

# EXPERIENCES IN STRUT LOAD MONITORING IN EXCAVATIONS FOR THE NEW METRORAIL CITY PROJECT

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## ABSTRACT

The continuing urban development boom has been accompanied by an increasing trend in underground construction, whether for underground transportation services or for basement inclusion in commercial buildings and residential apartment complexes. This inevitably means increasingly complex construction within retaining walls supported by strutting and bracing systems or retained by ground anchors. It is essential to monitor the forces in these supporting elements to ensure that they are behaving according to and within design, an essential safety measure remaining a contractual requirement in any significant excavation works.

Recently extensive excavation works were undertaken for a large infrastructural project, and a large number of the supporting struts in these excavations instrumented for monitoring. This paper shares the experiences gained in the strut load monitoring of these excavations, providing commentary on all aspects ranging from the choice and selection of instrumentation, namely vibrating wire strain gauges, the installation technique, related factors from cabling to data logging, and finally the data processing. It is hoped that the experiences shared will not only be of interest but also of benefit to those involved in a strut load monitoring instrumentation project.

## 1 INTRODUCTION

Recently a major infrastructural project was undertaken by Leighton Kumagai Joint Venture (LKJV) in Perth, Western Australia, to expand the existing rail network by the construction of twin cut and cover and bored tunnels through the heart of the CBD in addition to two complimentary underground stations. The magnitude and complexity of the works were of an order never before experienced in Perth and needless to say will not be repeated in the city for considerable time if ever again. The majority of the excavations in the project were constructed with sheet piled retaining walls, being for the Esplanade Station, launch and retrieval shafts and cut and cover tunnels. A portion of the cut and cover tunnelling works were retained by soil mixed piles. The William Street Station was constructed using diaphragm walls and of 'top-down' construction methodology.

The extensive strutting and bracing design throughout the project ranged from single propped retaining systems to multi-propped systems of four levels and corner bracing, with a variation in tubular strut section size ranging from CHS 406.6 x 9.5mm to the large diameter CHS 1016 x 16mm. A large number of struts were instrumented to monitor that the excavations were proceeding according to design and, most importantly, as a safety measure for site personnel working at depth. In total, the strut monitoring network included 158 spot weldable vibrating wire strain gauges (Slope Indicator model 52602100) installed to monitor 39 steel struts.

Figure 1 depicts the excavation for the Esplanade Station and is an example of the magnitude of the strutting works on the project. The station was constructed within a temporary sheet piled retaining wall with sheet piles to 22m depth and excavation to 13m depth. The 23.5m (average) width of excavation was supported by three strutting layers of 6m horizontal spacing and 4.5m vertical spacing.

In general, the ground conditions throughout the project predominantly consisted of interbedded layers of sand, silts and clayey soils originally referred to as the Guildford Formation and more recently redefined as the Perth Formation (Gozzard 2007) overlying Kings Park Formation bedrock. In some areas of cut and cover tunnelling on the city foreshore a thick stratum of the low strength Swan River Alluvium was present.



(a)



(b)

Figure 1. The Esplanade Station excavation (a) looking South across the excavation and (b) looking from the West of the excavation

## 2 INSTRUMENTATION CHOICE

There are two categories of instrumentation that may be used in strut load monitoring for excavations: load cells and strain gauges. By definition, load cells are “*interposed in the structure such that loads pass through the cells*” whereas strain gauges “*are attached directly to the surface of the structure or are embedded within the structure to sense the extensions and compressions in the structure itself*” (Dunnicliff 1998). In other words, load cells form an ‘interior’ component of the strut being installed ‘in series’ or in connection with the strut itself, whereas strain gauges are affixed directly to the exterior. In this project, strain gauges were used consistently throughout and elected over load cells for reasons of simplicity of installation, relative economy, confidence in and proven reliability of their results. Another factor of consideration was that the strut system was designed without the intent of the large loads of preloading, where it is often desirable to confirm the jacking load in the strut by the use of calibrated load cells in addition to the use of calibrated jacks.

There were two instrumentation options for the strain gauging for strut load monitoring: the installation of foil resistance strain gauges or vibrating wire gauges. Although foil resistance gauges had already been used on the project for various pile testing instrumentation systems, there was hesitation to base the strut monitoring network on this system of instrumentation, primarily due to the fact that reported case histories in the literature regarding the use of strain gauges for strut load monitoring of excavations reported the use of vibrating wire gauges, and in its own merit the vibrating wire gauge appeared simple to install with proven robustness and long term reliability.

