Strain Gauges**

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Abstract

Vibrating wire strain gauges are often the preferred technology for measuring strain in driven piles. However, measuring the residual strain after pile driving is challenging to accomplish using vibrating wire gauges. The driving process can cause a shift in the no-load reading from a relaxation of locked-in manufacturing strains in the pile or relaxation of the gauge wire tension. Also, there are temperature effects from installing piles below ground. A test pile program was developed using driven steel H-piles instrumented with vibrating wire strain gauges. The piles were subjected to dynamic forces by striking against a steel plate in attempt to relax the locked-in manufacturing strain prior to installation. The strain gauges and thermistors were connected to a data logger during pile driving to record strain and temperature changes following installation. It was observed that applying a dynamic impact to the piles prior to installation resulted in a shift of 0 to 5 microstrain. Temperature effects from installing the piles in cooler ground resulted in a shifts of strain in excess of 60 microstrain in some strain gauges. It is concluded that temperature induced shifts to strain must be measured following pile driving to interpret residual stresses.

Keywords: residual stress, driven, piles, strain gauge, temperature

30 Introduction

31 Vibrating wire strain gauges are often the preferred technology for measuring strain in driven piles
32 because of their long-term stability and durability, their ability to have long cable lengths without adverse
33 affects on measurements, and their ability to take measurements in conditions with excessive moisture
34 which would short circuit electrical gauges (Paikowsky and Hajduk 2004). Often the analysis is performed
35 assuming that no residual stress is present in the test pile, i.e., gauges are “zeroed” prior to a load test
36 (Briaud and Tucker 1984). In order to measure residual stresses in a driven pile, a representative reading
37 is required for the no-load condition or zero reading prior to installation. Even when acknowledged, it can
38 be challenging to accurately measure residual stresses. For example, Seo et al. (2009) reported that they
39 obtained no-load strain gauge readings on H-piles prior to installation. After pile driving, the strain
40 distribution did not reflect the expected distribution for residual loads in a driven pile. Fellenius (2002)
41 described several challenges when attempting to record a no-load condition for a strain gauge which
42 includes: (a) steel piles experience a relaxation of locked-in strain that existed due to uneven cooling from
43 the manufacturing process of the steel pile, (b) temperature change of the pile from installation in the
44 cooler ground environment will affect strain, (c) overstressing a gauge beyond its limits will cause a shift
45 in the no-load reading and disturb the calibration for strain, and (d) bending in the pile causes greater
46 strain on one side and a reduction in strain on the other.

47 Randolph et al. (1994) suggested that the locked-in manufacturing strain in a steel pile could be relaxed
48 or “shaken out” prior to taking the no-load reading by applying a dynamic forces to the pile before
49 installation. The authors are not aware if this methodology to relax the manufacturing strain has been
50 attempted in the past.

51 Thermal stresses are expected to develop in piles due to temperature change and friction between the
52 soil and pile which restrains the pile from expanding or contracting with temperature change (Budge and

Dasenbrock 2011). In many cases, temperature effects are ignored because temperature changes are minor at depths significantly below ground surface (Budge and Dasenbrock 2011). This is only true however after the pile and ground temperature reach an equilibrium some time after pile installation. GEOKON (2019) describes the necessity for correcting vibrating wire strain gauge readings for temperature changes if the ends of a structural member is restrained by a semi-rigid medium. In cases where the end of a structural member are free to expand or contract due to temperature changes without restraint, there is no need to correct the strain gauge readings because the vibrating wire has an identical thermal expansion coefficient to that of the steel member. If the ends of a structural members are restrained by a semi-rigid medium however, then thermal expansion or contraction of the structural member is restrained. In the case of piles being installed in cooler ground, the pile cools but is restrained from contraction from friction along the pile. The vibrating wire itself is not restrained from contracting due to temperature change however. The contraction of the vibrating wire is indicated by an increase in tensile strain in the datalogger. The authors are not aware of any pile instrumentation program where vibrating wire strain gauges were connected to a datalogger during installation to measure these temperature effects.

