Monitoring of Mining Induced Movements Between Bridge Components with Fibre Bragg Grating Sensors

M Brunton, BE Whelan
Monitor Optics Systems Pty. Ltd.

ABSTRACT

This paper outlines a novel use of Monitor Optics Systems' (MOS) Fibre Bragg Grating (FBG) sensor cables to monitor relative movements between bridge components. Twin bridges that form part of the M1 Motorway in Helensburgh were to be subjected to ground movements caused by subsidence from planned underground Longwall coal mining parallel to the bridges. An engineering assessment was carried out to determine the risk of movements of bridge pier and abutment footings relative to the bridges' headstocks, abutments and deck. It showed that relative movements of 5mm or more between headstocks and abutments could cause cracking in areas that cannot be visually inspected and that are difficult to repair, and relative movements of more than 16mm could lead to structural failure. A technical committee formed to manage subsidence effects on RMS infrastructure agreed that a surveying accuracy of 2mm was the minimum requirement to determine trends in movements between bridge components. As conventional relative 3D survey has a tolerance of +/-2.5mm, it was agreed that a more accurate monitoring solution was required.

MOS initially proposed using their FBG sensor cables between bridge footings to measure relative movements, but it was deemed impractical and expensive due to the difficulties associated with installing sensor cables underground. MOS then proposed using their sensor cables held in tension between headstocks and abutments to measure relative horizontal movements. The solution would provide measurements of relative horizontal orthogonal shifts at the corner of each abutment and headstock at an accuracy of approximately 0.02mm. Sensor cables could not be installed between headstocks and the bottom of piers due to the risk of vandalism, so tilt meters were proposed to measure in-plane transverse tilts of the outer piers instead, and traditional 3D surveying for all other measurements. The technical committee concluded that the proposed solution would be adequate for their requirements.

A clamping system was developed for the sensor cables and the monitoring system was installed in 2016. The sensors are monitored at pre-determined times with demodulation equipment that is battery powered. Data is automatically sent to key personnel which is post processed by engineers to determine stresses in key bridge components.

1 INTRODUCTION

Longwall mines LW301-303 are located west of the M1 Motorway and northwest of Helensburgh, with extraction to be approximately parallel to the motorway from north to south. LW301 is located closest to the motorway at a distance that varies between 210m and 335m. Two bridges that form part of the northbound and southbound carriageways of the motorway are also located parallel to the mines, with LW301 located approximately 330m from the bridges. The bridges, formally known as BN616 and BN617, but more commonly referred to collectively as "Bridge 2", carry traffic over the old Princes Highway. Figure 1 illustrates the above.