Turnbridge and Oien (1987) report that despite the invent of more accurate modern instrumentation such as foil resistance gauges, the default towards vibrating wire gauges in geomechanical applications has not been displaced due to a history of use and favourable factors being that:

- i) they remain cheap to design and construct
- ii) they have a well established and proven robustness, long term stability and reliability
- iii) they deliver an accuracy sufficient for geomechanical applications
- iv) the electrical characteristics of the cable does not influence the signal output, ie. long cable lengths can be used without significant signal degradation and without the need for signal amplification
- v) the gauge output has high immunity to electrical noise.

Vibrating wire strain gauges were chosen as the instrumentation of choice. There now remained a choice with respect to the type of gauge to use: the surface mounted (or arc weldable) vibrating wire strain gauge or the spot weldable vibrating wire strain gauge (Figure 2).



Figure 2 Vibrating wire strain gauge (a) surface mounted or arc weldable and (b) spot weldable

The surface mounted strain gauge is bolted to mounting plates which may be welded (by conventional welding and hence the common term of the arc weldable strain gauge) or bonded to the surface of the structure. A change in tension in the structural member results in a change in tension of the wire held between the two mounting blocks. The spot weldable gauge is spot welded along the entire length of the flange adjacent the vibrating wire. The gauge is constructed so that a wire is held in tension inside a small diameter, thin-walled tube that is welded to the structural member. Loading of the structural member changes the length of the tube and results in a change in tension of the wire. (Slope Indicator 2006a, 2006b). Both gauges have an in-built temperature sensor allowing for simultaneous temperature and strain measurements. Also the vibrating wire in both gauges is also thermally matched to the thermal characteristics of structural steel.

By advantage, the spot weldable gauge has a much lower profile than the surface mounted gauge (the vibrating wire is positioned only 0.96mm above the member to which it is attached), and also the full length of the flange is welded allowing reliable coupling of the gauge to the structural member and preventing misalignment of the end points. With that in mind, spot weldable vibrating wire strain gauges were selected as the instrumentation for strut load monitoring.

### 3 VIBRATING WIRE STRAIN GAUGE

#### 3.1 PRINCIPLE OF OPERATION

Vibrating wire instruments have been in existence since the 1930's. The fundamental principle of operation of the vibrating gauge is that the resonant frequency (f) of the gauge wire can be related to the square root of the tension (T) in the wire by the following equation:

$$f = \frac{1}{2L} \sqrt{\frac{T}{w}} \quad (1)$$

where L is the length of the wire  
w is the unit weight per length

When tension is applied to a tensioned wire, the natural frequency of vibration is changed. In the spot weldable vibrating wire strain gauge, an electromagnet incorporated into the strain gauge sensor is simply used to pluck the gauge wire and measure its corresponding frequency of vibration. The strain in that location is then calculated by applying calibration factors to the frequency measurement (Section 4.1).

### 3.2 INSTALLATION OF SPOT WELDABLE VIBRATING WIRE STRAIN GAUGE

The installation of the spot-weldable vibrating wire strain gauges proved relatively simple, and the method is illustrated in the following steps:

- i) Remove the surface rust of the steel strut in the desired location with an angle grinder (Figure 3a). It is preferable to use a Flap disc of fine grade (Figure 3b) instead of a standard grinding disc so as to alleviate surface scratches and produce a consistently smooth surface. Thoroughly clean the area with methylated spirits.



(a)



(b)

Figure 3. (a) Strut surface in preparation for gauge and (b) flap disc

- ii) Install the gauge by spot-welding the flange to the strut (Figure 4) in the configuration proposed by Slope Indicator (2004). Coat the entire gauge in 3M Scotchkote Electrical Coating to seal the gauge and provide a moisture barrier.



Figure 4 Spot welded strain gauge affixed to strut

- iii) Place the sensor over the gauge and spot weld the tie-down straps supplied to secure (Figure 5a). Again, coat the sensor with 3M Scotchkote electrical coating to seal the unit and provide a moisture barrier (Figure 5b). It is recommended to use an additional weld down strap to secure the cable a short distance away from the gauge to provide additional restraint to the cable.

