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Maximising the potential of strain gauges: A Singapore perspective

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ABSTRACT: Load monitoring of support struts in temporary excavations plays a crucial role in confirming the stability and safety of the excavation. Data gained provides valuable feedback for the design engineer to facilitate refinement of future designs. Much of this monitoring is undertaken by strain gauges, sensitive instruments attached to the temporary supports, which are then linked to automated alarms through real time systems. The success of the monitoring is directly linked to the performance and interpretation of the data derived from the strain gauges, and the reliability of the real time system. There are a number of factors which can interfere with the performance of the monitoring system, to successfully and usefully interpret the data; the influence of these factors needs to be understood. The emphasis must be on the production of high quality data that can be reliably processed and rapidly given to the end-user, such that erroneous readings are minimized and genuine load changes are identified for interpretation. Through a number of case studies of deep excavation projects in Singapore, influences on the monitoring system are reviewed, their potential impacts discussed, and recommendations given to produce a high quality and reliable monitoring system, thus maximizing the potential of strain gauges to be used for monitoring of performance.

1 INTRODUCTION

1.1 *Importance of instrumentation*

Instrumentation and monitoring has always played a crucial role within the construction industry and recent worldwide high profile construction failures have further raised its profile and importance. This rings very true for Singapore. Technological advancements have allowed the instrumentation industry to become more sophisticated in how data is monitored, collected and presented to the end-users. However the emphasis remains on the production of quality data for useful interpretation. Strain gauges are one very important component of a fully integrated and comprehensive monitoring system used to control the movements and loads generated during excavations. In Singapore they are used extensively for strut monitoring in deep excavations and provide invaluable data ensuring that construction control is maintained during excavation. The build-up of load in the strut is monitored in real time during construction and compared with the design predictions at the various excavation stages. If significant discrepancies are observed, reanalysis is required, and a review of the design assumptions undertaken. However strain gauges are notoriously sensitive instruments and their readings can be influenced by a number of factors, leading to misinterpretation when the data is reviewed.

There are a number of wide-ranging potential influences impacting the accuracy of strain gauge results, encompassing a number of related construction areas: These include installation, environmental effects, construction activities and their position relative to structural members, all of which can result in erratic changes in the strain gauge readings, some of which are genuine load changes, some not. With the development of real time systems, the results can be automatically transferred to the internet for interpretation or sent to a mobile phone, but without any filtering of the erroneous readings. If received by inexperienced

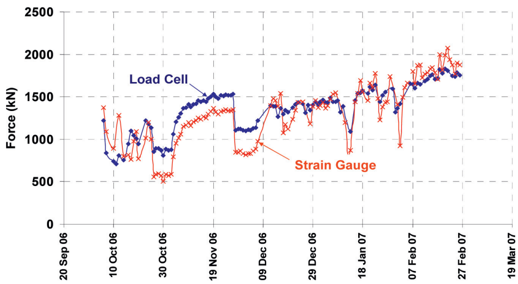

Figure 1. Comparison of strain gauge and load cell results.

personnel, commonly, all readings are treated as genuine, with the potential to cause unnecessary false panic and evacuation of the excavation, or erroneous and ignoring genuine changes in load. Either scenario results in a loss of confidence in the monitoring system. It is important therefore, that these very sensitive instruments and their performance be fully understood during interpretation and every effort taken to maximize the quality of the data.

1.2 *Reliability of strain gauge – a comparison with load cell*

Generally, load cell is known to provide reliable load measurement as it measures the full load across the full section of the strut. Strain gauge, on the other hand, measure less then 1% of the strut cross sectional area and then attribute that load to the whole strut. Figure 1 shows the data that gives an indication of the relative accuracies of strain gauges and load cells. The graph shows a general variance between 5% and 10%. Much of this difference can be accounted for by their different responses to the various construction influences, external factors such as temperature and EMI, and the different ways they monitor load. A detailed discussion of this topic is beyond the scope of this paper and needs to be part of a separate study. The correlation between the two instruments, however, is sufficient to indicate that strain gauge, is capable of monitoring the struts accurately.