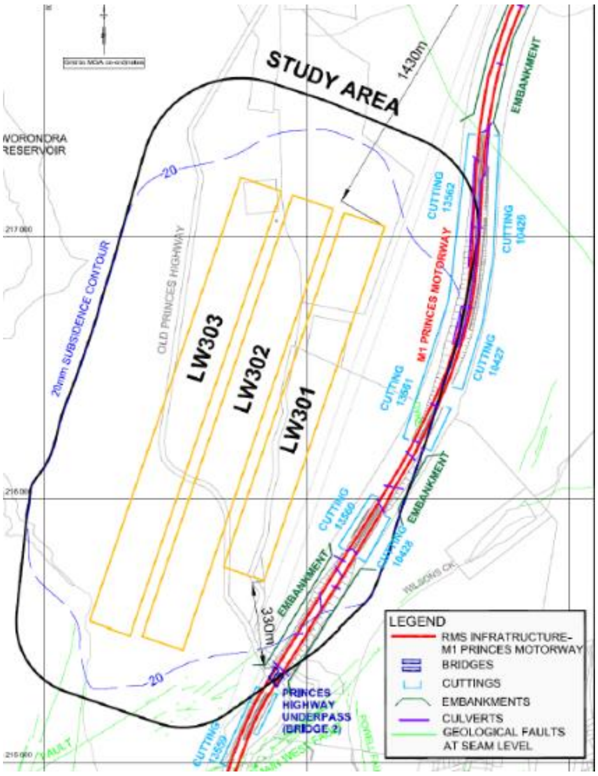

Figure 1: LW301-303 Plan

The RMS formed a technical committee comprising of various consulting engineers and experts to predict and manage the effects of subsidence on Bridge 2 and other RMS infrastructure. One of the requirements for the technical committee was to gain an understanding of the effects of subsidence induced ground movements on Bridge 2 with magnitudes that have a 1 in 100 and 1 in 2000 probability of occurring. The technical committee determined the absolute horizontal movement to be approximately 95mm with a 95% confidence level (1 in 20 probability), but the differential horizontal movements were more of interest as they are more significant to the bridge structures. Incremental relative opening and closing and mid-ordinate deviation was determined by analysing far-field horizontal movement data, and the results for different confidence levels is shown in Table 1.

Table 1: Incremental Relative Opening, Closing and Mid-Ordinate Deviation at 330m from Active Longwall

	1 in 20 probability (95% confidence level)	1 in 100 probability (99% confidence level)	1 in 2000 probability (99.95% confidence level)
Opening	8mm	14mm	44mm
Closing	6mm	13mm	44mm
Mid-Ordinate Deviation	9mm	15mm	32mm

The effects of the predicted movements on Bridge 2 were assessed, and it was determined that the bridge superstructure and bearings would not be adversely affected by differential ground movements. However, it was also determined that there is potential for local crushing of the girder concrete at the contact point of the dowel restraints on the pier headstocks. The 1 in 100 probability movements at the bridge dowels could cause cracking between 0.1mm and 1mm, but this cracking would be structurally acceptable as the girders would continue to be adequately supported. However, the 1 in 2000 probability movements at the bridge dowels could cause cracking above 1mm, which could lead to structural failure.

As the concrete at the dowel joints cannot be visually inspected, monitoring of the relative movements between bridge components was required. The 1 in 100 probability movements between the bridge and abutment footings translate to movements of 6-15mm at bridge headstocks and abutments. The technical committee agreed that a surveying accuracy of no less than 2mm was required. As conventional 3D surveying has a tolerance of +/- 2.5mm, a more accurate solution was sought out. Monitor Optics Systems (MOS) was asked to propose a Fibre Bragg Grating (FBG) based monitoring system to monitor the movements between bridge components.

2 MONITORING PROPOSAL

2.1 APPROACHES TO MONITORING

Ideally, the concrete around the dowels would be monitored for strains and crack growth. However, the dowel restraints in the pier headstock are inaccessible, so there is no way to monitor for concrete strains or visually inspect the area.

The next best approach is to monitor the ground movements that are occurring between the bridge footings. This information can be used to calculate the forces at the dowel locations. The installation of Fibre Bragg Grating (FBG) based sensor cables between pier footings under the Princes Highway was considered, but this would have required road closures and destructive installation procedures, which was deemed unacceptable. Additionally, this technique would have only monitored changes in distance between the pier footings as the abutment footings are inaccessible, providing only limited information of the bridge distortion.

It was also possible to monitor movements between the outer pier and abutment headstocks to calculate forces at the dowel locations. MOS proposed a monitoring system that would measure relative movements between key bridge components using their FBG-based Glass Fibre Reinforced Composite (GFRC) sensor cables, which could achieve an accuracy better than 0.1mm. The technical committee decided to proceed with this approach.

2.2 FIBRE BRAGG GRATINGS TECHNOLOGY BACKGROUND

Bragg Gratings are periodic perturbations of an optical fibre that results in the reflection of a narrow bandwidth of light when illuminated by a broadband light. The reflected central peak wavelength is a function of both the grating's period and the refractive index of the fibre's core. If strain is applied to the grating, the grating period changes, changing the reflected wavelength as a linear function to the strain applied. If the fibre undergoes a temperature change, the refractive index of the fibre will change, which also changes the reflected wavelength as a linear function of temperature. This linear response makes FBGs ideal strain and temperature transducers.

FBGs are often packaged to protect the delicate optical fibre, with some packages including a mechanism to convert other measurement types (e.g. pressure, acceleration) to a strain on the fibre. MOS developed its own proprietary method of embedding one or more optical fibre into a glass fibre reinforced composite (GFRC) cable, which protects the optical fibre while maintaining excellent strain transfer.