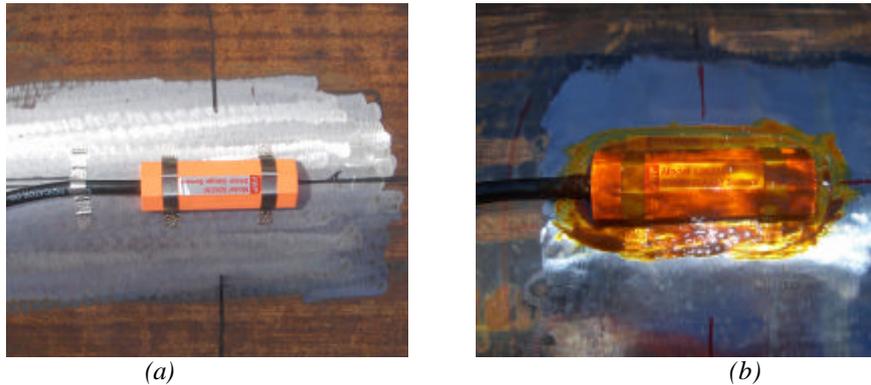


Figure 5 (a) Installing the sensor and (b) applying Scotchkote protection

- iv) Finally, a protective 3M bitumised mastic pad is fitted over the sensor (Figure 6).

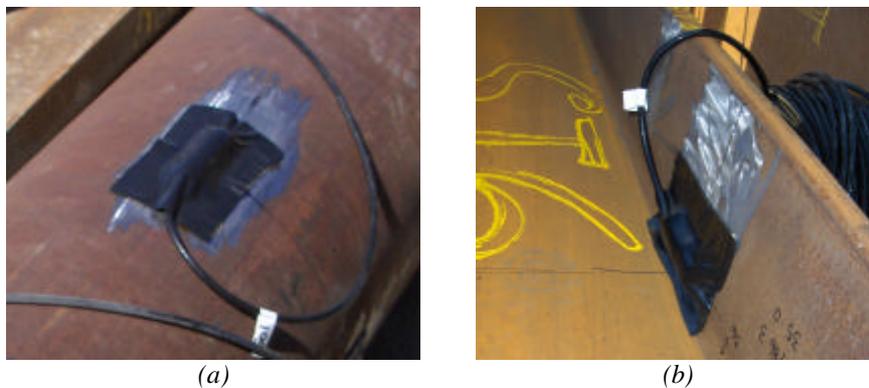


Figure 6 Mastic pad fitted over gauge installed on (a) tubular strut and (b) welded channel section

It is important to label both ends of the cable (ie. close to the strain gauge and at the free end) and record the name or number of the strain gauge and its position.

### 3.3 POSITION OF THE GAUGES

Batten et al. (1999) carried out finite element analysis to investigate the axial stress distribution at a distance of three prop diameters from the end of an unevenly loaded tubular prop, and further to investigate the variation in accuracy of the average load depending on the number of gauges installed. It was found that the minimum number of gauges (evenly spaced around a tubular prop) required to accurately measure the average load in the prop was three, with no benefit in terms of improved accuracy if the number was increased up to the maximum tested of six gauges. Citing the difficulty in installing three gauges so they are accurately spaced, their recommendation is the use of four gauges installed at the quarter points of a tubular strut as the most economical and practical option.

Throughout this project tubular struts were used predominantly and instrumented in the configuration recommended by Batten et al. (1999) in that four gauges at the 3, 6, 9, 12 o'clock positions (Figure 7a, 7c) were installed. The gauges were typically installed at a distance of three times the strut diameter from the end of the strut as an assumed distance at which the end effects of the strut waler connection would be negligible. There was an exception to this configuration where the strut was intended to be cast into the permanent structure (and later removed). At these locations 3m long welded channel (WC) sections were used at the tubular prop ends to alleviate the large circular void that a tubular strut would leave upon its removal. In this instance WC sections were instrumented on the inside of the four flanges close to the web as shown in Figure 7b and 7d.

