

## MEASURING THE DYNAMIC DEFORMATION OF BRIDGES USING A TOTAL STATION

**Emily Cosser, Gethin W Roberts, Xiaolin Meng, Alan H Dodson**

*Institute of Engineering Surveying and Space Geodesy (IESSG), University of Nottingham*

### Abstract

It is well known that long term movements of structures can be monitored using a total station. Measurements are taken over minutes, hours or weeks to a number of targets to measure settlement or long term permanent deformations. At the University of Nottingham research is concentrated on the dynamic deformation of structures, in particular bridges. Monitoring equipment includes GPS, accelerometers, pseudolites and now total stations. A recent bridge trial conducted by the authors on the Wilford Suspension Bridge in Nottingham included the use of a servo driven Leica TCA2003 total station measuring angles and distances at a 1 Hz data rate. The total station results are compared to the GPS data. Outlined in this paper are the results from initial total station trials, including the bridge trial.

### 1. Introduction

Total stations have been used to measure the movement of structures and natural processes with good results (Hill and Sippel 2002; Kuhlmann and Glaser 2002; Leica Geosystems 2002). Leica Geosystems (2002) quote accuracies of better than 1mm for their bridge and tunnel surveys. They use a remote system that logs measurements 6 times daily via a modem, with measurements still possible at peak times. Kuhlmann and Glaser (2002) use a reflectorless total station to monitor the long term deformation of bridges. Measurements are taken of the whole bridge every six years and statistical tests are used to confirm if the points have moved. Hill and Sippel (2002) use a total station and other sensors to measure the deformation of the land in a landslide region.

For all of the examples mentioned above the data rate for the total station measurement is slow. At the IESSG, University of Nottingham (UoN), the research aim is improving the monitoring of the dynamic deformation of bridges. For this a much higher data rate is needed. GPS needs a clear line of site to the satellites and so for bridge monitoring can only measure from the bridge deck and towers. Even on the bridge deck the cable and towers can cause obstructions to the signals. Total station prisms can be located underneath the bridge deck as long as there is a clear line of sight to the total station itself. For these reasons the possibility of dynamic deformation monitoring with a total station has become a current research topic.

There are advantages and disadvantages of using a total station for dynamic deformation monitoring. The advantages include the high accuracy as quoted above, the automatic target recognition which provides precise target pointing (Hill and Sippel 2002) and the possibility of measuring indoors and in urban canyons (Radovanovic and Teskey 2001). The disadvantages include the low sampling rate (Meng 2002), problems with measurement in adverse weather conditions (Hill and Sippel 2002) and the fact that a clear line of sight is needed between the total station and the prism.

Radovanovic and Teskey (2001) conducted experiments to compare the performance of a robotic total station with GPS. This experiment was conducted because GPS is not an option in many application areas such as indoors. Total stations are now capable of automatic target recognition and they can track a prism taking automatic measurements of angles and distances once lock has

been established manually. It was found that the total station performed better than GPS in a stop and go situation, where measurements were taken of a moving object only when it was stationary. In a completely kinematic situation GPS performed the best. It was found that there were two main problems with the total station in kinematic mode. These were a low EDM accuracy caused by a ranging error that was linearly dependent upon the line of sight velocity; and an uneven sampling rate over time worsened by no time tagging.

This paper outlines some initial tests conducted with the total station on the University campus, which included a trial with a moving monument and a metronome. The total station was also tested in a bridge environment and compared to results from a GPS antenna located close to the prism.

## **2. Technical Specifications and Software**

The UoN own a Leica TCA 2003 total station. The technical specifications for this instrument are angle measurements are accurate to 0.5", rapid tracking distance measurements are accurate to 10mm+2ppm, automatic target recognition up to 200m away adds an error of 1mm and the 360-prism adds errors of 5mm in distance and 5mm for the angles (Leica Geosystems 2000).

A piece of software called Geocom provided by Leica Geosystems with the total station makes displaying the angle and distance data to the screen of a laptop possible. The total station is put into Geocom mode and then all readings go directly to the laptop. This software was tested and modified slightly by the authors so that the angles, changed to output in radians rather than gons, and distances, in rapid tracking mode, were output to a file along with a time tag. The time tag was accurate to a second and taken directly from the laptop. Sub second time tagging was investigated, but there was no success with this for the visual basic program. After the modification of the software, testing needed to be conducted with the total station. When the total station was in rapid tracking mode it could measure angles and distances approximately every second, so at approximately a 1 Hz data rate. Since it was not possible to know the time more accurately than every second, the exact data rate could not be calculated. It is known from Radovanovic and Teskey (2001) and from the experience of the authors that this data rate is probably not constant.

