Thermal Calibration of Strain Gauges for High Quality Strut Load Measurement

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Abstract

Strut loads within braced excavations are commonly measured using resistance or vibrating wire strain gauges (VWSG's). There is a common misconception that modern strain gauges are thermally matched to the steel struts and that thermal and earth pressure loads can be determined accurately without initial thermal calibration of each strain gauge. Experience from a major construction project has shown that very high temperatures and thermal loads can develop within struts due to exposure to sunlight, and thus thermal calibration of strain gauges is essential in determining accurate zero load readings for calculation of earth pressure and thermal loads in struts.

The procedure for thermally calibrating strain gauges prior to loading is explained. This procedure allows the total strut load to be simply determined, whilst also being independent on the initial temperature at installation. Several examples of strain gauge calibration and determination of earth pressure and thermal effects for several sheet piled excavations for the New Metro Rail Project (NMRP) in Perth, Western Australia are presented. Comparisons of the loads measured with spot welded vibrating wire strain gauges and spot welded resistance strain gauges are also presented.

Keywords: Vibrating Wire Strain Gauges, Resistance Strain Gauges, Strut Loads, Excavation

1. INTRODUCTION

For flexible strutted (braced) excavations, loads within individual struts are commonly measured using VWSG's due to their simplicity and cost benefits when compared to load cells. During the initial development phase of VWSG's it was recognised that the difference between the thermal behaviour of the gauge and strut needed to be determined. However over the years, and with the commercialisation of VWSG's, this need for calibration has been forgotten by some in the belief that strain gauges are now thermally matched to the steel on which they are typically placed. Some examples of the misconceptions that have developed are as follows:

"thermally matched electronic gauges have virtually eliminated the need for such corrections" (Boone and Crawford, 2000).

"Most VWSG systems are self correcting to take into account the difference in coefficient of thermal expansion between the strut and VWSG. All of the VWSG's used to measure strut loads have been thermally matched and calibrated to the steel on which they are placed. This means that the co-efficient of thermal expansion of the gauge is equal to the co-efficient of thermal expansion of the steel" (Hashash et.al., 2003)

As no two VWSG's will ever be the same due to slight variations in manufacturing, along with minor variations in wire thickness and wire length, welding, and installation method, it is clear that no gauge shall possess the same co-efficient of thermal expansion as another gauge. Hence as each gauge possesses a different co-efficient of thermal expansion, there cannot exist the concept of thermally matched strain gauges. The co-efficient of thermal expansion for each VWSG under zero external load therefore needs to be determined, prior to a strut being placed within an excavation and loaded. A simple procedure for thermally calibrating each VWSG on a strut is explained within this paper, and is subsequently used to determine earth pressure and thermal loads upon a strut. The procedure also allows for expected thermal loading within a strut to confirmed prior to its installation and thus checked with design assumptions.

2. THERMAL CALIBRATION METHOD:

VWSG's are normally welded/installed on a strut outside of the excavation at least a week before installation into the excavation. For the NMRP, both circular hollow sections (CHS) and welded column (WC) sections were used as struts, with VSWG's were installed in groups of four on each strut as shown in cross section within Figure 1. The gauges used were Slope Indicator Spot Weldable Strain Gauges, which were welded directly to the strut at a distance of three strut diameters from the loaded end of the strut to reduce end effects. A typical installation prior to covering with waterproofing material is shown in Figure 2.

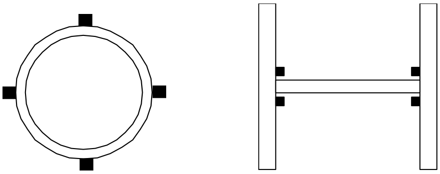

Figure 1 – Cross Sectional Location of Strain Gauges

Figure 2 – Typical Strain Gauge Installation

Once all VSWG's are affixed , the strut is laid on wooden timbers and simply supported in the same position as it would be in the strutted excavation (i.e. final upright position is also upright during the calibration), but with the ends free to move due to thermal expansion. If the strut was to span the whole excavation it was simply supported at both ends on blocks of timber, or if the strut was to have a king post attached as occurred with some of the larger CHS struts it was supported by additional timbers at the centre of the struts. A typical layout for thermal calibration is illustrated below.

