Monitoring on the performance of temporary props using wireless strain sensing

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ABSTRACT Although temporary props have been extensively used in underground support systems, their actual performance is poorly understood, resulting in potentially conservative and over-engineered design. This paper presents the performance monitoring of 4 temporary props in an urban construction site using a newly developed wireless strain sensor node featuring a 24-bit ADC. For each prop, 6 strain gauges and 3 temperature sensors were directly attached onto the prop surface using super glue, and then connected to a wireless strain sensor node mounted in the middle span. Each sensor node transmitted both monitoring data and network diagnostic messages in near-real-time over an IPv6-based (6LoWPAN) wireless mesh sensor network. The data were also stored locally at each node on a micro SD card. Extensive testing and calibration was undertaken in the laboratory to ensure that the system functioned as expected. The prop loads are presented without correction for temperature effects and compared with the design loads. The monitoring data reveal the development of loads in temporary props during excavation, the formation of the basement and the extraction of the props. The network performance characteristics in terms of message reception ratio and network topology evolution are also highlighted and discussed.

1 INTRODUCTION

Temporary support systems in underground construction have become increasingly complex due to the increased complexity of underground infrastructure and surrounding ground conditions. This has potentially resulted in both conservative or unsafe designs (Bhalla et al. 2005). It is therefore essential to monitor the real performance of these supporting elements to ensure their satisfactory behaviour.

Wireless Sensor Networks (WSNs) are nowadays a mature technology, increasingly used for various large-scale applications including precision agriculture, environmental and infrastructure monitoring. Compared to the traditional sensor networks, the use of wireless technology has proven to offer distinctive advantages, such as flexible, faster and denser deployment of sensors in the field (Xu et al. 2015; Liu et al. 2015). This paper concerns the deployment of a WSN for performance monitoring of 4 temporary props in an urban construction site, for which a newly developed wireless strain sensor node was used.

2 WIRELESS STRAIN SENSOR NODE

A new wireless strain sensor node was developed by the Cambridge Centre for Smart Infrastructure and Construction (CSIC). Extensive testing and calibration was undertaken in the laboratory to ensure that the system functioned as expected.

2.1 Wireless strain sensor node

The CSIC SmartPlank version 2 sensor node is an 8-channel 24-bit ADC sensor board, as shown in Fig. 1. The board supports 6 strain sensor analogue input channels, with a further 2 analogue channels specialised for use with load cells. The board also features three 1-wire connections for digital temperature sensors, such as the Maxim Dallas DS18B20, a real-time clock (RTC), power button, JTAG/ISP programming interface, a micro SD card socket for data logging purposes, and a multi-position switch for rudimentary in-field configuration. It provides a flexible and versatile platform to address the needs of a variety of applications. For example, depending on the application requirements, a quarter bridge or half-bridge can be easily reconfigured for foil strain gauges with either 120ohm or 340 ohm resistances.

Figure 1. Wireless strain sensor node developed in CSIC

The board is packaged in a robust (IP67) plastic housing.

2.2 *Wireless strain sensor software*

The application software running on the wireless strain sensor node was developed in Contiki OS (Dunkels et al. 2004). The program reads all 8 ADC sensors, the 3 digital temperature sensors and the time from the RTC. It then stores the readings on the micro SD card (if present) and transmits the sensor data via a UDP connection. Nodes use the Contiki OS standards-based IPv6 protocol stack (6LoWPAN/RPL) for link-local addressing and routing, and ContikiMAC at MAC layer for low-power operation. A more detailed description of the software can be found in Nawaz et al (2015).

2.3 *Wireless strain sensor characterization*

Sensor node testing and calibration was performed in a laboratory environment. The first test was to investigate the linearity and repeatability of strain gauges on all 6 channels. This was conducted using a 4-point bending test platform specially designed for sensor calibration. Fig. 2 shows the incremental ADC readings from all 6 channels with 9 loading steps (up to 681$\mu\varepsilon$). Note that the variation of each channel's reading at each loading stage is less than 0.05$\mu\varepsilon$, and sub-microstrain measurement can be easily achieved, as indicated in the inset (ch1) of Fig. 2.