This study was developed to address these limitations in interpreting residual loads in driven piles using vibrating wire strain gauges. The objectives of this study include: 1) to test whether subjecting a pile to a dynamic forces prior to installation can relax locked-in manufacturing strain for an improved no-load reading, and 2) to observe temperature effects on strain gauges after installation and provide recommendations to correct for potential shifts in strain. A full-scale test pile program was developed to test these objectives.

Test Pile Program Methodology

Site Description

The study site is located approximately 2.5 km west of Winnipeg, Manitoba in the R.M. of Headingley. The stratigraphy at the site consists of approximately 0.5 m of fill overlying high plastic lacustrine clay extending to approximately 7.5 m below ground surface over sandy silt till. The clay is stiff, heavily overconsolidated and contains trace amounts of sand and gravel. The till is very dense below depths of approximately 8.8 m. The till stratum in and around Winnipeg is typically a well graded mixture of clay to boulder sizes and is predominantly comprised of silt sized particles (Baracos et al. 1983). The groundwater table was measured to be approximately 2 m below ground surface at the time of pile installation.

Pile Instrumentation

Two HP 310x94 piles were instrumented with arc-weldable vibrating wire strain gauges (RST Instruments model VWSG-A). The piles are referred to as Pile A and Pile B. Two piles were instrumented for redundancy in the event strain gauges were damaged during pile installation. The arc-weldable strain gauge type was selected due to the long-term stability and successful survivability from previous studies on driven piles by others (Budge and Dasenbrock 2010, Budge et al. 2015, Drbe et al. 2017). The configuration of the strain gauges on the piles is shown in Figure 1. Figure 2 shows a strain gauge installed on the flange of a pile. The location of the instruments installed on the piles relative to the soil profile is shown in Figure 3. The strain gauge spacing was closer near the pile tip due to the risk of damage near the tip and the importance of interpreting the stress at the tip. Two strain gauges were installed at each elevation on opposite flanges to account for potential bending. The strain gauges were protected by welding a 76.2 mm x 76.2 mm x 9.5 mm steel angle along the flange of the pile. A telltale pipe was welded to the pile to measure compression during a static load test completed at a later stage.

The strain gauge pairs are labelled SG P1 through SG P10 on Figure 3. SG P8, SG P9 and SG P10 provide insight into whether there is a shift in strain from the pile driving process. The change in stress above ground is known to be that of the self-weight of the pile. An embankment was later constructed around

the test piles and the remaining stickup was cut prior to performing a static load test on the instrumented piles.

Each strain gauge and its thermistor were connected to an RST Instruments data logger (DT2040 model) to record periodic strain and temperature readings for the following stages of the test pile program.

Relaxing Locked-in Manufacturing Strain

Randolph et al. (1994) suggested striking a steel pile against a concrete pad prior to installation to relax or “shake out” the fabrication strains to obtain an appropriate no-load reading of the strain gauges. In this study, the pile head was struck with the hammer while the pile tip rested on a 25 mm thick steel plate on the ground. The pile was laid on the ground to measure strain for unloaded condition before and after striking against the steel plate. The piles were laid down on the edge of the flanges to minimize the bending across the X-axis indicated in Figure 1. Pile A was struck against the steel plate twice with approximately 3 kJ per blow. Pile B was struck twice with 3 kJ per blow and then once with approximately 7 kJ. This energy is less than what was later applied during pile driving. The piles were struck with only several blows and less energy than pile installation to avoid damage to the welds of the angle protection. A Pile Driving Analyzer (PDA) was not used during this stage to measure the stresses in the pile.

Pile Installation and Measurement of Temperature Effects

Pile A and Pile B were driven to approximately 8.8 m and 9.1 m depth, respectively with a Junttan HHK 5S hydraulic hammer. The piles were driven to be end-bearing on the silt till below the very dense 8.8 m boundary. Pile A and Pile B were driven with an approximate energy of 13 kJ and 14 kJ, respectively, at end of initial driving (EOID) as measured using a PDA. An additional six piles were installed at the site for use as reaction piles for the static load test. Pile A was installed on Sep. 18 and Pile B was installed on Sep. 19, 2019. The piles were subjected to several sets of restrikes within one day following EOID. Figure 4 shows the test piles and reaction piles after installation.