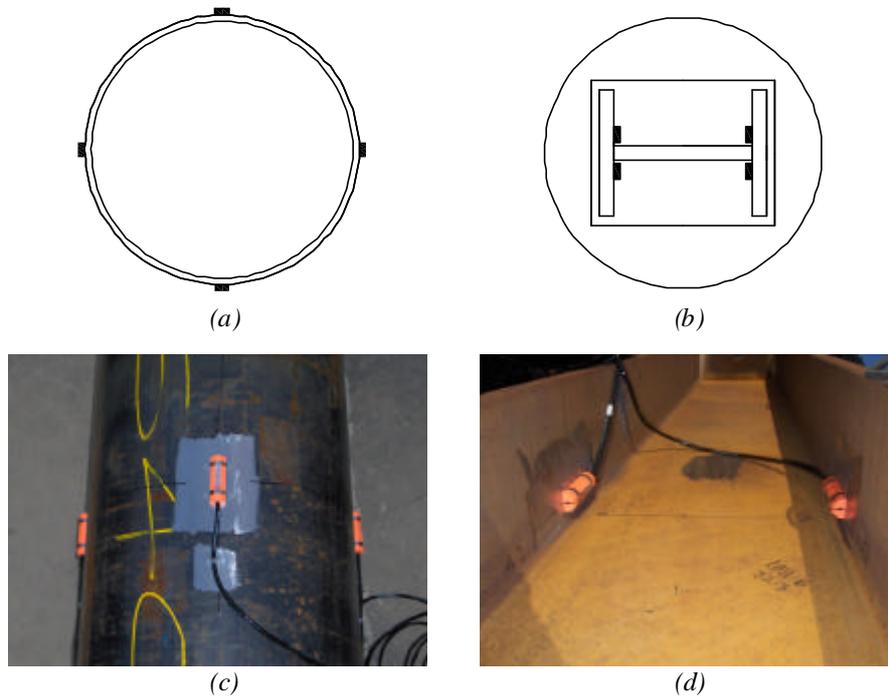


Figure 7 Gauge locations on (a) and (c) a tubular prop, and (b) and (d) a welded channel section

The average load in the strut was then simply taken as the average of the four loads recorded at each of the gauges.

Often due to timing and space restrictions on site, gauges have to be installed once the strut itself is installed in the excavation. In this project the strain gauges were installed outside of the excavation. This is a safer and more practicable option for the installer as it alleviates the urgency in installing the gauges to the installed strut, removes the hazards associated with working under overhead plant, and removes the discomfort to the installer in attempting to spot weld a gauge to the underside of a strut in often cramped and uncomfortable conditions. Also, the gauges can be confirmed to be in working order prior to strut installation in the excavation, after which the readings are critical. This approach also enables baseline readings of the gauges to be taken (Section 4.2).

### 3.4 PROTECTION OF THE GAUGES

Protection to the gauges was provided in the form of tack welded angle section. Usually 600mm of angle section was tack welded to the strut at the extremities of the section (Figure 8a). In the case of the WC sections, steel plate was either tack welded to the top of the flanges in the section over the gauges or heavy piece of plyboard (formwork) was used and secured in place. Where it was not possible to weld angle section over the gauges (where the resources were not available) the area of the gauges was simply sprayed with fluorescent spray paint to make the plant operators aware that the gauges were at that location. Ultimately the rate of survival of the gauges rests with the plant operators and in their awareness and co-operation to protect them.



Figure 8. Instrumented strut with gauges protected by (a) welded angle section and where it was not possible to protect with welded section, (b) painted in fluorescent spray paint

### 3.5 CABLING

Originally the strain gauge sensors were ordered with 60m length of cabling attached. It was soon found that after strut installation it was very cumbersome to handle such long cabling lengths and difficult to pull the cabling through a dedicated protective piping system to the ground surface and to the datalogger.

In subsequent orders of strain gauges a different approach was taken in that only 6m of cable length was ordered with the gauges from the instrumentation supplier, and from a local electrical supplier a 16 core (16 wire) instrumentation cable was ordered. By this method the solitary 16 core cable was then ran down the excavation to the appropriate depth (the installation depth of the strut) or fed down the dedicated protective piping system and the strain gauge wires soldered to the ‘mother’ wire. Although the soldering was an additional task, it was far more convenient than the previous method. An additional bonus was that the data cable<sup>1</sup> ordered from the local supplier was cheaper than the cable ordered in conjunction with the strain gauge sensor from the instrumentation supplier. Although it may not be considered ideal to join cables on site leaving a possible weakness susceptible to water ingress, soldering the cables accurately and waterproofing with heat shrink left no undesirable side effects associated with an interrupted cable.