## **3. Initial Tests**

Some initial tests were conducted on the University Campus to test the software and the total station. The first test took place on the 6<sup>th</sup> June 2002. A prism was attached to a monument which was forced to move up and down (see Figure 6 for a picture of the monument in a subsequent experiment). The amount that the prism could move up and down was measured and the total movement was found to be 0.09m in the vertical direction and no movement in the horizontal direction. The total station in Geocom mode was attached onto the top of another monument. Four setups were carried out with the distance between the two monuments changed at every setup (these distances were 12m, 22m, 40m and 60m). The prism was moved up and down a number of times at each setup and the results were recorded.

Figure 1 and Figure 2 show the vertical and horizontal movement of the prism as recorded by the total station. It can be seen that the vertical movement is 0.09m as expected and the horizontal is about 0.004m. Since there was very little or no movement in the horizontal direction the measurement of 0.004m in that direction is attributed to the errors of the instrument. The results at all distances were similar, all showed a clear movement of 0.09m in the vertical direction and the movement in the horizontal direction was always around 0.004m. So, at this slow speed the total station measured the movement well.

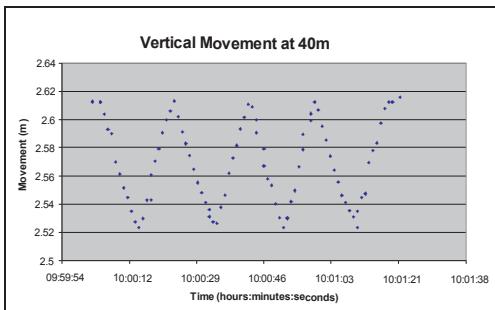


Figure 1 Vertical movement of the prism at a distance of 40m

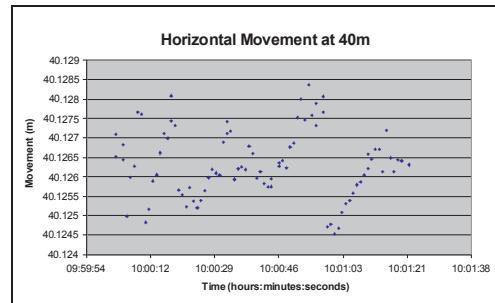


Figure 2 Horizontal movement of the prism at a distance of 40m

In the second experiment that occurred on campus a small sticky retro target was attached to the hand of a metronome. The metronome was made to move from side to side at various speeds, 120, 100, 80, 60 and 50 beats per minute. These speeds corresponded to approximately 60, 50, 40, 30 and 25 horizontal oscillations per minute respectively, as there were 2 ‘beats’ per oscillation. The total station was set up about 14 metres away from the target. For each speed about one minute of data was collected.

Figure 3 and Figure 4 show the X coordinate and Y coordinate verses time for 80 beats per minute. The Y coordinate particularly shows an irregular pattern of movement, further demonstrating the uneven sampling rate of the total station, as the movement of the metronome was regular. Figure 3 shows a period of approximately 1 minute when measurements were taken. The metronome was moving at approximately 80 beats per minute and so about 40 oscillations should be seen in the X direction. Figure 3 shows 33 oscillations. The weight of the retro target caused the metronome to beat slightly slower than it would have done on its own, so 33 oscillations is a perfectly plausible amount. However, in the vertical direction 80 beats per minute should correspond to 80 cyclic movements up and down. Figure 4 only shows 26 oscillations which does suggest that the total station did not pick up anywhere near all of the oscillations in the vertical direction. This did seem to imply that when the metronome moved faster than 1 Hz it was too fast for the total station to be able to pick out all the movement.