2.3 MONITORING OF RELATIVE MOVEMENTS

MOS proposed suspending their GFRC sensor cables between key bridge components, held under tension, to measure the opening and closing between anchor points using one FBG between the anchor points.

The proposed installation points were between:

1. The outer pier and abutment headstocks on each side of the bridge, longitudinally and diagonally relative to the bridge deck, as shown in Figure 2
2. The outer headstock corners and bottom of piers, as shown in Figure 3

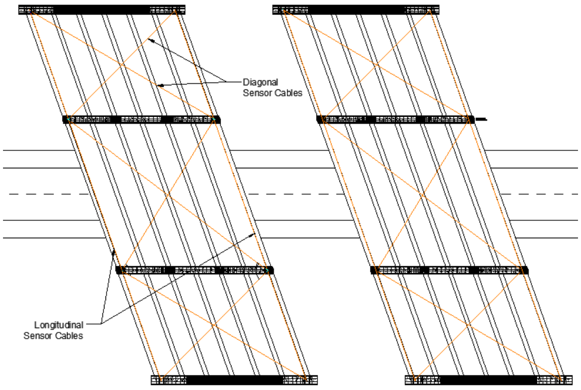

Figure 2: Longitudinal and Diagonal Sensor Cables Suspended between Outer Piers and Abutments

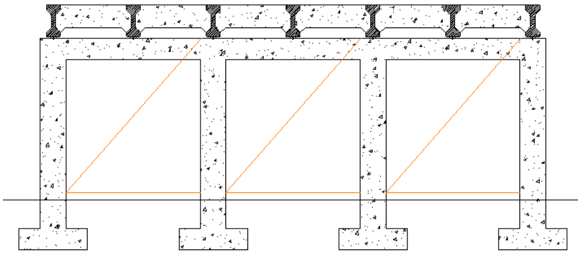

Figure 3: Sensor Cables Suspended between Headstock and Piers

The sensor cables between the outer pier and abutment headstocks are used to calculate orthogonal horizontal measurements at each anchor point relative to one of the abutments.

The sensor cables suspended between the outer headstock corners and bottom of piers was considered impractical due to the risk of vandalism. Tilt meters were proposed as an alternative, with tilt meters located on one side of the outer piers to determine transverse tilt, and in turn, transverse movements of the outer piers, as shown in Figure 4. This was considered as an acceptable alternative.

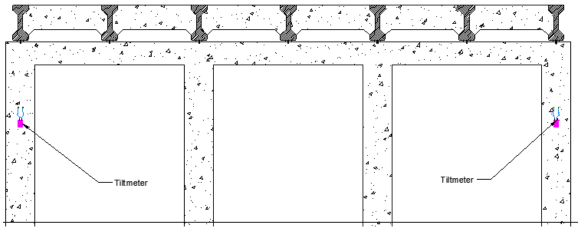

Figure 4: Tilt meters Located on Outer Piers

It was noted that although these approaches would provide valuable high accuracy data of the relative movements of bridge components, it was not a comprehensive system, and was to be conducted in conjunction with 3D surveying of the bridge.

2.4 SENSOR CABLE ACCURACY

The change in length of the sensor cables between anchor points is determined by the change in strain multiplied by the original length, or:

$$\Delta l = \Delta\varepsilon_{FBG} \times l_o \tag{1}$$

The original length is obtained by surveying the distance between anchor points, and the FBG strain is monitored using an optical interrogation unit, which can measure FBGs to an accuracy of 1 x 10^{-3}mm/m. From equation (1), the accuracy of the change in length is dependent on the length of the anchor points. The distance between anchor points is between 13m and 27m, which results in an accuracy of between 0.013mm and 0.027mm.

The accuracy of the FBGs were not brought into question by the technical committee because of their previous experience with MOS sensor cables on a different project. MOS sensor cables were embedded into the shoulders of a major highway pavement to monitor for changes in strain caused by mining-induced subsidence from a longwall coal mine that ran beneath the highway. The MOS sensor cables were tested in Universities and in the field prior to their deployment into the highway, and were further validated after their embedment into the highway by surveying results during the active subsidence period.

