Continuous Monitoring of Mining Induced Strain in Bridge Stepped Joints Using Fibre Bragg Grating Sensors

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

Summary

This paper outlines the use of Fibre Bragg Grating (FBG) based sensors to monitor strains in concrete stepped joints. The Douglas Park Twin Bridges that form part of the M31 will be subject to mining-induced ground subsidence caused by scheduled underground Longwall coal mining. Engineering assessments of the bridges have determined that ground movements may overload two of the north eastern stepped joints of each bridge. These stepped joints were subsequently reinforced with carbon fibre rods, and a solution to monitor the stepped joints was required.
A long-gauge strain sensor was considered to be the best method to measure strain in the concrete stepped joints as a short gauge length can be subject to peaks and troughs in the strain profile if cracks form over the gauge length. Engineering assessments showed that the ideal gauge length would be 200 to 300mm. Monitor Optics Systems (MOS) proposed using the Micron Optics Inc. Fibre Bragg Grating (FBG) based os3610 strain sensor, which has a gauge length of 254mm, to monitor the strain in the bridge stepped joints.
The long-gauge strain sensors were trialled at two locations. The system was then expanded to a total of eight strain sensors at eight locations, and temperature probes were installed inside the stepped joint walls at each location to measure the concrete temperature to calculate thermal strain. The sensors are monitored through demodulation equipment which provides continuous monitoring of the 8 stepped joints. Data is captured every 15 minutes, and a daily average of this data is sent to key personnel for analysis, with the 15-minute data provided if further analysis is required.

1. Introduction

The Douglas Park twin bridges are are located south of Douglas Park town and form part of the Hume Highway (M31), spanning over the Nepean River. The bridges have been subject to mining-induced ground subsidence from a number of underground Longwall coal mines, with ground movements from mines between 1999 and 2001 resulting in adverse effects to the bridge structures. Mitigation of the effects of these ground movements were carried out in 2001 and 2007, which involved moving the superstructures of each bridge transversely relative to the supporting piers and abutments at some locations at the northern ends.

It was determined that scheduled Longwalls 901-904 could potentially cause further ground-movements at the bridge locations. A review of the methodology and computer modelling previously used to determine the effects of ground movements on key bridge components, as well as the effects of the mitigation works on key bridge components, was undertaken in anticipation of the planned mining. The review allowed better estimations of the forces in key bridge components, and it found that the concrete of some of the stepped joint nibs could be the most critical elements if ground movements occur.

Longitudinal forces (relative to the bridge deck) induced by ground movements are transmitted to the concrete stepped joints by the hinge bearings. This combined with normal service loads, could result in an overload if the hinge bearings are much stronger than the concrete's minimum design capacity, which could lead to failure of the stepped joint. Although it was found that this scenario is unlikely to occur, due to their critical function, recommendations were made to strengthen key stepped joints and to monitor strain at critical areas. Monitor Optics Systems (MOS) were asked to propose a Fibre Bragg Grating (FBG) based monitoring system to monitor these strains.

2. Reinforcement of Concrete Stepped Joints

Investigations into the effect of ground movements on the Douglas Park Bridges found that the nibs at the two north eastern stepped joints (spans 2 and 3) of each bridge were most critical. These nibs were strengthened by embedding three carbon fibre rods on each side of the stepped joints. This is illustrated in Figure 1.

Carbon fibre rods were selected to reinforce the nibs because they met the required Ultimate Limit State capacity and their installation procedure was feasible. Consideration was given to strengthen other stepped joints, but investigations found that the strengthened stepped joints would reach their strength limit first regardless of the magnitude of differential transverse ground movements that may occur.