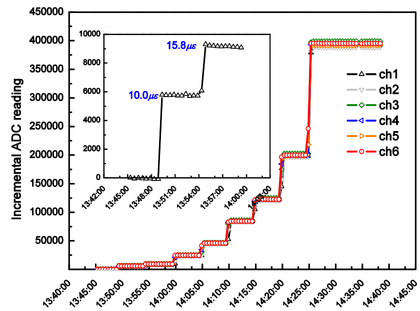
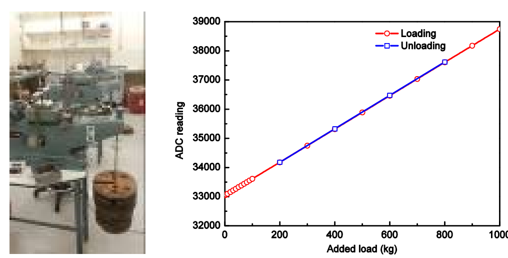


Figure 2. Calibration on the strain gauges using 4-point bending test platform.

The DS18B20 temperature sensors were tested in a water bath under heating and cooling cycles, with temperature readings from the sensors differing by no more than 0.3125 °C from the water bath reference temperature. The load cell was tested using a direct shear apparatus (see Fig. 3(a)), and the results is given in Fig. 3(b). To further check the temperature effect, and robustness of the packaging, the sensor node was emerged in the water (5-45 °C cycles), with all 6 strain gauges, 3 temperature sensors and 2 load cells connected, as shown in Fig. 4.



(*a*) Test apparatus (*b*) Test results

Figure 3. Calibration on the load cell using direct shear apparatus: (*a*) Test apparatus; (*b*) Test results.

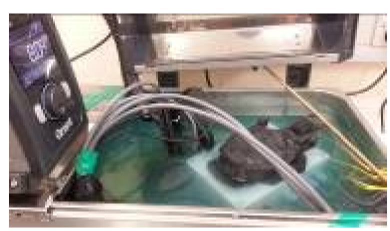


Figure 4. Robustness testing on the wireless strain sensor node.

3 APPLICATION

A wireless strain sensor network was deployed in an urban excavation site in Cambridge (UK), to provide an opportunity to understand the real performance of temporary supporting props in near-real-time.

3.1 Field overview

The Trinity Hall excavation site was situated on the eastern side of Thompson's Lane and 60m north of St. Clement's Church and Bridge Street, at the north-western end of Cambridge city centre. The proposed new student residence is to be a four storey building housing student flats with a single basement across the building footprint providing cycle parking and a common room. The approximately rectangular redevelopment site extended 24 m to 28 m eastwards from its 43 m long frontage onto the eastern side of Thompson's Lane. The site was bounded to the south by CATS library and Cambridge Spiritualist Church; to the north by Bishop Bateman Court and its rearward car park; and to the east by the rear boundaries of residential properties lining Portugal Place and Portugal Street.

The site stands at an approximate elevation of 7.7 m above sea level on land that slopes gently down towards the north. The investigation found a thick cover of made ground beneath the site associated with the historical raising of the site above the River Cam flood plain, together with the later construction of St. Clements Gardens. The foundations for the new four-storey residential block and basement will need to penetrate this made ground, the Alluvium and Terrace River Gravel, and could be based on the underlying Gault clay.

A number of monitoring technologies with which CSIC is familiar were used at the site in order to understand the real performance of various elements in the ground works during the basement excavation (as indicated in Fig. 5). For example, an array of wireless MEMS inclinometers and accelerometers (together with humidity and temperature sensors) were deployed along the boundary wall of the CATS library to monitor the movement of the adjacent building during the sheet pile installation and subsequent basement excavation. The instrumentation was installed for a period of time prior to the works commencing. Fibre Bragg Grating (FBG) sensors were attached on a number of sheet piles along the southern and eastern walls of the basement to monitor the dynamic strain response of the sheet piles during installation, excavation and construction of the superstructure. For the temporary props both the newly developed wireless strain sensors and FBG sensors were used to monitor the load development in the temporary propping system during the basement excavation.