2.5 MONITORING REQUIREMENTS

The sensor cables were required to measure orthogonal movements at the abutment and pier headstock corners with suitable allowance for +/- 15mm movements longitudinally relative to the bridge deck and +/- 30mm movements transversely relative to the bridge deck. The required accuracy is +/- 0.5mm, which the sensor cables can easily achieve.

The tilt meters were required to measure tilts of the piers with a minimum accuracy of 0.01° and a resolution of 0.001°. The Smartec Tilt meter have these exact measuring capabilities and were deemed adequate. The tilt meters were to be installed 2m below the headstock.

As FBG sensors respond to changes in temperature as well as strain, temperature sensors were also required to compensate for temperature induced changes to the strain FBGs. Temperature sensor cables were to be installed alongside the longitudinal sensor cables in all cases, with the temperature FBG located alongside the strain FBG. The diagonal sensor cables were to be compensated using the average of the two temperature sensors that are located in their bay.

3 INSTALLATION

3.1 PROTECTION OF SENSOR CABLES

Prior to the installation of the sensor cables, ducting was installed to protect the sensor cables from wildlife and other environmental factors. The longitudinal sensor cable ducting was simple to install as it could be attached directly to the bridge girders, as shown in Figure 5.

Figure 5: Longitudinal Sensor Cable Ducting

The installation of ducting to protect the diagonal sensor cables was more challenging as there were sections of up to 2.5m that were not supported. To prevent sagging, aluminium angle was attached to the girders and the ducting was attached to the angles. The aluminium angle and ducting is shown in Figure 6.

Figure 6: Diagonal Sensor Cable Ducting Attached Using Aluminium Angle

Junction boxes were also fitted over the clamping plates on the headstocks to protect the sensor cable egress from the clamping plates, as shown in Figure 7.

Figure 7: Junction Box Fitted Over Headstock Clamps

3.2 CLAMPING SYSTEM

A clamping system was developed to anchor the sensor cables and apply an appropriate amount of tension to the cables. In all cases, the 1mm diameter sensor cable was glued into the groove of an aluminium clamp that was attached to a steel plate that in turn was attached to the bridge. The clamping system consisted of:

- 30mm x 6mm aluminium "slug" with a 1.2mm x 3mm deep groove
- Aluminium clamp with a 1.2mm wide groove, which varied in dimensional and groove depth depending on location
- Steel plate which the aluminium clamp is attached to, which attaches to the bridge
- Tensioning tool

The slug was glued to one end of the sensor cable in all cases. Once the sensor cable was suspended between anchor points, the end without the slug was glued into the aluminium clamp that is attached to the steel plate. Once the glue on the first clamp was set, the slug was fitted into the tensioning tool, which was placed behind the second aluminium clamp. Figure 8 shows an example of the tensioning tool being setup

Figure 8: Sensor Cable in Clamping System with Tensioning Tool

Suitable tension was then applied and the sensor cable was glued into the second clamps' groove. Once the glue was set, the tensioning tool was redeployed to tension other cables.

3.3 TENSIONING OF SENSOR CABLES

The MOS sensor cables have a tensile capacity of 10,000με, allowing for a potential of +/-5,000με. From equation (1), a shorter length between anchor points requires a larger pre-tension strain for a given measurement allowance. The shortest distance between clamp locations is 13m; suitable tension to allow 30mm of closure over this distance is 2,400με.

As there was significant capacity, MOS decided to tension the longitudinal sensor cables to 30mm between anchor points and tension the diagonal sensor cables so they had allowance to move 40mm longitudinally, and 50mm transversely.

The assigned pre-tension strain on each sensor cable was achieved by monitoring the tensioning process using an interrogation unit. Once the required strain was obtained, the tensioning tool maintained the tension while the cable was glued into the groove of the clamp. The tensioning of S_B1_DNE1 (Bridge 1 NE diagonal cable in the northern bay) is shown in Figure 9.