With this fact established, strain gauge has other advantages over load cell. One fundamental benefit is the cost effectiveness of strain gauge in Singapore; with a strain gauge costing approximately U.S. $200 and a load cell considerably more at U.S. $4000. With cost, normally to the industry's detriment, significantly influencing the selection process, strain gauges are the instrument of choice. Cost aside from a technical perspective, introduction of load cell in the strut can create non typical loading conditions, but strain gauge does not change the loading condition on the strut. In addition, strain gauge can also be replaced easily if damaged.

1.3 *Choice of strain gauge type*

Once a strain gauge is chosen to monitor a strut, there are two commonly available types for strut monitoring; spot weldable strain gauges (SWSG) or arc weldable (AWSG), also referred to as surface mount strain gauges. Both strain gauges are widely used in Singapore, with slightly different attributes and advantages. SWSG have the advantage of being attached low to the strut, therefore minimizing the impact caused by bending error. However the AWSG is more robust, its greater area fixed to the strut resulting in a better area to area connection, making it in theory less sensitive to fluctuation from vibration caused by accidental impact to the strut. By far the most important factor in ensuring the performance of the strain gauges is that they are installed correctly and not damaged during installation.

For SWSG the gauge flanges are spot welded to the strut, this requires exposing the thin 1.45mm gauge, increasing the possibility of damage. After the welding, the vibrating wire plucking coil housing is mounted onto the gauge for measurement and as a form of protective cover. It is crucial that the coil does not touch the gauge, which can occur with some brands, otherwise subsequent readings are affected. AWSG are arc welded to the flange, however a dummy gauge should always be used during welding to avoid damage, then replaced with the actual gauge, followed by mounting the vibrating wire plucking coil and further protection as required. The only potential problem with this installation is the introduction of residual stress into the structural member by the welding process. On overall comparison of the respective merits of the two gauge types the authors believe AWSG will provide more reliable results – a view shared by Broone & Crawford (2000).

2 FACTORS INFLUENCING THE PERFORMANCE OF STRAIN GAUGE

2.1 *Location of strain gauge*

When bending within the prop is likely to be significant, strain gauge reading will be affected by its location in the prop. Strain gauges placed at the same section may give different reading as they experience different stresses in the prop subject to bending. Connections between the prop and waling result in non-uniform stresses, as do connections to kingposts, cross-bracing or runner beams. Thus strain gauges installed near to these locations are likely to be affected by the non-uniform stresses and will not give a representation of the loads in the props.

2.2 *Impact of electromagnetic interference*

As vibrating wire strain gauges operate at a frequency between 600 to 1500 Hz, they are subject

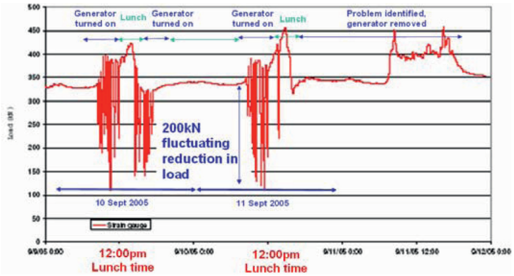

Figure 2. Impact of EMI noise on strain gauge readings.

to electromagnetic interference (EMI). This compromises the accuracy of the readings by introducing noise into the raw data, which can be very difficult to separate from genuine data, and therefore can be processed and calculated as load. There are numerous potential sources of EMI noise on construction sites including: arc welding, machinery ignition, power generators and power cables on the site. The noise takes one of two forms, either as a general underlying trend impacting the overall accuracy of data by increasing its spread. Or as a high voltage surge, causing a spike in the load readings when, for example, a machine ignition is started, electronic noise tends to lower readings, whereas magnetic noise increases them. With the advent of real time monitoring and data processing at 10 minute intervals, the impact of this interference becomes more significant. The first case leads to a general questioning the accuracy of the strain gauge readings as the accuracy range appears wider. The data spikes can result in an alarm being breached, with the potential for work to stop unnecessarily.

The impact of EMI noise can be clearly seen in Figure 2. During the working day on 9th & 10th September, electronic noise interference from a generator and power cable caused a 200 kN fluctuating reduction in load. The lunch hour can also be clearly seen when the generator was turned off. By the 11th September the noise had been identified and the generator removed, hence more stable readings.