The cabling route for strain gauges installed at depth in an excavation must be considered and incorporated into the strutting and bracing works. For instance, where there is no void between the retaining wall and walers (as in the case of concrete packing between the waler and sheet pile retaining wall) allowance needs to be made in the form of piping incorporated into the concrete formwork to allow for the unobtrusive passage of the cabling from the top of the excavation to the instrument depth. For multiple layers of propping a piping system was implemented to carry the cables down the excavation, for shallow excavation works with minimal strutting layers the cable was run unexposed down the excavation and survived without interference.

### 3.6 SUB-CONTRACTOR vs IN-HOUSE INSTALLATION

Instrumentation for civil works is a specialised field and an initial quote from a local independent instrumentation installer to install the vibrating wire strain gauges was outlandish. Instead of outsourcing the installation LKJV worked in co-operation with the instrumentation supplier and took the initiative to bring a skilled technician from Singapore to train an engineer of the project staff to install the gauges. As well as the considerable cost saving by performing the installation in-house there was the added benefit and flexibility in having the installer on site, which also meant that inevitable delays did not result in costly downtime from the third-party installer.

<sup>1</sup> Olex Dekoron instrumentation cable was used (this has now been renamed to Instrolex) consisting of 8 paired (16 core) individually and overall screened cable. It was purchased in 100m reels and cut to the required length on site.

### 3.7 THE SPOT WELDER

Due to the large number of installations and long time duration for the scope of the works LKJV purchased a spot welder to install the spot weldable gauges in favour of hiring a unit. At that time the source of the unit hired was Singapore and it was simply more convenient, and in the end more cost-effective, to purchase a unit out-right. In addition, a portion of the initial outlay was recovered by selling the welder after completion of the installation scope.

A HotSpot II Thermocouple Welder was purchased (Figure 9a). A well used yet still reliable unit hired from Singapore is shown in Figure 9b.

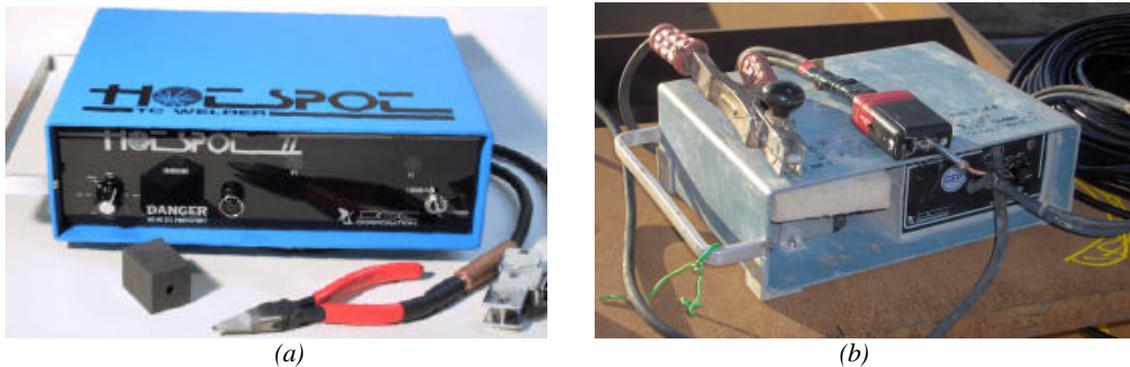


Figure 9. Spot welder: (a) as new (without modified handpiece) and (b) still going many years on

The spot welder does not weld the strain gauge to the strut per se, but at the small spot at the location of the welding point it quickly heats up the thin metal of the flange to melting point sufficiently to bond it to the clean steel underneath. It is important to have welding tips spare and to change the tips as they become blunt to ensure the accuracy and competency of the weld application. Another point of note is to ensure that at all times during operation that the welder is earthed.

Although the spot welder unit has a rechargeable battery allowing for portability on site, it was quickly found that the recharge time or lag between welds (ie. the time waiting after one weld for the unit to recharge to form the next weld) was greatly reduced by powering the unit off a 12V rechargeable truck battery. This enabled the strain gauge to be installed faster and with more ease.

### 3.8 DATALOGGING

After the struts were instrumented outside of the excavation they were connected to Slope Indicator Miniloggers. The minilogger is a reliable, low cost portable data logger designed to monitor a single vibrating wire sensor. This enabled data collection for baseline datum readings and also provided a continuous data record during the installation of the strut so that no data was lost in awaiting connection of the strain gauges to the permanent data logger unit.