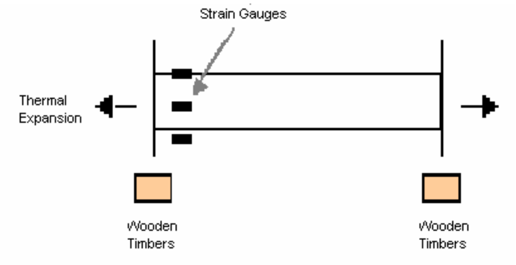

Figure 3 - Typical Calibration Layout

Once the strut is in the calibration position, a portable datalogger (Slope Indicator VW Minilogger) is attached to each VWSG and the strut allowed to expand and contract (undisturbed) over a period of 1-5 days. The change in microstrain in each of the VWSG's over a typical calibration period is illustrated in Figure 4a. The change in microstrain is due to the thermal expansion of the gauge, as the strut ends are free to move thus not under any load. The effect of thermal expansion gauge of the gauge therefore must be determined (calibrated) and the calibration subtracted from the measured microstrain once the strut is lowered into the excavation and the ends fixed. The thermal calibration of each VWSG is then a simple procedure of plotting the temperature v microstrain response of each gauge for the calibration period. The calibration is typically a linear response as illustrated in Figure 4b.

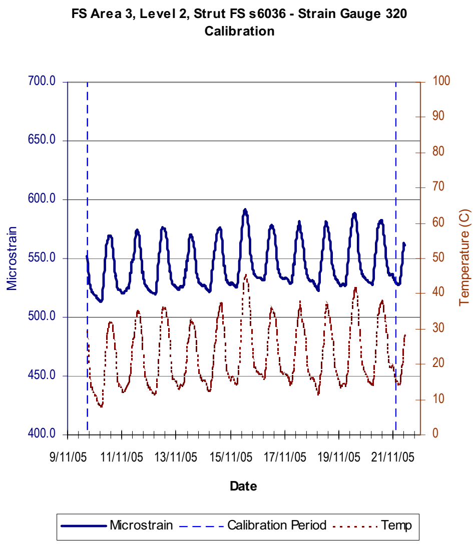

Figure 4a – Variation of Gauge Microstrain with Temperature under Zero External Load

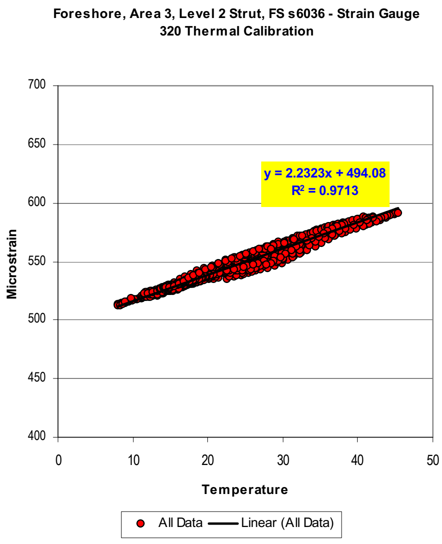

Figure 4b – Thermal Calibration of VWSG under Zero External Load

The orientation of the strut is critical to the VWSG calibration process as illustrated in Figure 5, where a rotation of the strut resulted in significantly different thermal response to that observed in the initial position.