The strain gauges and thermistors were connected to the data logger during installation. The data logger was programmed to read instruments at 40 s intervals to record strain and temperature following pile installation. Later, the data logger was programmed to collect data in hourly intervals after the temperature stabilized.

Results

Relaxing Locked-in Manufacturing Strain

A representative set of strain gauge data is shown for Pile A and Pile B in Figures 5 and 6, respectively. The data is from strain gauge pairs SG P4 on each pile. The no-load or zero reading was taken at approximately 12:00 am on the day of installation when the ambient temperature was relatively stable and the strain gauge readings were stable. The data shown includes greater than 30 minutes before lifting the piles and greater than 5 minutes after laying the pile down.

The change in strain is observed from comparing the average strain before and after striking the pile against the steel plate. Despite always placing the piles on the edge of the flanges to minimize bending, evidence of bending is observed from one gauge measuring an increase in strain and the other measuring a decrease in strain.

This exercise was completed for Pile A during the afternoon of September 18, 2019. The ambient temperature was not stable and the pile was subject to direct sunlight which caused strain readings to fluctuate before the procedure. The procedure was performed for Pile B the following morning when temperatures were more constant and strain readings were more stable. Therefore, the shift in strain can be more accurately quantified when observing results from Pile B. The change in average strain from applying the dynamic impact is approximately 1 microstrain for SG P4 of Pile B in Figure 6. The absolute change in average strain from all strain gauge pairs on Pile B ranged from approximately 0 to 5 microstrain.

There was not a significant shift in the measured strain from performing this process, therefore the no-load reading obtained at 12:00 am on the day of installation was deemed suitable.

Measured Strain and Temperature

A representative sample of early strain gauge and thermistor data for Pile A and Pile B is shown in Figures 7 and 8, respectively. Data is shown from EOID for three hours after EOID where temperature decreased rapidly from installation in the cooler ground. Positive strain is representative of compressive strain. The strain and temperature data shown is an average of the two instruments installed at the elevation. For both piles, the hammer was resting on top of the pile after EOID until following a restrike at 2.4 hours after EOID. A sudden change in strain is observed when the weight of the hammer is permanently removed at this time. The measured decrease in strain for strain gauge pairs above ground surface was approximately 25 to 30 microstrain when removing the hammer weight.

For Pile A, EOID occurred at 3:53 PM on September 18, 2019. Restrikes were performed at approximately 15 minutes and 143 minutes after EOID. The hammer was resting on the pile between restrikes and was removed at approximately 146 minutes after EOID. A temperature decrease greater than 15°C was observed at SG P3 within two hours after EOID from installation in the cooler ground. The compressive strain decreased by over 60 microstrain during this time. There appears to be a proportional decrease in measured strain and temperature after EOID.

For Pile B, EOID occurred at 9:55 AM on September 19, 2019. Restrikes were performed at approximately 4 minutes, 19 minutes, and 148 minutes after EOID. The hammer was resting on the pile between restrikes and was removed at approximately 166 minutes after EOID. A decrease in temperature was similarly observed after installing the pile in the cooler ground. The temperature measured for Pile B at EOID were less than Pile A because Pile B was installed in the morning. The temperature decrease was less than 10

°C for each strain gauge pair. Similar to Pile A, there appears to be a proportional decrease in measured strain and change in temperature.

The relationship between the measured strain and measured temperature for an isolated timeframe shortly after EOID is shown in Figure 9. The time range is indicated from the boxed area in Figures 7 and 8. The time frame was selected to include the rapidly decreasing temperature and exclude restrikes where there are sudden shifts in the measured strain. During this time frame, the relationship between measured strain and temperature is observed to be linear. Additionally, the majority of the pile length is installed within high plastic clay in which excess porewater pressure from pile installation dissipates slowly. The loads in the pile are expected to be constant after coming to an equilibrium or can increase with time due to reconsolidation of soft soil that was displaced from pile driving (Briaud and Tucker 1997). For these reasons, the temperature change after pile installation is believed to be the dominant affect on the measured strain. The decrease in measured strain is not believed to be representative of a change in external loading on the pile or along the shaft. Therefore, calculating stress in the pile from the measured strain will result in an incorrect interpretation of residual stress.