The carbon fibre rods were successfully installed in July 2015

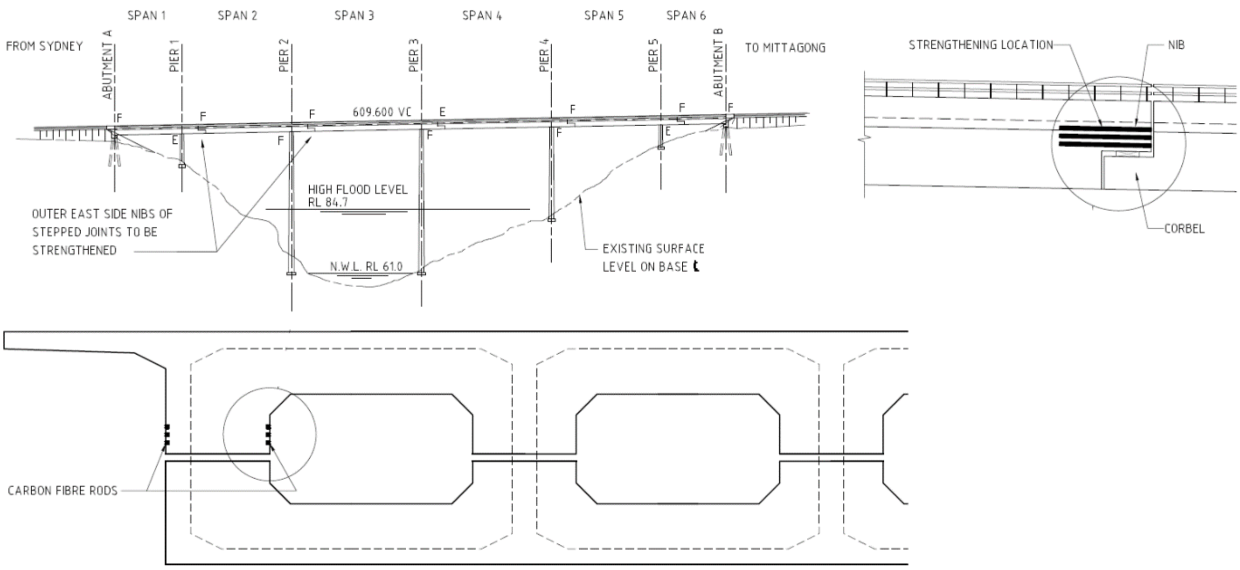

Figure 1 Reinforcement of Stepped Joints

3. Monitoring Strain in the Concrete Stepped Joints

3.1. Approaches to Monitoring

Consideration was initially given to embed MOS FBG based Glass Fibre Reinforced Composite (GFRC) sensor cables in with the carbon fibre rods to monitor their performance throughout mining. However, monitoring the strains in both the eastern and western stepped joints of spans 2 and 3 was required, so this option was not pursued further.

The soffit of the nib was determined to be the most critical area, under both the influence of normal service loads and ground movements. It is difficult to mount strain sensor devices on the soffit due to the presence of the fillet and restricted access between the nib and the corbel. It was therefore decided to mount the strain sensor on the nib as close as possible to the soffit. The proposed location is illustrated in Figure 2.

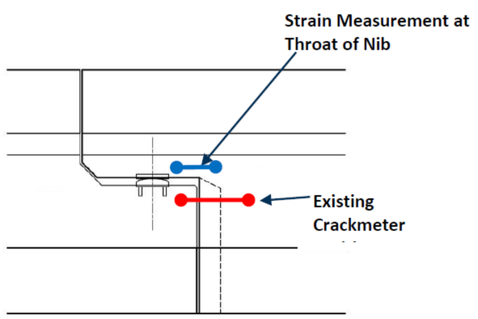

Figure 2 Proposed Location of the Strain Sensing Device

3.2. Measurement of Strain in Concrete

Monitoring tensile strain in concrete with strain sensors has its challenges. If concrete undergoes tension, relieving cracks can occur, which dissipates the stress in the area immediately surrounding the crack. If the gauge length of a strain sensor is located over a crack, it can exaggerate the actual strain within the concrete. Conversely, if the gauge length is located adjacent to a crack, the strain sensor reading could be close to zero after the crack has formed.

Monitoring tensile strain in concrete can be achieved by using a long-gauge strain sensor. All strain sensors measure the average strain over their gauge length. Small gauge lengths can be approximated to infinitesimal changes in the measurand, while long gauge lengths measure the average of all strains accumulated over the gauge length, which allows for small cracks forming at various locations. However, if a gauge length is too long, it may incorporate areas that are not under stress, which will under report the stresses in the concrete.

3.3. Recommended Gauge Length

A Finite Element Analysis (FEA) of the critical nibs found that potential strains caused by ground movements would be approximately consistent over 200mm lengths just above the soffit. A gauge length of 200mm to 300mm was recommended, with one anchor installed just 100mm past the fillet, and the other towards the hinge bearing. This is illustrated in Figure 3. MOS recommended using the Micron Optics Inc. os3610 long-gauge strain sensor to monitor strains at the concrete nibs. This sensor has a gauge length of 254mm.