2.3 *Temperature effect*

The impact of temperature on the performance of strain gauges installed on struts has long been recognized as a significant factor affecting their performance, with papers first published on the issue in the early 1960s in Norway and Japan (NGI 1962 & Endo & Kawasaki 1963). Despite the advent of thermally matched strain gauges, thermal influence persists. In the United Kingdom for an un-decked excavation subject to the thermal effects due to sunlight, an annual temperature range of 50°C was measured leading to a variation of 2750 kN in strut loads, after the base of excavation was reached (Batten M et al. 1996). This equates to a change of load of 65 kN per 1°C. Similarly in the United States significant variations were measured and reported. Boone and Crawford 2000, recorded an 18.75 kN change per 1°C, with an annual temperature variation of 45°C on their site resulting in an annual fluctuation of 844 kN. The difference in these variations is due to the strut area, in combination with the stiffness of the retaining system, the ground it supports and the end restraint, with a greater stiffness resulting in a greater impact due to temperature variation.

Singapore lying 1.5° North of the equator experiences minimal seasonal variation in temperature, but a significant diurnal range, with temperatures fluctuating from a low of 20°C to a high of 36°C. This poses a different set of problems. The problem of temperature variation was first published by Niu et al (2005) discussing fluctuations due to a deep excavation in Singapore for the North East Line metro, in 1999. A load change of 37 kN per 1°C was recorded, against a theoretical change of 48 kN per 1°C. This being calculated by:

$$\Delta P = A_s E_s \alpha\, \Delta T \tag{1}$$

Where ΔP is change in load due to temperature change (ΔT), A_s is cross sectional area of the strut, E_s is Young's modulus of steel and α is the thermal coefficient of expansion for steel.

For this excavation, 23% of the theoretical increase in load was not observed in the instrumentation. The absence of this monitored load was explained and demonstrated by an outward movement of 2 mm of the retaining system during the higher temperatures. This phenomenon has been observed in the U.S. where a potential 13 mm movement into the ground was recorded in glacial till, (D. Druss 2000) and on other projects in Singapore, with a 2 mm movement into the ground of a 1.5 m thick diaphragm wall in soft Marine Clay.

The same temperature phenomenon is seen consistently across deep excavations in Singapore. For a 25 m deep excavation in soft Marine Clay on the Circle Line project an increase of 30 kN per 1°C was measured, Figure 3, across three different struts, over four days of non excavation. This equates to only 56% of the theoretical increase being transferred to the strut load. In this case the critical factor in mobilizing the full effect of the temperature lies in the ground. The retaining system was very stiff, with 1.5 m thick diaphragm walls, compared to the NELP example where a soldier pile system in considerably stiffer ground was used. Further to the general trend in the figure, there is some scatter in the data, this is due to readings taken at between 8:00 and 9:00 am and attributed to the very localized effect of plant start-up up causing EMI.

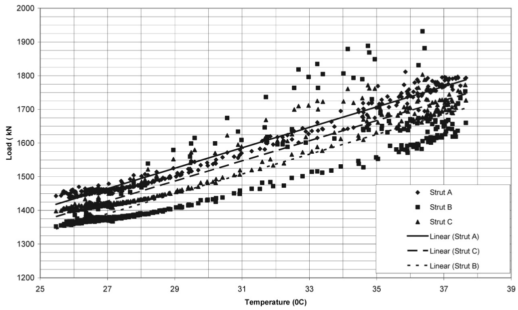

Figure 3. Impact of temperature on strut load.

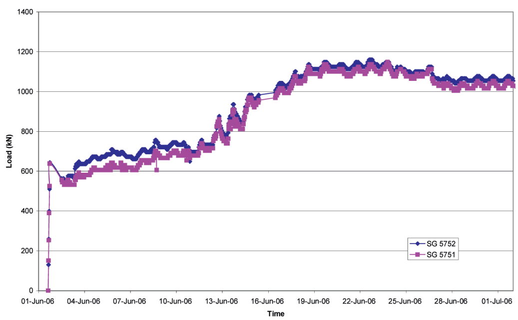

Figure 4. Loss of preload after strut installation.