Once the strut was installed in the excavation the miniloggers were removed and the strain gauges connected to the permanent datalogger. Campbell Scientific CR10X<sup>2</sup> dataloggers were used throughout the project to record strut load data, and teamed with a radio transmitter to enable transmission of the data to a database for real time monitoring. The datalogger and associated data transmission system form an expensive component, therefore it is in best interest to minimise the number of datalogger units throughout the project. The CR10X datalogger is teamed with a component which gives the datalogger the capability to measure vibrating wire instruments, an AVW1, and an array of Multiplexers each of which provide 16 channels for the connection of 16 vibrating wire strain gauges. The maximum number of manageable multiplexers that it is recommended to install to the CR10X is 5 or 6. To get the maximum capacity from the dataloggers it is good practice to space the multiplexers in separate housing units along the excavation length ie. coincident with the

<sup>2</sup> The Campbell Scientific CR10X has now been replaced with the CR1000.

locations of the instrumented strut array's, and interconnect them to the main datalogger unit via cables run in protective piping outside the retaining wall. This minimises the total amount of instrumentation cable run to the datalogger.

It is ideal to power the datalogger of mains power. During early stages of the works this may not be possible and the datalogger may need to be powered of a battery or a solar panel.

## 4 DATA PROCESSING

### 4.1 CONVERSION TO MICROSTRAIN

The frequency output from the gauges is converted to microstrain by applying the following equation in accordance with Slope Indicator (2004):

$$m\epsilon = A(F^2) + C \tag{2}$$

where  $m\epsilon$  is the strain in microstrain  
 F is reading output from the vibrating wire strain gauges  
 A is a constant of 0.0007567  
 C is a constant of -2030.1

### 4.2 BASELINE READINGS

The struts in this project were instrumented 'outside' of the excavation, with portable miniloggers connected to take readings at 15 minute intervals whilst the strut remained unloaded and simply supported such that it was free to expand or contract. Under zero load it was evident that the gauge output was influenced by temperature (Figure 10a). As both strain and temperature were recorded simultaneously, strain could be plotted against temperature and the linear response of the gauge to temperature effects under zero load determined (Figure 10b).

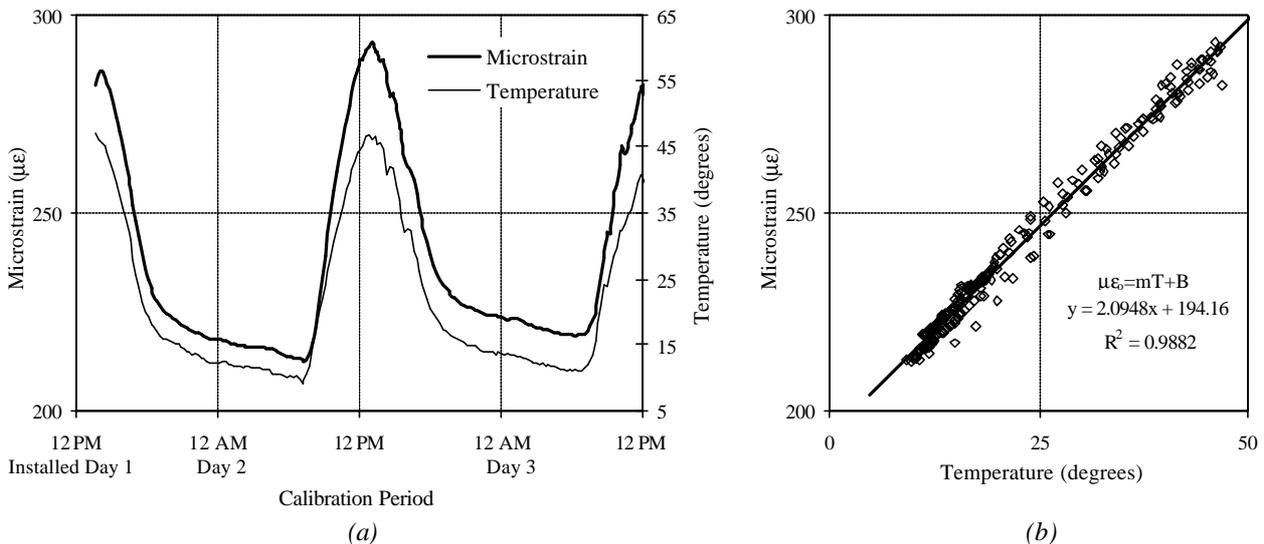


Figure 10. Example of data obtained 'outside' the excavation and under zero load (a) Microstrain and Temperature plotted with time, and (b) Microstrain plotted against Temperature