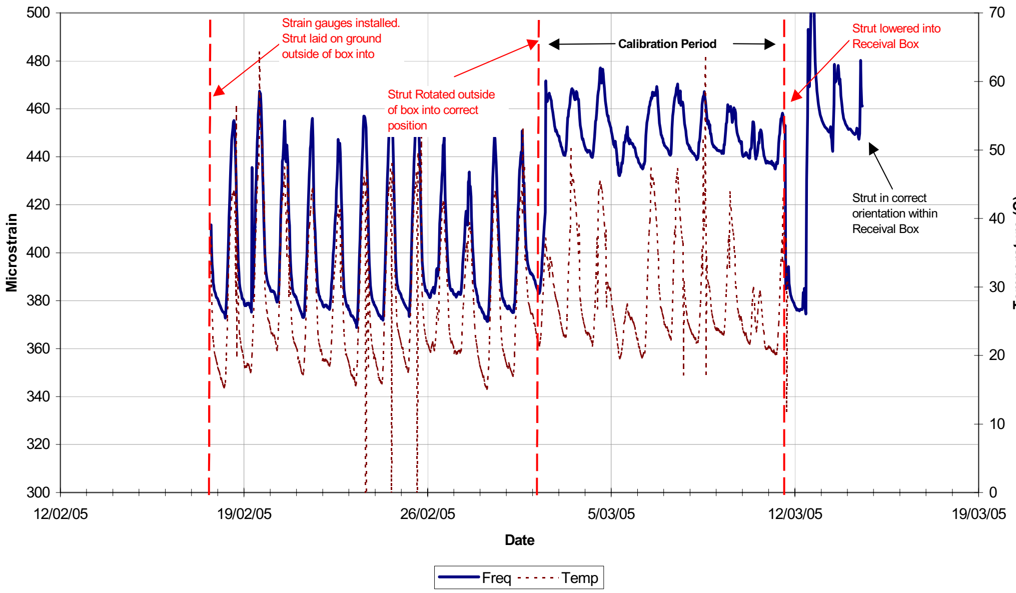

Figure 5 – Variation of Gauge Microstrain with Strut Orientation under Zero External Load

This calibration is then used to account for the self expansion of the gauge, with the calculated microstrain for the gauge at any temperature (and at zero load) subtracted from the measured microstrain at the corresponding temperature. Thus the change in microstrain is used to determine the actual load within the strut. An example of the calculation process in shown below where strain is calculated from the raw frequency and temperature readings of the VWSG.

$$\varepsilon_t = B * f^2 + C$$

$$\varepsilon_i = (T * \alpha_{g1}) + (\alpha_{g2})$$

where
ε_t = *Measured Strain*
ε_i = *Strain due to Gauge Thermal Expansion*
B = *Frequency to Microstrain Conversion Factor*
C = *Factor*
α_{g1} = *Coefficient of Thermal Expansion of Gauge*
α_{g2} = *Microstrain Intercept for Gauge*

and then $d\varepsilon = \varepsilon_t - \varepsilon_i$

As the load and moments due to self weight of the strut is neglected in calculating applied loads the load (N) in each VWSG is then calculated from change in strain as per the equation

$N = Es * As * (d\varepsilon * 10^{-6})$ where N = *Gauge Load (kN)*

When the VSWG's are placed in the positions shown in Figure 1, the average load in the strut is determined by simple averaging of the four VWSG loads. The effect of the gauge calibration procedure is confirmed by the zero net strut load during the calibration period, and also during the initial strut installation, as illustrated in Figure 6. In contrast, if thermal effects of the gauges were not considered there would have been apparent variations in load of up to +/- 250kN during the calibration period as illustrated in Figure 7, which equates to an error of up to 500kN in this case, given that the ends were free to move and there were no external loads on the strut. In many cases an error of 500kN would equate to 10% to 25% of most design strut loads.

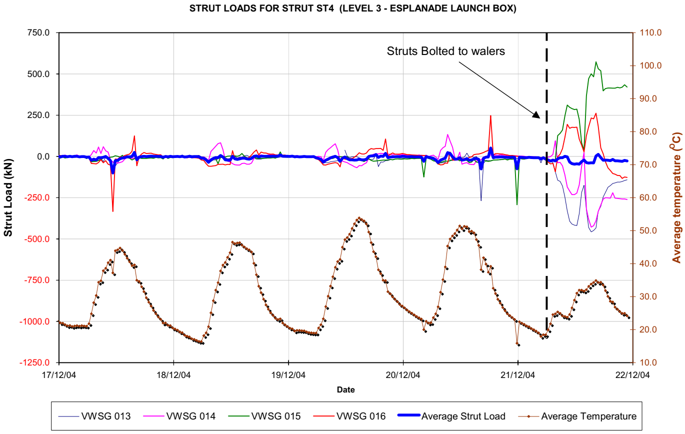

Figure 6 –Effect of thermal calibration of strain gauge in negating gauge thermal expansion in unconfined and semi confined state

