The use of GNSS to aid the Structural Health Monitoring of the Seven Suspension Bridge's Suspension Cables and Support Towers.

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Key words: Engineering Surveying, Deformation Monitoring, Suspension Bridge

SUMMARY

The Severn motorway Suspension Bridge is a 1,600m long suspension bridge, with a main span length of 988m, and towers of 136m in height. The Bridge spans the River Severn and the River Wye, and took three years to construct. The Bridge was opened on the 8 September 1968 by Queen Elizabeth II. The Bridge was granted a Grade I listed status on the 26 November 1999.

The Bridge is a conventionally designed suspension bridge, where the deck is supported by two main cables slung between two pairs of steel support towers. The cables that support the Bridge deck were spun from 29,000km of wire, and each of the two main cables are made up of 8,322 individual 5mm diameter wires. The hanger cables connecting the deck to the suspension cables are not vertical, but are arranged in a zig zag manner. This was a part of the design to help reduce the vibrations of the Bridge, as is the use of Stockbridge dampers upon the cables.

In 2010, a series of field trials were conducted whereby 9 GNSS receivers were placed upon the Bridge, and two were placed as reference stations adjacent to the Bridge. Of the 9 on the Bridge, 4 were located at the tops of the two pairs of towers and the remaining 5 were placed at strategic locations on the Bridge's suspension cables. Four on the north side cable, and the 5th on the south side cable. This configuration allows the movements of the north cable to be analysed, at 3 different locations, as well as the differential movement between the two suspension cables. In addition, this configuration allows the movements of the tops of the towers to be compared to the cables, as well as to each other. All in all, allowing the relative movements of the various locations on the Bridge to be compared. This is possible in terms of the magnitude of the movements in the 3-dimensions of the Bridge, as well as the frequencies of the movements.

Four days of data at 10Hz or 20Hz were gathered at all these locations. During these periods, normal traffic flow was experienced. This paper focusses on the accuracy of the measurement of movements of the towers, and how they correlate to the movements of the suspension cables, as well as the correlation of frequencies of movements experienced at each location.

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1. INTRODUCTION

The use of GPS and GNSS for monitoring the deflections and deformations of bridges has been an ongoing area of research for many years [Ashkenazi *et al.*, 1996; Roberts, 1997; Brown *et al.*, 1999]. The authors have been involved in carrying out such research work on the Humber Bridge [Ashkenazi *et al.*, 1997], the Forth Road Bridge [Roberts *et al.*, 2012a], the London Millennium Bridge [Roberts *et al.*, 2006], a viaduct in the UK [Ogundipe *et al.*, 2014], a small suspension bridge in Nottingham [Meo *et al.*, 2004], a small suspension bridge in Sydney, Australia [Roberts *et al.,* 2002] and the current work on the Severn Suspension Bridge in the UK [Roberts *et al.,* 2012b].

The Severn Suspension Bridge has an overall length of 1,600m, and a main span length of 988m. The Bridge's support towers are 136m in height, and support two suspension cables that are spun from 29,000km of wire, and each of the two support cables are made up of 8,322 individual 5mm diameter wires.

This paper outlines the field tests carried out on the Bridge by the authors in 2010, by collecting 10Hz or 20Hz GNSS data from 9 GNSS receivers located at key locations upon the suspension cables as well as on the tops of the four (two pairs) of support towers.

2. GNSS ON THE BRIDGE

11 GNSS receivers were used during the field tests. In all, 4 days of data were gathered on the 10-12 March and the 18 March 2010. The GNSS antennas were located at 2 reference stations; a main one and a backup station. In addition, 8 out of the 9 locations on the Bridge locations gathered data at any time, as we only had access to 10 GNSS receivers in total at the time. Figure 1 illustrates the locations of the GNSS receivers, also showing the receiver types. They were all Leica, but a mixture of SR510, SR530 and 1200 series GNSS receivers. Figure 2 illustrates the locations of all the GNSS antennas upon the Bridge. It is worth noting that location B is at the middle of the mid-span, and all the GNSS antennas, apart from location E, are located on the north side cable. It wasn't possible to locate E opposite to B, as there was some maintenance work going on here. Therefore, we located E opposite to location C. This results in the possibility of being able to analyze the torsional movements of the Bridge.