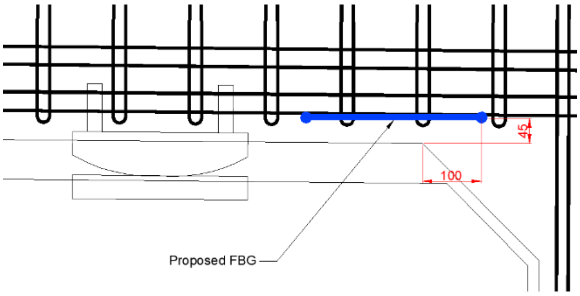

Figure 3 Detailed Location of Strain Sensing Device

3.4. Range and Accuracy

The long-gauge strain sensor is required to monitor forces in the nib as low as 100kN. The FEA of the nib found that a 100kN force would result in a change in strain of approximately 13 x 10^{-6} m/m (13με). The os3610 sensor has a strain accuracy of 1με, which was more than sufficient.

The expected maximum force due to ground movements in the nib was 1,000kN, but allowance for a forcew of 3,000 kN was required. The FEA results showed that a force of 3,000 kN would result in a strain of approximately 400με. The os3610 sensor has a total range of 5,000με, with the zero-point set by the user. Setting the zero-point at 2,500με allows a +/- 2,500με strain measuring capacity, which was well in excess of the minimum requirements.

3.5. Temperature Compensation

FBGs respond to changes in strain and changes in temperature. The os3610 strain sensor has two FBGs; one to measure strain between anchor points, and the other to measure changes in temperature to compensate for temperature induced wavelength shifts in the strain FBG. Each FBG is located within the sensor housing, alongside one another to ensure accurate compensation.

4. Installation

4.1. Trial of os3610 Sensors

Two os3610 sensors were installed in December 2015 on the northbound carriageway at the east and west sides of span 3 to trial the sensors. The sensors were installed using the followings steps:

1. Identify the locations of the rebars at the drill locations

2. Drill holes for the anchors as specified in Figure 3, taking care to avoid rebar locations, and install and glue the anchors

3. Use a setting bar for correct orientation, as shown in Figure 4

4. As the epoxy cures, install the signal cables to monitor and multiplex the sensors

5. Once the epoxy has set, attach the os3610 sensor to anchors as shown in Figure 5, and set zero point

The installation was completed in one day.

Figure 4 Installation and Setting of the Sensor Anchors

Figure 5 os3610 Sensor Installed on Stepped Joint Nib

After the installation, the sensors were monitored on two occasions using a generator to power the interrogator, as power was not available for monitoring at that time.

After reviewing the data, it was agreed that the system would be expanded to a total of 8 sensors, and temperature probes would be installed into the concrete walls at each strain sensor location.

4.2. Full Installation

The additional 6 strain sensors and eight temperature probes were installed in May 2016. The same procedure that was used in the trial installation was used to install the strain sensors. The Micron Optics Inc. os4230 temperature probes were selected to monitor temperatures inside the concrete. The probe length is 143mm, with a 5mm diameter, and it has an accuracy of 0.6°C. Figure 6 shows the temperature probe.

Figure 6 os4230 Temperature Probe

The temperature probe was required to be installed 150mm into the concrete, 300mm above the bottom of the nib in line with the strain sensor, taking care to avoid the rebars. A hole was drilled for each temperature probe at the required location, and they were epoxied in at each location. No calibration was required as they are calibrated to calculate absolute temperature.

A signal cable was installed between the northern abutment of the northbound bridge to the northern abutment of the southbound bridge to monitor the sensors on the southbound bridge stepped joints. This is illustrated in Figure 7.