Temperature Correction for Residual Stress

A correction of the measured strain was considered for an improved estimate of residual stresses. The measured strain was corrected by neglecting the decrease in strain caused by a decrease in temperature. This correction was considered for up to 120 minutes after EOID when temperature appears to have stabilized. The strain was considered to be constant after reaching a peak compressive strain after installation until 120 minutes after EOID. Figure 10 and Figure 11 show the residual stress for the representative strain gauge pairs below ground. The axial stress (σ) is calculated as:

$$(1) \quad \sigma = \varepsilon E$$

where ε is the average strain and E is Young's modulus of the pile. σ is calculated both directly using the measured strain and a corrected strain to account for the temperature effects shortly after EOID.

There are several construction activities that caused stress changes shown in Figures 10. For Pile A, a decrease in strain was observed for all strain gauge pairs below ground around 18 hours after EOID. This coincides with the time that Pile B was being initially driven. This indicates that the increased porewater pressure due to ground vibrations from driving the adjacent pile resulted in a decrease in effective stress and decrease in shear stress along the shaft. Also, there is an observed increase in compressive strain at approximately 24 hours after EOID. This increase corresponds to a time shortly after a restrike of Pile A and the hammer was temporarily resting on the pile top.

The distribution of axial force (F) with depth is shown for Piles A and B in Figure 12 at a time of 6 hours after EOID. The axial force (F) is calculated from:

$$(2) F = \sigma A$$

where A is the cross-sectional area of the pile. A is approximately equal to 146 cm² for the HP310x94 with the welded angle protection. These residual loads are representative of an unloaded pile at a time where the residual loads are changing very gradually. The residual loads are shown as calculated from both the measured strain and corrected strain. If there were no residual loads, then the measured load would be equal to that of the self-weight of the pile. The residual loads as calculated from the corrected strain indicates that there are compressive residual loads. The residual loads are considerably smaller when interpreted from the measured strain. If the residual loads are calculated from the measured strain, then, the residual loads appear to be minor or even in tension.

The change in axial force is known above ground to be equal to the self-weight of the pile. It is evident from the strain gauges above ground surface that there was a shift in the no-load reading from pile installation. This shift is less than the difference in the apparent force and corrected force below ground.

Calculating the load from the corrected strain better reflects the expected distribution of residual loads with accumulation of compressive force with depth due to negative skin friction and a compressive tip force. Studies have shown that a stiffer end-bearing response at the pile tip will result in a neutral plane that is lower along the pile shaft (Lucarelli et al. 2014). The maximum force in Pile A and Pile B is at the pile tip. This indicates that the neutral plane is at or near the pile tip and there is an accumulation of drag force from negative skin friction along the majority of the pile. The residual tip force is equal to approximately 220 kN for Pile A and 140 kN for Pile B.

Discussion and Conclusions

The aim of the study was to overcome limitations of using vibrating wire strain gauges to measure residual stresses in driven steel piles. The procedure of striking the piles against a steel plate in attempt of relaxing locked-in manufacturing strains prior to pile installation resulted in shifts of 0 to 5 microstrain for the no-load strain gauge reading. It was identified from measuring temperature and strain immediately after pile installation that temperature decreases caused a greater shift in strain, with a shift in excess of 60 microstrain measured for some gauges on Pile A. The strain readings were corrected for the temperature effects to achieve an improved measurement of the residual stresses following pile driving.

It is the authors' opinion that applying a dynamic impact to instrumented piles prior to installation as suggested by Randolph et al. (1994) is not necessary based on the relatively small shift in strain. It is possible that prior handling of the piles applied sufficient dynamic force to relax any locked-in manufacturing strains. Alternatively, the energy and stress applied during this procedure was insufficient to relax the locked-in manufacturing strains. This procedure did however provide greater confidence that there were not large shifts in strain during pile installation and the measured strain after EOID was representative of the actual stress in the pile. The shift in the no-load reading from pile driving was much smaller than the shift from temperature changes following installation.