Location	10.03.10 AM	10.03.10 PM	11.03.10 AM	11.03.10 PM	12.03.10 AM	12.03.10 PM	18.03.10
A	1200	1200	1200	1200	1200	1200	SR510
B	1200	1200	1200	1200	1200	1200	1200
C	1200	1200	1200	1200	1200	1200	1200
D	1200	1200	1200		1200	1200	1200
E				1200			1200
T1	SR530	SR530	SR530	SR530	SR530	SR530	SR530
T2	SR530	SR530	SR530	SR530	SR530	SR530	SR530
T3	SR530	SR530	SR530	SR530	SR530	SR530	SR530
T4	SR530	SR530	SR530	SR530	SR530	SR530	SR530

Figure 1. Session times, locations, dates and corresponding GNSS receiver types.

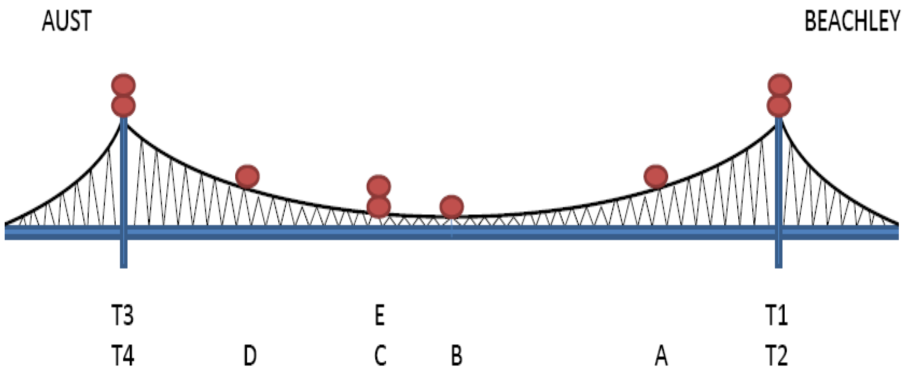

Figure 2. Survey points upon the Bridge.

Figure 3 illustrates the location of the main reference receiver located on top of the Bridge toll offices adjacent to the Bridge, and on solid land, Figure 4 one of the GNSS antennas located on the top of tower T2, and Figure 5 shows one of the antennas located on location C.

Figure 3. The principal reference GNSS antenna located upon an adjacent building to the

Bridge.

Figure 4. The GNSS antennas located at survey point T2 on the Bridge, the north side Beachley end. The illustration shows the choke ring GNSS antenna being installed.

Figure 5. GNSS light weight choke ring antenna located on the suspension cable at location C.

The antennas located on the cables were lightweight choke ring antennas, whilst those located on the tops of the towers and the reference stations were standard choke ring antennas. The GNSS receivers at the tops of the towers were located within the Bridge tower itself, allowing access to mains power supply, as well as being in a sheltered location during high winds. The GNSS receivers for the Bridge cable locations were located on the Bridge deck. The antenna cable was trailed down one of the hanger cables to the Bridge deck. There are wide footpath/cycle paths on each side of the Bridge, which provided a safe environment for the authors to be able to download the data as well as swap batteries when required.

The GNSS data and results were converted into directions and movements along the axis of the Bridge (longitudinal), across its axis (lateral) and in the vertical.

3. RESULTS

This paper represents a very small portion of the data gathered and results obtained so far. Various movements are evident in the data, due to traffic loading, wind loading, as well as longer term effects due to changes in temperature, and possibly the weight of the water due to a large tidal movement of up to 12m.

Figures 6 and 7 illustrate the lateral, longitudinal and vertical movements of the Bridge, in the Bridge Axes. These data were gathered on the 11th March between 11-12 am. There is correlation in the movements, and also it can be seen that he maximum deflection in this data span is of the order of 30cm in the vertical direction. It can also be seen that there are movements in all 3 axes of the Bridge.

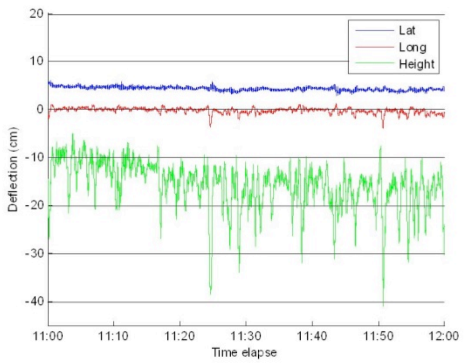

Figure 6. Lateral, Longitudinal and Vertical GNSS movements at location A over a 1 hour period on the 11 March 2010, 11:00 to 12:00.