3.2 Wireless strain sensor field deployment

Four props in total, two centre props (props 1 and 2) and two corner props (props 3 and 4), were instrumented with wireless strain sensor, as indicated in Fig. 6. These field deployments took place in stages as the excavation and associated archaeological work progressed. Due to the timing and space restrictions on site the wireless strain sensors were only deployed once the prop itself had been installed in the excavation. For example, the first wireless strain sensor was attached on prop 1 on 19th June 2015, while the last one was installed on prop 2 on 14th July 2015. FBG sensors were also installed on prop 1 and 4 for comparison, as indicated in Fig. 5. Unfortunately however, these fibre-optic cables were damaged by mechanical diggers prior to the deployment of the wireless strain sensors. The wireless gateway and data logger was installed in February 2015, prior to the deployment of wireless MEMS tilt sensors on CATS library.

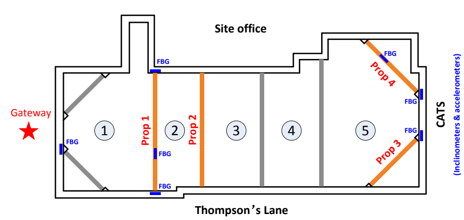


Figure 5. Layout of the instrumented temporary props, sheet piles and sensor network at Trinity Hall site

For each instrumented prop, one wireless strain sensor node was attached to 6 strain gauges and 3 temperature sensors. There were two kinds of props used in this project, namely tubular (props 1 and 3) and rhombic (props 2 and 4) ones. Gauges were attached at the 3, 6, 9 and 12 o'clock positions at the centre of the tubular props, as the most economical and practical option (Batten et al. 1999). The temperature sensors were attached next to the strain gauges to provide for temperature compensation of the measured strains. There was an exception to this configuration where one of the strain gauges on prop 1 (channel 3) was attached ¼ prop length away from the end of the prop at the Thompson's Lane side. The wireless sensor node was located in the middle of each prop. Detailed configuration of wireless strain sensors on each prop is described in Fig. 6.

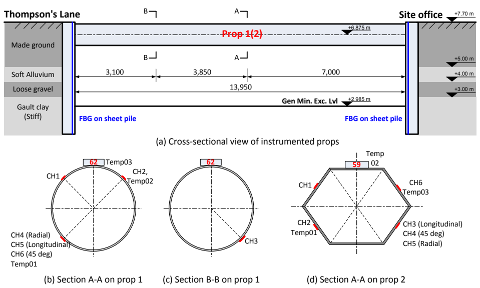
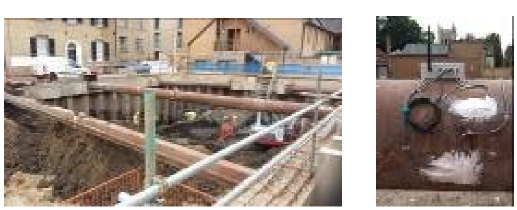


Figure 6. Configuration of wireless strain sensor on instrumented props and geological strata at Trinity Hall site

Foil strain gauges demand considerable care during field installation, due to their fragile nature. The attachment method is as follows: (1) remove the surface rust from the steel prop in the desired location with a battery-powered wire brush, and then with coarse and fine sand paper. Thoroughly clean the area with acetone; (2) apply super glue and align the gauge in the appropriate location. Immediately apply firm thumb pressure to tape placed directly over the gauge; (3) connect the gauge terminals to a wire from the sensor node using a gas-powered portable soldering kit.



(*a*) Instrumented props (*b*) Wireless strain sensor on prop

Figure 7. Field deployment of the wireless strain sensor network at the Trinity Hall excavation site.

In addition, foil strain gauges are very prone to deterioration due to water. They must be properly sealed if used in the underground structures or outdoor environments, where they are likely to encounter excessive moisture or erosion. For the first two props, the strain gauges were protected only with large quantities silicone sealant, as shown in Fig. 7. This proved to be unsuccessful for water ingress protection, as evidenced by some of the sensor readings, which exhibited dramatic changes. For the later installations, a coating of M-Coat A was first applied over the entire gauge and terminal area. The installation of temperature sensors was relatively simple. These were embedded in silicone sealant to capture the temperature change of the prop itself, rather than that of the surrounding environment.