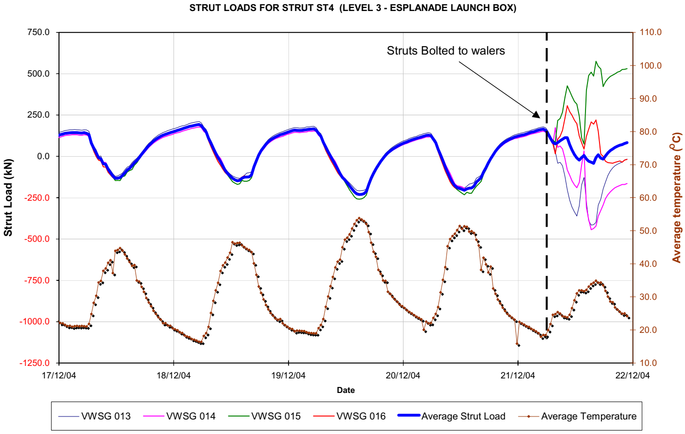

Figure 7 –Apparent loads within unconfined strut with no thermal calibration of strain gauge

Once the struts become constrained (i.e. concrete packing installed between the waler and sheet-pile walls), the effects of thermal expansion of the strut becomes apparent, with definitive thermal loads being recorded above that of the normal VWSG thermal expansion as illustrated in Figure 8.

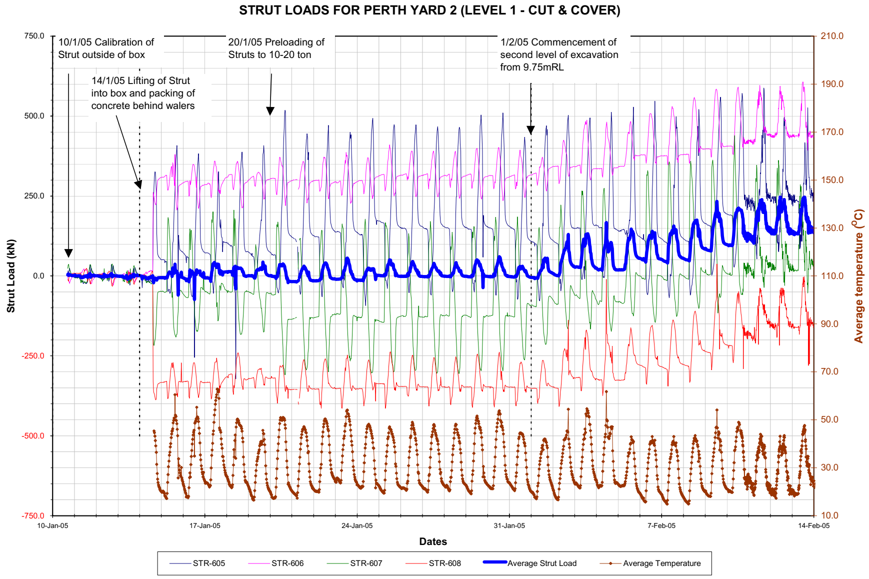

Figure 8 –Development of thermal loads within strut once confined position established (Note: tensile forces induced by bolting to walers)

3. VALIDATION OF THERMAL CALIBARTION METHOD VIA COMPARISON OF VWSG'S AND RESISTANCE STRAIN GAUGES

In a diaphragm wall excavation several struts were instrumented with welded VWSG's at one end of the struts, and welded RSG's at the other, allowing direct comparison of the results. The VWSG's were thermally calibrated as per the procedure but with one improvement. In this instance the struts were installed with the walers and loosely bolted together, but not attached to the walls. The waler and struts were then supported by cables from the roof thus allowing system the hang and expand under self weight as it would be once excavation commenced. This was considered a perfect calibration set up and is shown in Figure 9.