2.4 *Preloading*

Preloading has an important bearing on the strain gauge performance in early stages. The fundamental action is to install the strain gauge, take base readings and check it is working correctly prior to the onset of preloading. Base readings should ideally be taken prior to the strut being connected to its end supports.

During pre loading the load registered in the strain gauge and load cell should be checked against the jack load; however loads cannot be expected to match perfectly. The jack registers the highest load, followed by the strain gauge and then the load cell; this sequence tends to be the case observed in Singapore.

This can be attributed to a number of factors: the relative positions of the instrument, relatively low loads being used; construction difficulties in placing the strut truly perpendicular to the retaining system; temperature effects; the introduction of load cell in the struts affecting the overall load transfer pattern.

2.5 *Disturbance by construction activities*

As with all excavations, the accuracy of the instrumentation readings can be accidentally influenced by a number of different construction activities, leading to potential misinterpretation of the readings. One of the obvious is the accidental damage of strain gauge

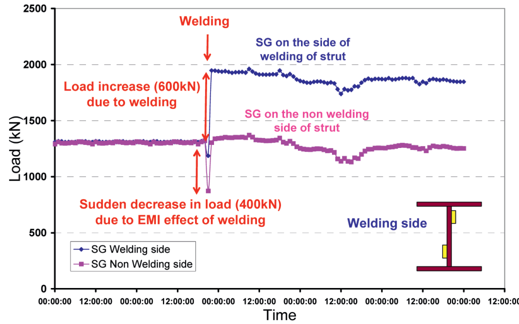

Figure 5. Impact of welding on adjacent strain gauges on the same strut.

by worker, which can either permanently damage the gauge or partially damage the gauge or connection.

2.6 *Welding*

One of the construction effects resulting in erratic and significantly high loads registered by the strain gauge is welding. High heat from welding of horizontal ties or lacings to the strut member, which usually commences after preloading, can result in a high and sudden increase in the strut loads. As shown in Figure 5, the welding of lacing to a strut has caused the strut load measured by a pair of strain gauges located close to the lacing, to rise suddenly.

The impact of this welding on the strut load is clearly evident.

As shown in Figure 5, the readings on both sides of the strut web show a sudden drop, probably associated with EMI noise, followed by a sharp increase of load on the welding side. An increase from 1300 kN to 1900 kN was recorded. On the non-welding side a minimal rise in load was registered. On completion of welding the impacted gauge did not recover to its original load but remained at its elevated level, which is not representative of the overall load in the strut. This residual stress, recognized since 1964, is not representative of the actual load of the strut, and if clearly identified from the readings and construction activity, the reading can be adjusted to account for this effect.

2.7 *Casting of permanent slab*

Another construction impact on temporary supports, and their strain gauges, is the effect due to casting of permanent components of a top-down excavation. During the casting of a 1.5 m thick roof slab, the impact of the curing and expansion of the slab can clearly be seen in the two layers of struts above the roof slab, Figure 6. A significant drop of 500 kN was observed across the full excavation, followed by an increase several days later and a return to the ongoing trend of the

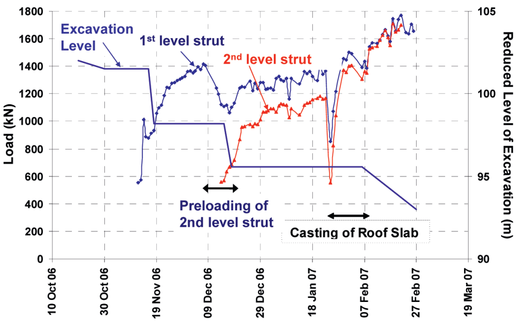

Figure 6. Impact of casting of permanent roof slab on strut loads above.

load. Once clearly identified, this phenomenon can be easily linked to construction activity, and not used to cast doubt on the accuracy of the strain gauge results.