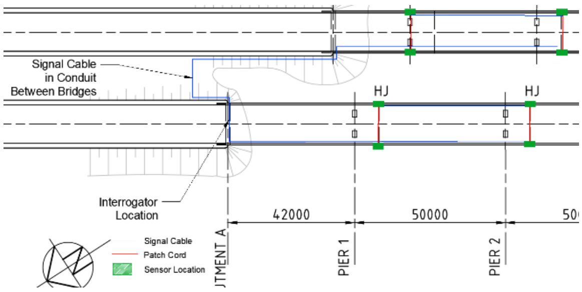

Figure 7 Plan View of Monitoring System

5. Monitoring System

5.1. FBG Sensor Network

To efficiently use interrogator bandwidth, FBGs can be serially multiplexed into a single string that can be acquired on a single channel. The strain sensors each have two pigtails which allowed for serial multiplexing. However, the temperature probes each only have one pigtail, which does not allow multiplexing. To incorporate the temperature probes into a multiplexed string, an optical splitter / coupler was used to split the optical signal into two, so each sensor could be acquired while further multiplexing could be achieved. This is illustrated in Figure 8.

This arrangement allows the successful acquisition of all sensors on one channel, but has two issues:

1. Redundancy. The splitter / coupler only allows the signal to be split one way – if tail B of the last strain sensor was connected to the signal cable instead of Tail A of the first strain sensor, only the strain sensors will be acquired. This limits redundancy in the network

2. Optical losses. Each splitter / coupler introduce optical losses when the signal is split into two. The sm125 interrogator has considerable dynamic range to cope with these losses, however, if further losses occur, the sensors may not be acquirable.

The interrogator cabinet is located on the north abutment of the northbound carriageway. The signal cable from each bridge terminate in the cabinet to connect to the interrogator.

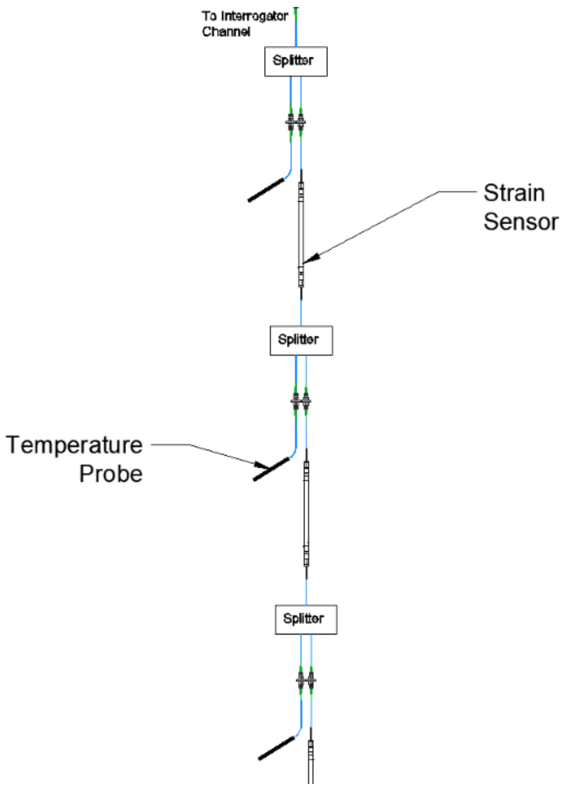

Figure 8 Multiplexing the Temperature Probes

5.2. Demodulation System and Power

The optical interrogation unit is a Micron Optics Inc. sm125-500 static interrogator, which has an acquisition frequency of 2Hz, that was redeployed from the Hume Highway monitoring system and is over 8 years old. The interrogator is connected to an industrial PC with monitoring software, which was also redeployed from the Hume Highway monitoring system.

The monitoring system is powered by electricity supplied by the bridge security system.

5.3. Data Acquisition and Processing

FBG central peak wavelengths are acquired by the sm125-500 interrogator and converted to strain and temperature measurements using acquisition software provided by Micron Optics Inc. The data is remotely extracted by MOS over a 4G internet connection on a weekly for review and further processing by key stakeholders throughout the active subsidence period.

6. Results

6.1. Verification of Trial Sensors

The trial sensors were initially verified by capturing strain data at a high acquisition rate as vehicles were filmed crossing the stepped joint the sensors were monitoring. Although vehicle weights were not known, it was observed that larger vehicles would induce larger strain steps than smaller vehicles. It was also observed that the sensor on the western nib had a smaller response than the sensor on the east nib. Figure 9 shows captured high acquisition data, with west strain data in blue, and east strain data in red.