Figure 9 – Calibration of Struts and Waler System in Hanging Position

In contrast the RSG's were installed by a specialist instrumentation contractor with no thermal calibration of the gauge. The initial RSG reading was taken as zero irrespective of the temperature. Figure 10 is an example of the loads within one of the double instrumented struts. The results validate that both types of strain gauges measure the same load variations and similar scale of load, but the uncalibrated RSG's consistently recorded lower loads (as was the case in all other double instrumented struts). The lower loads within the RSG's were expected, given that no allowance for apparent increase in load due to thermal expansion of the resistance gauge wires was considered. The example shows that the effect of strain gauge expansion is up to 300-400 kN of the 1750 kN peak loads (17-22%), thus indicating that the uncalibrated RSG's were underestimating loads by a significant amount. In Figure 11 this under-estimation of load was also evident when the strut /wall connection was cut and the strut left in its hanging position until it was removed. There was an apparent daily variation in tension of 100-250KN in the uncalibrated RSG's in a strut that had no load and was unconfined. As the strut was in its original position, the tensile load should have been closer to zero with no daily variation as was the case with the thermally calibrated VSWG's (which consistently showed a minor tensile load of 50kN, thus confirming the validity of the thermally calibrated readings prior to, and after loading). In addition to the above, the potential error in choosing a baseline reading with the uncalibrated RSG's was potentially in the order of 100 kN as there was a variation in microstrain readings in the unloaded state. Given the above the potential total errors in using an uncalibrated strain gauge could approach 30%, which poses significant risk to people working in strutted excavations.

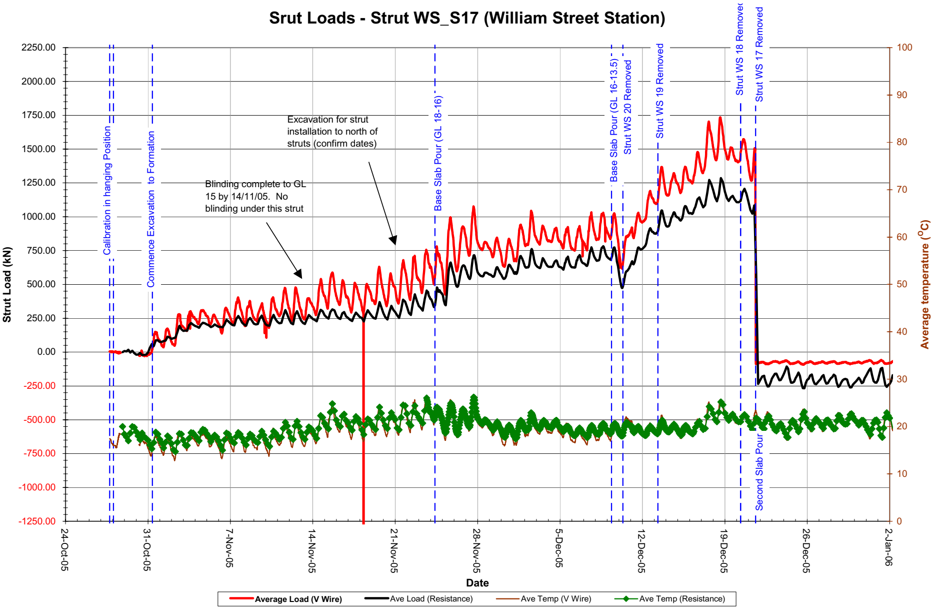

Figure 10 – Comparison of VWSG and RSG's Results

4. CONCLUSIONS

In recent times measurement of strut loads within strutted excavations has typically been undertaken using strain gauges which are typically more cost effective than load cells. The misconception that strain gauges are thermally matched with steel struts has developed and evidence has been shown that thermal calibration of individual strain gauges is required and should form best practice for strut monitoring. A method has been explained for thermally calibrating strain gauges in order to accurately determine the load within a strut. Thermal calibration method was validated in by comparison to excavation activities and comparison of measured loads in unconfined struts before and after excavation. It was shown that thermal expansion forces in struts can be significant and should accounted for in strut designs, and validated by measurement.

5. REFERENCES

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