2.8 *Negative values*

Another phenomenon seen in strain gauge in deep excavation, particularly in soft clay, is that of negative loads in the top strut layers, indicating that the struts are in tension. This is frequently blamed on the instruments themselves and regarded as error readings. However investigations into a number of these cases have identified that the strain gauges are functioning well and recording genuine loads. Independent checks through cut off tests and inserting jacks have demonstrated that these struts are in tension. This is due to a combination of factors: the loads in the struts tend to be originally low at higher levels; loss of preload; and the deflection profile of the retaining wall. With soft clays, significant retaining wall movements are recorded, with deep seated movements occurring below excavation levels. As the excavation progresses, stiffer struts with greater preloads are used. Combined with these large movements below the struts, the retaining wall can rotate about the strut, resulting in a small backward movement into the soil at higher level. This is also reflected in the inclinometer readings.

2.9 *Problem related to real time system*

To make the most effective use of strain gauge data, for deep excavations, it is prudent to link the instruments via data logger to the office computer and mobile phones in a real time system. However by implementing such a system two noteworthy problems need to be considered.

First the potential high number of alert alarms generated. The erroneous alerts can lead to a loss of confidence in the system and potentially a genuine alert being 'lost' amongst the false alarms.

The second and potentially more serious problem lies with the robustness of the real time system itself. The simile, a chain is only as strong as its weakest link, rings very true when applied to any real time system. Any failure of any component within the system compromises the whole monitoring scheme leading to an absence of results to the end user. Apart from the strain gauges, the potential numbers of points that can fail within the system are numerous. These include the cabling, the data logger itself, the phone system, the power and the server. Failures of all of these components have been experienced.

3 HOW TO MAXIMIZE THE POTENTIAL OF STRAIN GAUGE

3.1 *Right location of strain gauge on strut*

There are two important considerations when locating a strain gauge on a strut. First it's location on the strut, and then its position relative to other structural members. If bending within the prop is likely to be significant, strain gauges should be located to account for it, four gauges for a circular prop or proportionately spaced along the web for an I-beam. Connections between the prop and waling result in non-uniform stresses, as do connections to kingposts, cross-bracing or runner beams. Therefore the gauge locations should be at maximum distance from these areas, to be fully representative of the loads passing through the strut.

3.2 *Cross referencing with load cell*

British CIRIA C517's guide on temporary design (Twine & Roscoe 1999) recommends strain gauges over load cells. However as cross referencing of data from different instrument types is critical to gaining a full picture of the excavation induced movement, it is recommended that at least some load cells be included in the instrumentation design. This concept is fully recognized in Singapore.

The Building Control Authority of Singapore (BCA) states that deep excavations must be monitored by a combination of strain gauges and loads cells. Land Transport Authority of Singapore (LTA), the client for the majority of deep excavations in Singapore which are for the continually growing underground rail network, specifies that as a minimum requirement, 25% of all struts for deep excavations shall be monitored for load by strain gauge and/or load cell, and of those monitored by strain gauge, 15% shall also be monitored by load cell.

3.3 *Minimizing EMI effect*

EMI noise can be avoided by a few simple measures on site. It is recommended that cabling lengths be kept to a minimum; the cables and datalogger be located at least 5 m away from any potential source of EMI. Figure 7 shows a typical layout of data logger in an excavation site. Regular checks should be undertaken

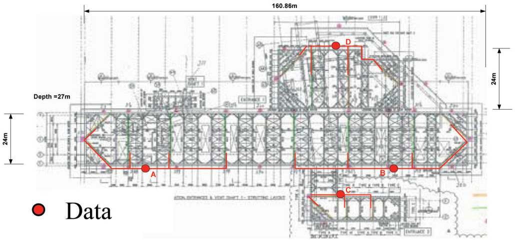

Figure 7. Typical layout of data logger on an excavation site.

by a portable EMI meter to ensure that cable and datalogger zones remain EMI free. Although cables can be protected from electronic noise, cable joints and the inevitable on site cutting and re-splicing of cables are weak points that can be easily corrupted, therefore particular attention should be paid to these locations.