3.3 *Wireless strain sensor network*

Fig. 8 presents the layout of the wireless strain sensor network at the Trinity Hall site (Triangle: strain sensor nodes on props; Square: tilt sensors on the wall of CATS library). Data messages are sent from each node at fifteen minutes intervals. Interestingly, it shows that sensor nodes were mainly routing message via the distant node 67 on prop 4, rather than using nearby nodes to forward messages.

Fig. 9 shows the data message delivery ratio (MDR) computed from 4 wireless strain sensor nodes during the entire monitoring period. MDR for each node was obtained as the number of data messages successfully delivered to the gateway with respect to the total number of expected data transmissions. It can be observed from the figure that, the values of MDR for props 1 and 4 were above 80%, with their average PDRs of 99.7% and 97.5% from 11th July to 23th September 2015, respectively. The reduction of MDR in prop 1 between 7th July and 10th July 2015 was due to a transient fault with the gateway.

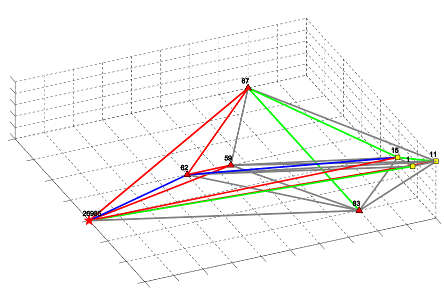


Figure 8. Network topology in Trinity Hall. Link colour represents the average number of connections made to the gateway per day during the 110-day period. Grey lines indicate one or two connections; blue lines between 2 and 5 connections; green lines between 5 and 15 connections; and red lines more than 15 connections.

For props 2 and 3, it was observed that there were significant variations in MDR time history, with their average MDRs of 88.5% and 71.5%, respectively. The former may have been due to the ongoing excavation work, while the latter was probably due to the use of an internal chip antenna. It was witnessed that the external antenna on prop 2 was frequently disturbed by the digging bucket, as highlighted in Fig. 7(a). Fortunately, all the data that failed to be delivered via the wireless network was later recovered from the local micro SD card storage.

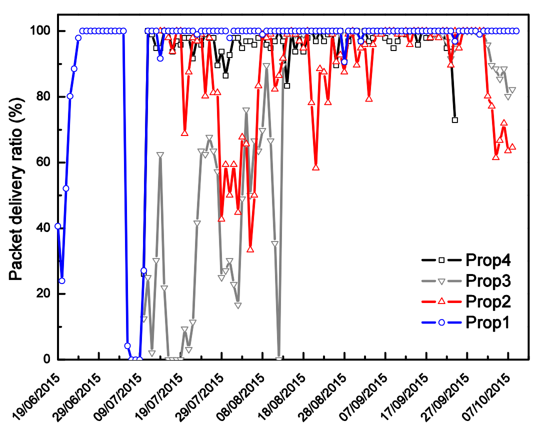
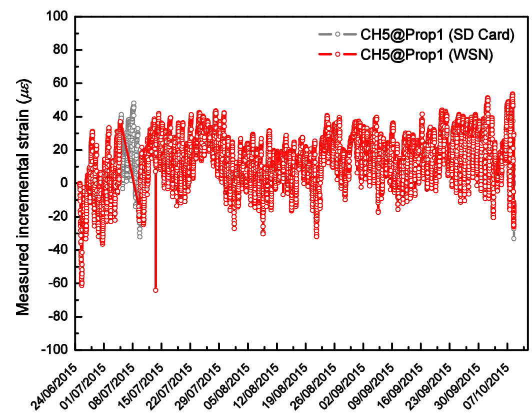