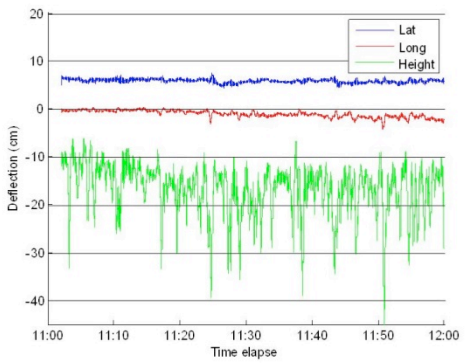

Figure 7. Lateral, Longitudinal and Vertical GNSS movements at location B over a 1 hour

period on the 11 March 2010, 11:00 to 12:00.

It is possible to see that there is a gradual drop in the mean height of the Bridge over this 1 hour period. This is thought to be due to the temperature heating the Bridge during the morning, thus causing the steel on the Bridge to expand, and hence causing the Bridge and cables to droop.

Figure 8 illustrates the movements in the vertical direction for locations C and E, as well as the longitudinal movements for the four tower locations over this same time period of 11-12am on the 11th March 2010. There is clear correlation here between the two cables, C and E, as well as the tower locations. There is relative movements between locations C and E, as well as relative movements between the Aust towers (T3 and T4) and the Beachley towers (T1 and T2), as well as movements between the two Aust towers, and movements between the two Beachley towers. All in all, there are correlations in the movements, but also some points move slightly differently to each other due to the nature of the loading. At 11:56am in particular, there is significant movements in all 6 locations. This is expanded upon in Figure 9.

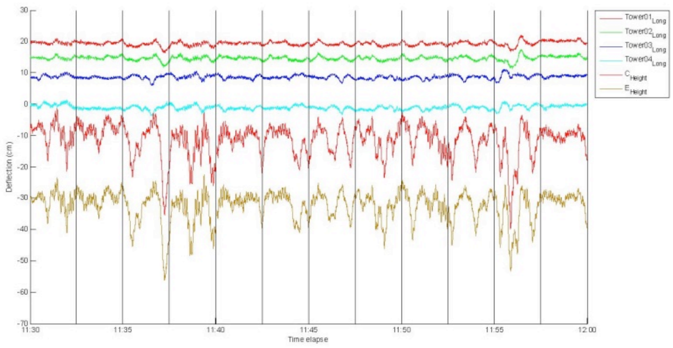

Figure 8. Vertical movements at locations C and E, and longitudinal movements of T1, T2, T3 and T4 over a 1 hour period on the 11th March 2010, 11:00 to 12:00.

Figure 9 illustrates the movements of location C over a 10 minute period, 11:50 to 12:00 on the 11 March 2010. Here it can be seen that there is a significant movement, probably due to traffic loading, which is also seen in Figure 10. The vertical displacement of the Bridge at location C is 361mm, with a corresponding longitudinal movement of 69mm, Figure 9. This corresponds to a longitudinal movement of 74mm at T4, Figure 10.

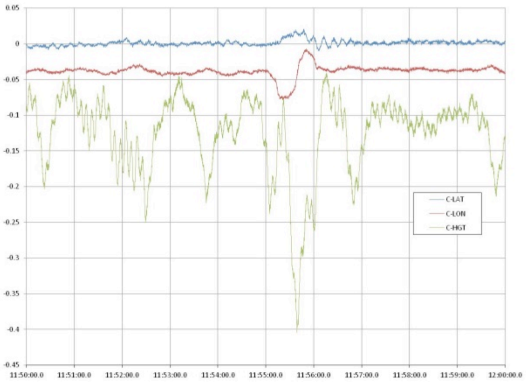

Figure 9. Lateral, longitudinal and vertical movements at locations C over a 10 minute period on the 11 March 2010, 11:50 to 12:00.

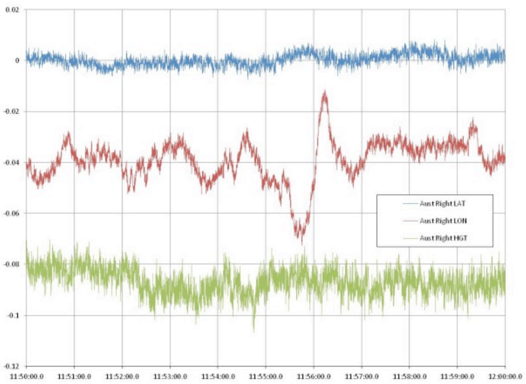

Figure 10. Lateral, longitudinal and vertical movements at location T4 over a 10 minute period on the 11 March 2010, 11:50 to 12:00.