3.4 *Account for temperature effect*

The temperature range is less in Singapore, and therefore the impact of load less than elsewhere in the world. However strut loads are very closely linked with monitoring control of excavations. The maximum design load of a strut, using moderately conservative soil parameters, is used as the work suspension level, with an alert set at 70% of this capacity. There can be significant implications on the work, including stoppage of works if the temperature effect is not properly accounted for in the strut loads. A number of different solutions include painting struts white and daily spraying to reduce temperature impact. It is suggested that the most appropriate solution is to account for the theoretical temperature effects during design and to add them to the monitoring control values to ensure that work is not impacted unnecessarily.

3.5 *Protection against disturbance by construction activities*

Damage to strain gauge and disturbance on the data due to construction activities can be avoided through a combination of adequate protection, education of site staff through tools box talks and clear well marked signs on site. If damage occurs on a frequent basis, the more extreme measure of fining individuals or companies can be considered.

3.6 *Maximizes strain gauge reading with real time system*

To maximize strain gauge reading for monitoring of deep excavations, it is prudent to link the instruments via data logger to the office computer and mobile phones in a seamless fully automated machine to machine (M2M) system where no human intervention is required for onward transmission of results, resulting in a fully real time system (Tan et al 2004). It is strongly recommended that the capacity for data transfer of any such system is in minutes and that a wireless system be utilized.

An understanding of the potential problems can reduce false alerts, combined with alerts going only to knowledgeable personnel who are fully cognizant of the construction works being undertaken.

Potential failure of the cabling, the data logger, the phone system, the power and the server within the system can lead to loss of data or delay in transmission of data. To ensure that the system is fully automated and seamless, all these areas need to be rigorously checked and fail safes written into the systems to inform the system manager if any of these components fail, rather than assuming that all are functioning smoothly.

4 CONCLUSIONS

It is clearly evident that strain gauges are essential in monitoring and controlling deep excavations. With the increasing sophistication of the real time systems producing vast quantities of data, combined with M2M capabilities allowing automated alerts, and strict alarm limits on the monitored loads within the temporary structural systems, the results from strain gauges are under very close scrutiny. Therefore quality data and a clear understanding of both strain gauges and how the construction activities impact that data are crucial to the interpretation of strain gauge results. Without this, confidence in the performance of the system is lost, resulting in results being ignored as errors, very dangerous in the monitoring environment, or numerous unnecessary alarms received impacting the construction progress.

To maximize the potential of strain gauges, their locations and that of the cabling must be planned, installation carried out by skilled personnel aware of the problems and the potential to compromise data. Data interpretation should also be by skilled personnel fully aware of the design predictions for the excavation, the excavation progress and the potential impact of the excavation on the strain gauge results. Finally the processing system taking data from the strain gauge to the end user must be seamless and robust such that this component does not fail leading to a complete breakdown of the whole system.

REFERENCES

Batten, M., Powrie, W., Boorman, R. & Yu, H. 1996. Measurement of Prop Loads in a large excavation during construction of the JLE station at Canada Water, East London. Proceedings of *Geotechnical Aspects of Underground Construction in Soft Ground, London 1996 pp 7–12*

Boone, S.J. & Crawford, A.M. 2000. The effects of temperature and Use of Vibrating Wire Strain Gauges for Braced Excavations. *Geotechnical News September 2000.*

Druss, D.L. 2000. Discussion The effects of temperature and Use of Vibrating Wire Strain Gauges for Braced Excavations, *Geotechnical News Vol. 18 No. 4 pp 24.*

Endo, M. & Kawasaki, T. 1963. Study of Thermal Stresses Acting on Struts. *Transactions of the Architectural Institute of Japan No. 63 pp 689–692*

NGI. 1962. Vibrating Wire measuring Devices Used at Strutted Excavations, Technical Report No. 9. *Norwegian Geotechnical Institute, Oslo*.

Niu, J.X., Wong, I.H. & Makino, M. 2005. Temperature Effects on Strut Loads and Ground Movements for a 31m deep excavation in Singapore. *Proceedings of Underground Singapore 2005.*

Tan, G.H., Ng, T.G. & Brownjohn, J. 2004. Real Time monitoring and Alert Systems for Civil engineering Applications using Machine to machine Technologies. *Int. Conference on Structural and Foundation Failures, Singapore 2004.*

Twine, D. & Roscoe, H. 1999. Temporary Propping of Deep Excavations, *CIRIA Guide C517*.