Figure 9. Packet delivery ratio at the gateway

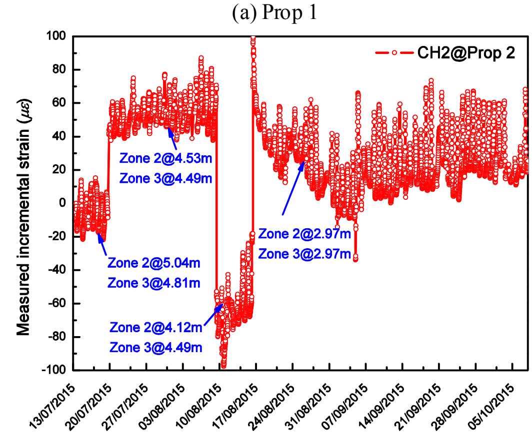
3.4 Monitoring results

Fig. 10 presents two examples of the measured incremental axial strain on prop 1 and 2 during the excavation period, with respect to the baseline readings taken immediately after the installation. Negative strains indicate compression. It can clearly be observed from Fig. 10(a) that prop 1 mainly experienced slight tension, rather than compression. The data from the FBG measurements in the sheet piles at both ends of the prop also confirmed the prop performance. This is probably due to local reinforcement at each end of the prop. (Note that data received by via the WSN, shown in red, is incomplete; however the missing data, shown in grey, was subsequent retrieved from the SD card.)

Similar field performance was observed on prop 2, as indicated in Fig. 10(b). The measured incremental strain increased to around 50$\mu\varepsilon$ on 20th July, and reduced to approximate -60$\mu\varepsilon$ on 10th August. It again increased to about 80$\mu\varepsilon$ on 17th August, and then gradually decreased to around 10$\mu\varepsilon$ by the end of the monitoring period. Excavation levels are shown in Fig. 10(b), for zones 2 and 3 (as indicated by the circled numerals in Fig. 5). The excavation and backfilling was completed on 25th August 2015. Although the excavation level data is sparse, it is clear to see that the measured strain variations were in good alignment with the excavation levels.



(a) Prop 1



(b) Prop 2

Figure 10. Examples of the measured incremental strain

Fig. 11 plots the incremental axial loads on 4 instrumented props. The axial prop load was calculated using the measured incremental strain, Young's modulus for the steel (210GPa) and the cross-sectional area of steel props (0.021048m^2 and 0.016 m^2 for tubular and rhombic props, respectively). Although not temperature compensated, it is clear from the Figure that all the 4 props were not carrying much compression load in comparison to their design loads. Instead, somewhat surprisingly, tension loads were observed. These will be further investigated by looking into the data from the other channels on each prop. Nevertheless, this observation was confirmed by the FBG measurement data from the sheet piles at the ends of prop 1.

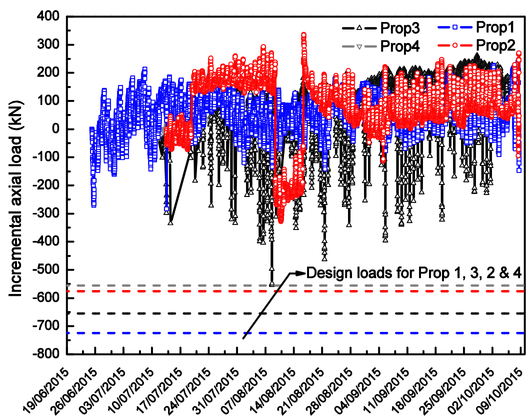


Figure 11. Incremental axial load on 4 instrumented props.

It is well know that the effect of temperature on prop loads can be very significant. The measured temperature on the 4 props varies from 3.75 °C to 51.56 °C, and the temperature inside the sensor node box varies from 4.06 °C to 41.13 °C. It can be seen from Fig. 10 and 11 that there was a considerable amount of load cycling due entirely to temperature effects as the prop warms during the day and cools at night. The temperature effect on the real performance of these temporary props requires further investigation.

4 CONCLUSIONS

The paper presents the performance monitoring of 4 temporary props in an urban excavation site using a newly developed wireless strain sensor. Preliminary analysis on the sensing data from these props would seem to suggest that there is scope for more efficient design and construction in future schemes. The temperature effect on the real performance of temporary prop is to be further investigated.

The overall performance of the wireless sensor network in this construction site proved to be satisfactory, with average MDR of 88% over 110-day monitoring period. The small amount of data lost was recovered later from the on-board micro SD card storage.

The results of the lab calibration and field application of the new wireless sensor node shows very good performance. This presents the opportunity to build smarter temporary support systems, using props with integrated wireless strain and temperature sensors and load cells.

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