This resulted in a linear relationship of the form:

$$\boldsymbol{\mu e}_o = mT_i + B \quad \text{or} \quad \boldsymbol{e}_o = (mT_i + B) \times 10^{-6} \quad (3)$$

where  $\mu\epsilon_o$  or  $\epsilon_o$  is the microstrain or strain that would be recorded in the gauge under zero load for a given temperature ( $T_i$ )  
 $m$  and  $B$  are constants in the linear relationship between strain and temperature

Therefore during excavation, for any temperature  $T_i$  the baseline reference strain or datum strain that would be apparent in the gauge under zero load is  $\epsilon_o$ .

### 4.3 CALCULATION OF AVERAGE STRUT LOAD

Once the strut was installed and excavation had commenced, the change in strain from the initial condition of zero load ( $\Delta\epsilon$ ) from the initial baseline reading ( $\epsilon_o$ ) is as follows:

$$\Delta\boldsymbol{e} = \boldsymbol{e}_i - \boldsymbol{e}_o \quad (4)$$

where  $\epsilon_i$  is strain output (multiplied by  $10^{-6}$  to convert from microstrain to strain) at a particular time and recorded with a temperature reading of  $T_i$   
 $\epsilon_o$  is the reference strain or the initial strain reading in the gauge under zero load that would exist for a temperature  $T_i$  from Equation 3

With the change in strain known since installation, the strut force can simply be calculated according to:

$$F_{strut} = -EA(\Delta\boldsymbol{e}_{avg}) \quad (5a)$$

where  $E$  is the Young's Modulus of the steel in units of  $\text{kN/m}^2$   
 $A$  is the cross-sectional area of the steel strut in units of  $\text{m}^2$   
 $\Delta\epsilon_{avg}$  is the average of the change in strain since installation of the four gauges installed on the strut  
 (Note the negative sign in the equation: in the gauge output tension is positive, when considering strut loads we require compression positive)

The procedure adopted at LKJV was to calculate the change in strain for each gauge and then the force at each individual gauge location ( $F_i$ ) ie:

$$F_i = -EA(\Delta\boldsymbol{e}) \quad (5b)$$

The average force in the strut was then taken as the average of the four forces recorded at the gauge locations.

A typical plot of strut load and average strut temperature is shown in Figure 11.