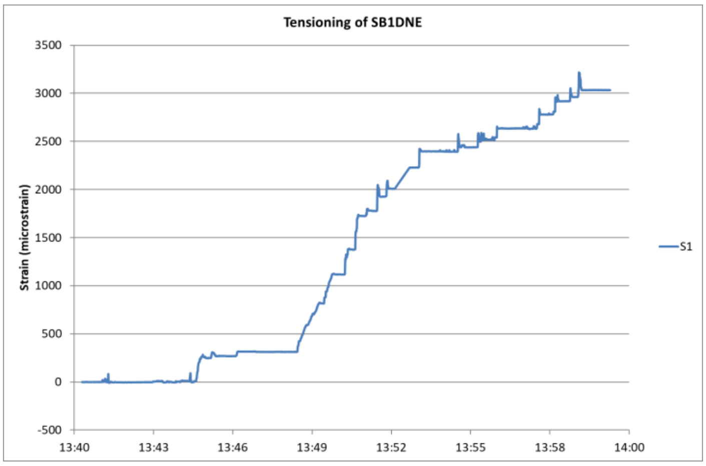

Figure 9: Tensioning S_B1_DNE1

3.4 TILT METERS

All tilt meters were installed 2m below the headstock on the outer piers of each bridge and were installed into junction boxes. The tilt meters were installed away from the Princes Highway for discretion. Cages were then installed over the junction boxes for protection from vandalism. The tilt meter installation is shown in Figures 10 and 11.

Figure 10: Tilt Meter Installation

Figure 11: Cage Installation Over Tilt Meters

3.5 SECUIRTY FENCING

Security fencing was installed at all abutments so the sensor cables were out of reach from the public, and to provide a safe place to install the interrogator cabinet. The security fencing is shown in Figure 12.

Figure 12: Security Fencing

4 CALCULATION OF ORTHOGONAL MEASURMENTS

A fixed reference system was defined for each bridge that uses the northern abutment as its reference point so the orthogonal movements of each bridge component could be calculated from the sensor cable values. Within this frame of reference, the northern abutment is assumed as fixed. The co-ordinate system is displayed in Figure 13.

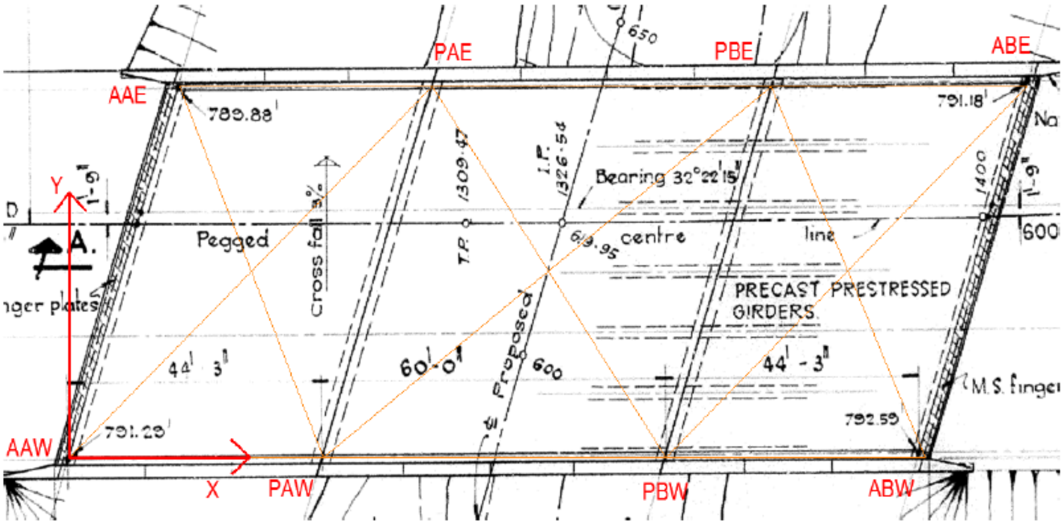

Figure 13: Fixed Reference System (Similar for each Bridge)

Within this reference frame, AAW and AAE are the corners of the northern abutment (Abutment A), which are considered fixed. The orthogonal values of PAE and PAW are first calculated using the four sensor cable values in the northern bay, and the surveyed distance between AAE and AAW, in the Cosine Rule. PBE and PBW are calculated using the Cosine Rule again with the four sensor cable values in the middle bay, except the distance between PAE and PAW is calculated from the results of PAE and PAW. This approach is also used for the measurements of ABE and ABW, using the calculated distance between PBE and PBW as well as the four southern bay sensor cable values. This ensures all measurements are relative to Abutment A.