Figure 11 shows an example at location B in the vertical direction of the frequency analysis of the data. This is a simple FFT analysis, and it picks up the various natural frequencies in the data. There is a strong frequency seen of 0.146Hz, as well as secondary frequencies.

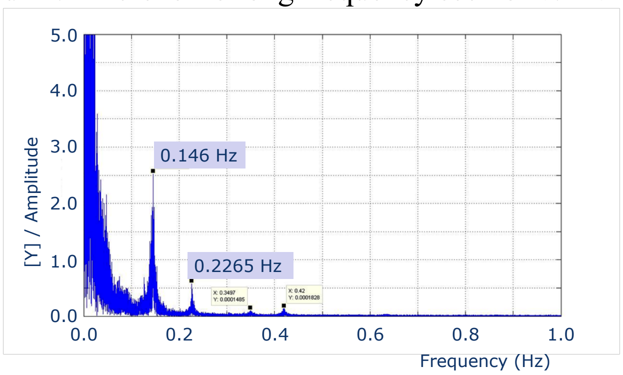

Figure 11. Frequency response in the vertical direction at point B.

Figure 12 illustrates the frequencies detected at all four of the tower locations in the longitudinal direction of the Bridge. Here it can again be seen that the frequency of around 0.146Hz is evident. Figure 13 brings all the results from all the locations together, showing the correlation in the frequencies at these locations with each other.

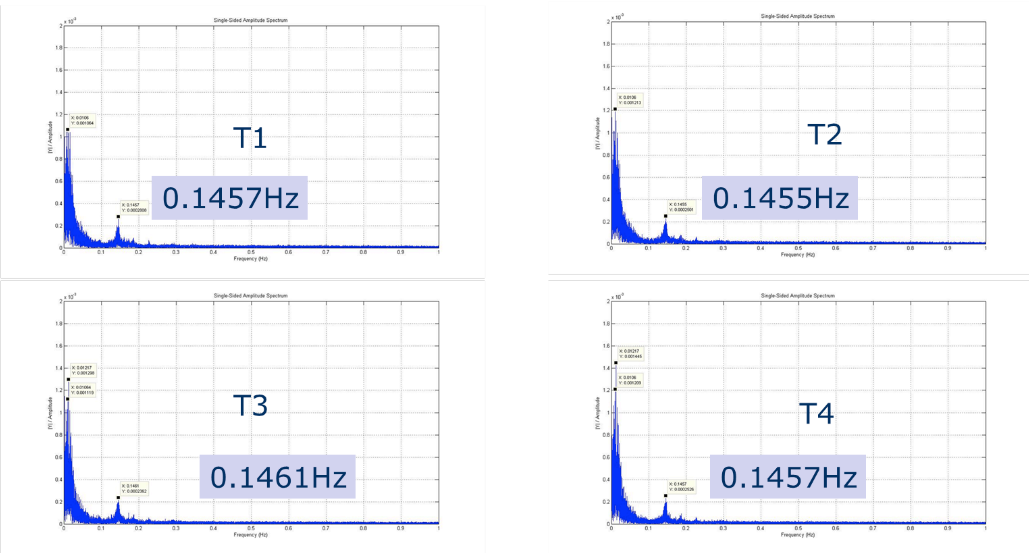

Figure 12, Longitudinal frequency analysis of the 4 tower GNSS antennas

	vertical					longitudinal			
Position	A	B	C	D	E	T1	T2	T3	T4
Freq	0.0595								
Hz	0.1453	0.146	0.1448	0.1457	0.1457	0.1457	0.1455	0.1461	0.1457
	0.1862		0.1847	0.1847					
		0.2265	0.2264		0.2264				

Figure 13. Natural Frequencies derived from the GNSS results at the various locations.

4. CONCLUSIONS

These results show an overview of the vast amount of results obtained from these field trials. Further analysis is under way, comparing the relative movements, and investigating the frequencies of the relative movements. We are also investigating the correlation between the traffic and wind loading with the movements, as the weigh in motion data and wind data is available.

The results do show a correlation between the movements on the towers as well as on the suspension cables.

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BIOGRAPHICAL NOTES

Prof Gethin Wyn Roberts is Professor of Geospatial Engineering at the University of Nottingham Ningbo China. He has been at the University of Nottingham since 1989, but on the UNNC campus since September 2010. He is the Chairman of Commission 6, Engineering Surveys, as well as the UK representative for commission 6 through the support of the Chartered Institution of Civil Engineering Surveyors. He is also a Fellow of the Chartered Institution of Civil Engineering Surveyors.

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