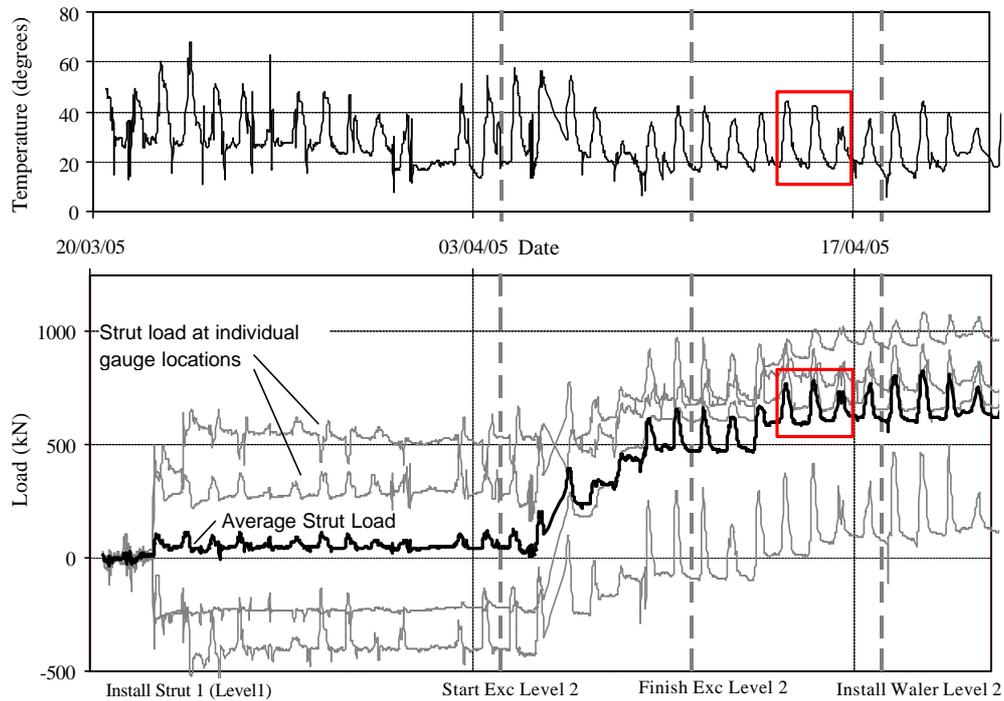


Figure 11. Example of strut load and temperature (first level strut)

#### 4.4 TEMPERATURE EFFECTS

Taking simultaneous strain and temperature readings at 15 minute intervals throughout the project allows the temperature effects on the struts to be investigated. With a number of the struts in place for over a year, minimum and maximum temperatures of 4°C and 56°C respectively were experienced on the project. The maximum mean daily temperature change observed was in the order of 30-35°C, which has the potential to induce significant temperature loading in the strut. Strut load and average temperature data for a three day period of no excavation is considered for the example strut of Figure 11 (with the 3 day period shown boxed) and replotted in Figure 12. It is evident that the strut force increases by around 180 kN and that this is due alone to a 25°C increase in temperature. The strut of consideration is a first level strut in a sheet piled excavation.

If the installed strut was fully restrained, then an increase in temperature would result in an increase in strut load of:

$$F_{fixed} = EA\alpha(\Delta T) \quad (6)$$

where  $F_{fixed}$  is the force in the fully fixed strut due to a temperature change ( $\Delta T$ )  
 $\alpha$  is the coefficient of thermal expansion for steel

In this example, if the ends of the strut were fully restrained an increase in temperature of 25°C would result in an increase in strut load of 750kN. The observed increases in load are, however, only about a quarter of this value primarily due to the finite stiffness of the soil and any other slack between the waler and sheet pile. This concept is expanded further in Zaremba and Lehane (2007).

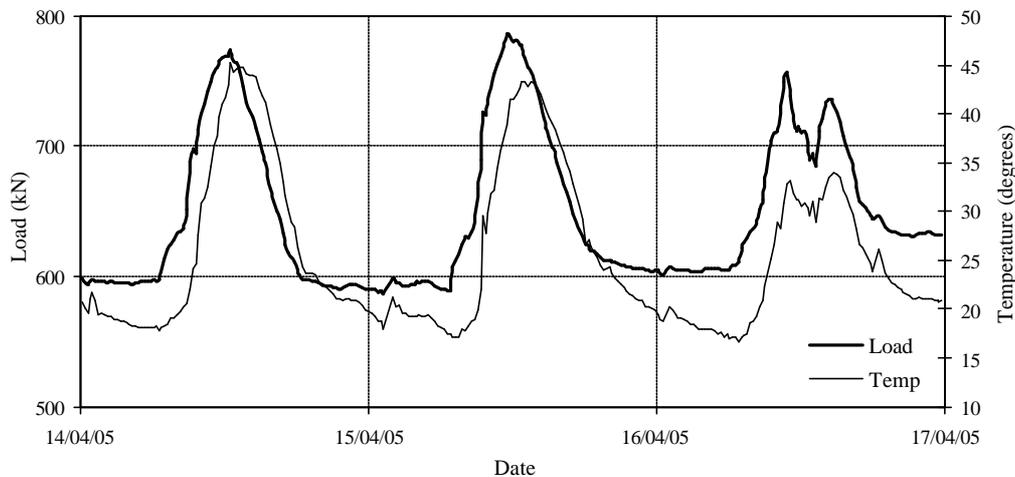


Figure 12. Variation in strut load due to temperature for a period of no activity (taken from the example strut illustrated in Figure 11)

## 5 CONCLUSIONS

This paper describes the experiences gained during the strut load instrumentation and monitoring of a recent underground excavation in the Perth CBD. Vibrating wire strain gauges were used extensively and proved a reliable and accurate means of determining strut loads. The simultaneous measurement of strain and temperature also allows the temperature effects in the struts to be identified and assessed.

## 6 ACKNOWLEDGEMENTS

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