The trial sensors were also verified by capturing strain data throughout the day on two occasions. The data captured was limited because a generator was used to power the interrogator as no power was available on site at that time. Data was captured in December 2015 and February 2016. This data capture is shown in Figures 10 – 13, with strain data graphed in blue and temperature data graphed in red.

The data captured in December was on a day that was overcast and had limited temperature variation and the data in February was captured on a day that was sunny and had a higher temperature variation. In each case, however, the internal temperature FBG in the strain sensor recorded only small variations. A decision was then made to install temperature probes in the concrete walls at the strain sensor location to better understand thermal expansion of the concrete.

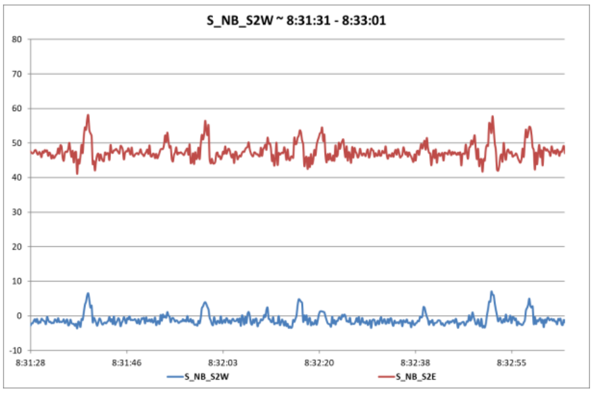

Figure 9 High Acquisition Capture of Sensors with Traffic Flow

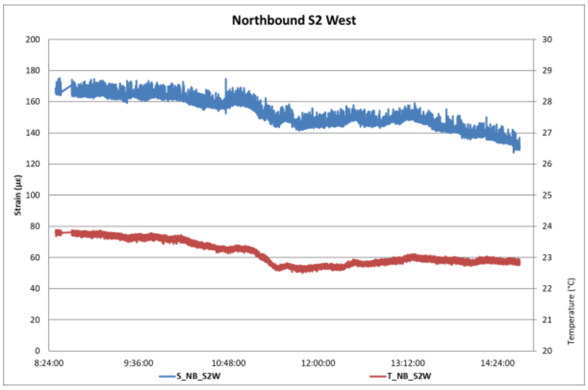

Figure 10 Western Stepped Joint Trial Data in December 2015

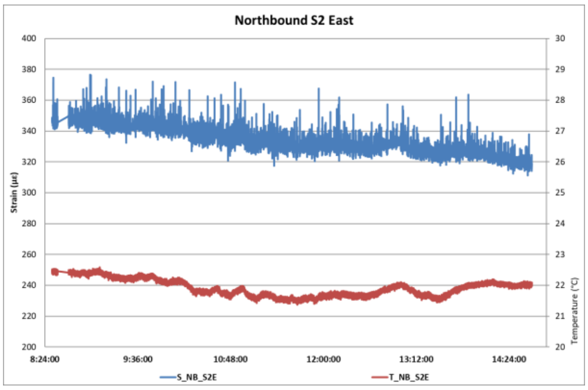

Figure 11 Eastern Stepped Joint Trial Data in December 2015

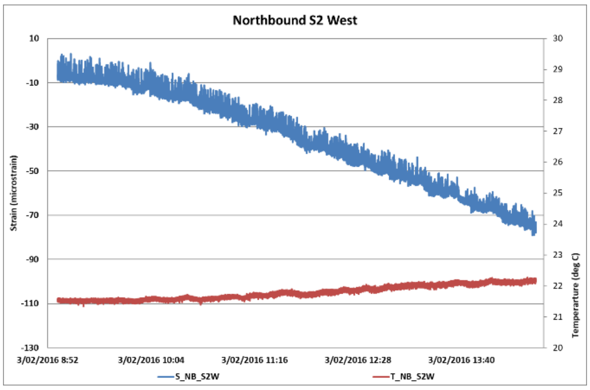

Figure 12 Western Stepped Joint Trial Data in February 2016

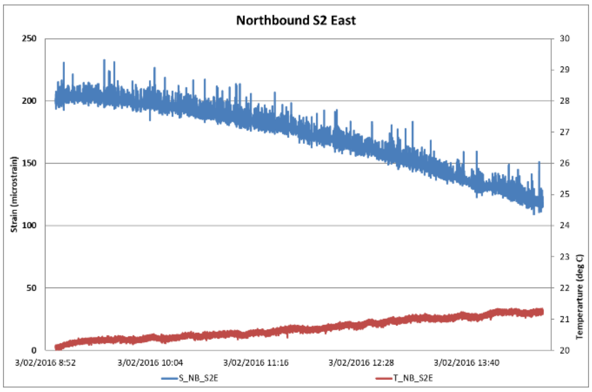

Figure 13 Eastern Stepped Joint Trial Data in February 2016

6.2. Full Installation Results

The remaining strain sensors were installed in May 2016, and power was introduced for monitoring in late 2016. After power was installed, the strain and temperature data was captured every 15 minutes, which was reported to key stakeholders. Following a review of the data, it was agreed that the 15-minute data should be averaged into a single daily average value, which is now reported. The 15-minute data is still available if required. The daily average values are illustrated in Figure 14.

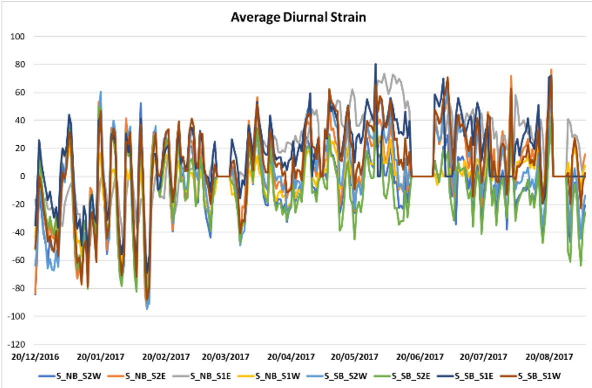

Figure 14 Daily Average of All Strain Sensors