The distances between clamp points were all surveyed following their installation, so are known to within +/- 2.5mm accuracy.

5 MONITORING SYSTEM

5.1 FBG SENSOR NETWORK

To make efficient use of interrogator bandwidth, the FBGs were serially multiplexed into two strings per bridge; one with 15 FBGs, and one with 11 FBGs. Multiplexing of the network was achieved through patch-cords between sensor locations that did not have a common focal point. Redundancy was also allowed for, with signal cables connecting to both ends of the four sensor strings. The signal cables terminate in the interrogator cabinet which is located in the north abutment of the northbound carriageway.

5.2 DEMODULATION SYSTEM AND POWER

The optical interrogation unit is a Micron Optics Inc. sm125 static interrogator, which has an acquisition frequency of 2Hz. The interrogator is connected to an industrial PC with monitoring software.

The monitoring system is powered by a battery with inverter that is programmed to switch on at specific times and days during the week to acquire data. As the inverter draws power from the battery, the switch is located between the battery and the inverter. Two batteries are dedicated to the project and are swapped on a monthly basis.

5.3 DATA ACQUISITION AND PROCESSING

FBG central peak wavelengths are acquired by the interrogator and converted to relative displacement, temperature and tilt measurements using acquisition software provided by Micron Optics Inc. Custom Utility Software designed by MOS then processes the data to calculate the total orthogonal movements of each bridge component relative to Abutment A of each bridge. The data is then sent to key technical committee members at an agreed frequency, typically monthly. This data is then fed into a computer along with the survey data to understand the stresses at the dowel joints and other key areas of the bridge.

6 RESULTS

6.1 SYSTEM PERFORMANCE

The monitoring system has been in operation since June 2016 and acquired data since. No sensors have gone offline or slipped in tension over this time.

The software provided by Micron Optics Inc. was initially used to calculate the orthogonal values from the sensor cable data. However, when performing this task, the load time for the software was more than 20 minutes from boot up. This is likely due to the calculation heavy dependant nature of the results. As the monitoring system runs off batteries, software was developed in Labview to perform the complex calculations to reduce the required system run-time.

6.2 ORTHOGONAL SHIFTS

The orthogonal shift range for each bridge component has been approximately 6mm in the longitudinal x-direction and approximately 4mm for the transverse y-direction. Some examples of data are shown in Figure 14. Seasonal trends can be observed in the results.