Budge and Dasenbrock (2011) corrected vibrating wire strain gauge readings to account for thermal stresses for seasonal temperature changes near ground surface. In that study, the vibrating wire gauges were installed on sister bars which were lowered into a driven pipe pile before pouring concrete. Therefore, the no-load reading in their study was taken after the pipe piles were driven and there was no attempt to measure residual loads. Although temperature correction of vibrating wire strain gauges has been performed before, the authors are unaware of any previous studies where the temperature induced strain change from pile installation was measured and corrected to interpret residual stresses.

Seo et al. (2009) installed vibrating wire strain gauges on steel piles and obtained no-load readings prior to pile driving. They observed that the residual load distribution did not match the expected distribution and the discrepancy was attributed to the dynamic impact of pile driving causing shifts to the no-load reading. This discrepancy would similarly be reported in the current study if the residual loads were calculated from the measured strain. By correcting for the change in strain due to temperature change, the residual load distribution better matches the expected distribution with an accumulation of negative skin friction along the pile shaft. Significant residual stresses are expected when the pile is driven to a very hard end bearing layer (Briaud and Tucker 1997). Had the strain and temperature data not been collected immediately following pile installation, it would likely be concluded that there was a shift in the strain gauges similar to Seo et al.'s (2009) conclusions.

The procedure presented for temperature correction assumed that the decrease in strain during 120 minutes after EOID was entirely due to temperature effects. The residual stress was therefore assumed to be constant during this time after reaching a peak immediately or shortly after EOID. In reality, excess porewater pressure is expected to dissipate with time. Also, the reconsolidation of soft soils disturbed during pile driving can cause soil settlement and negative skin friction (Briaud and Tucker 1997). Lastly, there were several restrikes which occurred in this timeframe and the corresponding strain change was neglected in this time interval. Therefore, some error is expected in the presented corrected residual

stress, but the interpretation with temperature correction is an improvement versus calculating residual stresses from the directly measured strain.

The following key conclusions are drawn from this study:

- Applying dynamic force to the pile by striking against a steel plate resulted in a minor shift in the no-load condition strain gauge reading compared to the shift caused by temperature effects.
- The decrease in temperature from installing the pile in the cooler ground resulted in significant decrease in the measured compressive strain.
- In order to estimate residual loads of a driven pile using vibrating wire strain gauges, the strain gauge and accompanying thermistor must be connected to a data logger during pile installation to observe the change in measured strain due to temperature change. The measured strain can then be corrected for an improved measurements of residual stress.
- Residual stresses will be underestimated if a pile is installed in a cooler ground environment and temperature corrections are not performed.

This study demonstrated that an improved estimate of residual stress from pile driving can be achieved by obtaining the no-load reading prior to pile installation and correcting strain readings for temperature effects immediately after EOID. Applications for vibrating wire strain gauges on piles include measuring long-term negative skin friction for foundations subject to ground settlement or measuring the resistance distribution during static load tests. In any application, ignoring the residual loads for driven piles due to the pile driving process will results in an incorrect interpretation of the load in the pile, shear stress acting along the shaft, and compressive stress at the pile tip.

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Figure Captions

Figure 1: Layout of instrumentation and protection on test piles.

Figure 2: RST Instruments VWVG-A model strain gauge installed on H-pile flange.

Figure 3: Soil profile and strain gauge locations.

Figure 4: Installed test piles and reaction piles.

Figure 5: Pile A SG P4 strain readings before and after applying dynamic force.

Figure 6: Pile B SG P4 strain readings before and after applying dynamic force.

Figure 7: Pile A SG P3 strain and temperature data after pile installation.

Figure 8: Pile B SG P4 strain and temperature data after pile installation.

Figure 9: Linear temperature-strain relationship for strain gauge pairs.

Figure 10: Comparison of corrected and apparent stress after EOID for Pile A SG P3.

Figure 11: Comparison of corrected and apparent stress after EOID for Pile B SG P4.

Figure 12: Residual Axial Forces at 6 Hours after EOID. (a) Pile A. (b) Pile B.

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