As at September 2017, there has been no significant Longwall induced strains caused by ground movements from Longwall 901. The variation in results has coincided with seasonal changes.

It has been noted that the strain sensor at NB_S1E has responded different to all other sensors since installation, as seen in Figure 15 (NB_S1E is shown in grey). This behaviour has not been investigated further.

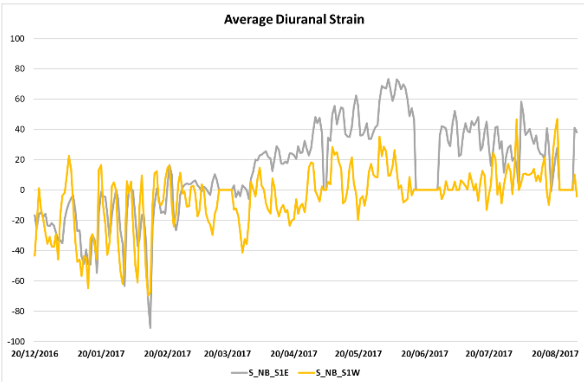

Figure 15 Daily Average of S_NB_S1E Vs S_NB_S1W

6.3. System Performance

The industrial PC that was redeployed from the Hume Highway monitoring system had some reliability issues, where it would lose online communication and would have to rebooted on site. However, the industrial PC was purchased in 2010, so it’s reliability issues can be attributed to age. A new industrial PC was installed in August 2017.

7. Conclusion

An optical fibre sensing system comprising of 24 FBGs is being used to monitor the strains in key concrete stepped joints of two bridges in Douglas Park that may be subject to mining induced ground movements. Following a trial of two sensors, the full monitoring system was installed and has been running for approximately 9 months of continuous operation.

The monitoring system uses long-gauge strain sensors which are attached to the concrete stepped joints with embeddable anchors, and temperature probes embedded in the concrete. Both are supplied by Micron Optics Inc. and are off-the-shelf sensors that can be installed in a short amount of time.

The FBG sensors are monitored using a Micron Optics Inc. sm125 interrogator that was redeployed from the Hume Highway monitoring system, and that is over 8 years old, demonstrating its long-term reliability. The sensors will continue to monitor concrete strains for Longwalls 901 – 904, ensuring the Douglas Park Bridges’ on-going safety and serviceability.

8. Acknowledgements

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 the mining company.

9. References

R. Woods, Cardno 2015 “Douglas Park Bridges – Monitoring Report – Draft 3”

MSEC et al 2015 “MSEC771 LW901-904 Management Plan for M31 Hume Motorway Rev C”