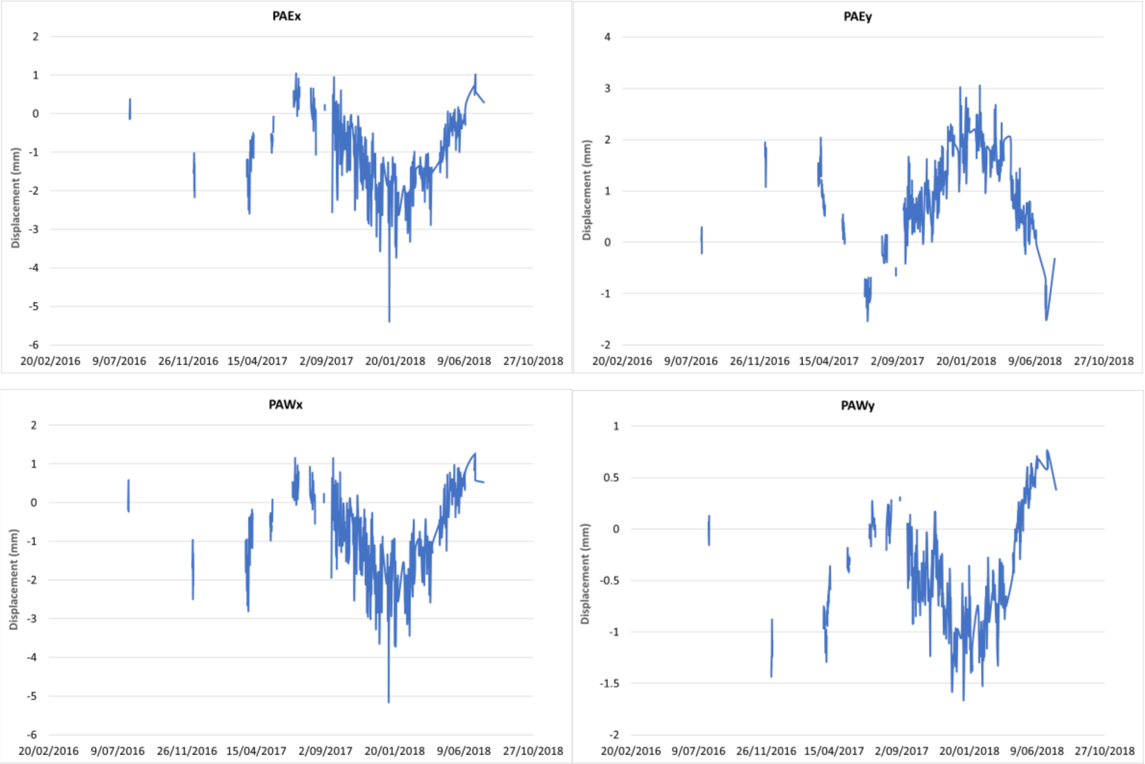

Figure 14: Orthogonal Shifts for Bridge 1

6.3 TILT MEASUREMENTS

The tilt measurements have been susceptible to noise from traffic that uses the bridge, and as such, the tilt meter data has been averaged to obtain more accurate results. Occasional outliers are still evident, however, there are seasonal trends in the results, as shown in Figure 15.

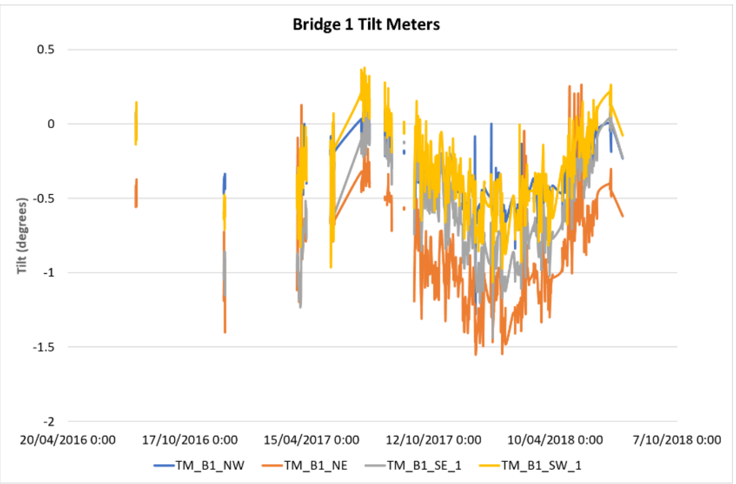

Figure 15: Tilt Meter Results

7 CONCLUSION

An optical fibre sensing system that comprises of 44 FBGs has been installed onto two bridges in Helensburgh to monitor differential movements between bridge components caused by subsidence induced ground movements. The monitoring system installation was concluded in June 2016, and data has been acquired since.

The monitoring system uses MOS FBG sensor cables for highly accurate measurements between bridge components, which is converted to orthogonal movements of each end of the pier and abutment headstocks for each bridge. Tilt meters are also employed to monitor pier tilt to deduce transverse movements of the piers. The data is used to calculate stresses in the concrete in the bridge girders at the headstock dowel restraints. Pre-tension was applied to all sensor cables to allow opening and closing between bridge components using a tensioning system developed by MOS. The tensioning system has proven to be robust since installation, with no slip in tension or losses occurring.

The FBG sensors are monitored using a Micron Optics Inc. sm125 interrogator and industrial PC. The monitoring system will monitor for bridge distortion for the duration of three Longwalls, ensuring the bridges' on-going safety and serviceability.

8 ACKNOWLEDGEMENT

The on-going success of this monitoring project relies on the valuable contributions of a team of specialists in bridge engineering, geotechnical and subsidence engineering, and project management, acting under the auspices of the RMS and mining company.

9 REFERENCES

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