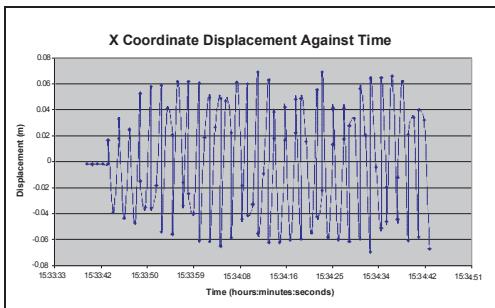


Figure 3 X displacement verses time for the metronome beating at 80 beats per minute

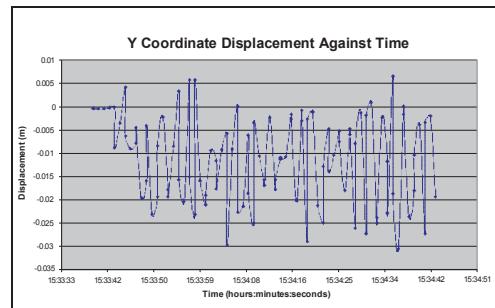


Figure 4 Y displacement verses time for the metronome beating at 80 beats per minute

The results for each metronome speed were similar to that shown in the graphs. The X displacement always showed clear oscillations of movement whereas the Y did not. This results was not too encouraging as it is known that the first natural frequency of the Wilford Suspension Footbridge is 1.75 Hz (Dodson, et al. 2001). It was now known that the total station could measure up to about 1 Hz and show the displacement clearly; however, faster than that not all oscillations were shown.

#### 4. GPS Housed With the Total Station Prism

The initial tests had shown that the total station was capable of monitoring moving objects, but how did it compare to GPS? A further test was undertaken on the University campus where a GPS antenna and a circular total station prism were housed together as one unit and placed on top of a monument (a picture of this can be seen in Figure 6). The prism was made to move up and down as in the previous monument experiment, however this time the movement was slightly greater, measured as 0.1m. A Leica dual frequency GPS receiver recording in RTK mode at a 1 Hz data rate was used as the rover with a similar receiver as reference transmitting corrections.

The result of this test can be seen in Figure 5. It can be seen from this Figure that the agreement between the GPS measurements and the total station is good. They follow the same pattern of movement, showing a displacement of approximately 0.1m which is the amount the monuments was made to move in this case. This result also demonstrates well the precision that is attainable from GPS in the vertical direction. The laptop time was manually set so that it was as close to GPS time as possible; however the original total station data was still offset from GPS time by 11 seconds, but this was compensated for before the graph was plotted. At present the authors cannot exactly align the laptop time to GPS time, which can cause problems when trying to compare the data from both systems.

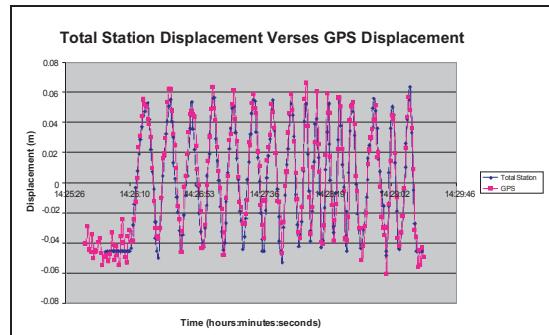


Figure 5 The displacement of the total station prism and the GPS antenna



Figure 6 The GPS antenna and the total station prism housed together as one unit on a monument

Most of the initial tests had shown that the total station was a good tool for kinematic monitoring, but the metronome test had shown that the total station could not keep up if the speed was too high. The total station was taken to the bridge to test if it could pick up the movement effectively. It was known that the total station would only be able to pick out movement; it would not be able to be used for the calculation of the natural frequencies as the data rate is far too slow.

#### 5. Bridge Trial

A GPS, accelerometer and total station bridge trial was conducted at the Wilford Suspension Footbridge, over the River Trent in Nottingham, on the 19<sup>th</sup>, 20<sup>th</sup> and 21<sup>st</sup> June, 2002. This bridge has been the focus of a number of trials carried out by the UoN (for more information about trials conducted see, for example Roberts, et al. (2001)). The layout of the equipment for this trial can be seen in Figure 7. Single and/or dual frequency Leica system 500 GPS receivers were located at points Bdg1, Bdg2, Bdg3, Bdg4, Ref1 and Ref2. The total station prism was located next to the cage that housed the GPS antenna and accelerometer at point Bdg2; a picture of this can be seen in Figure 2. Figure 3 shows the total station with the Wilford Bridge in the background.

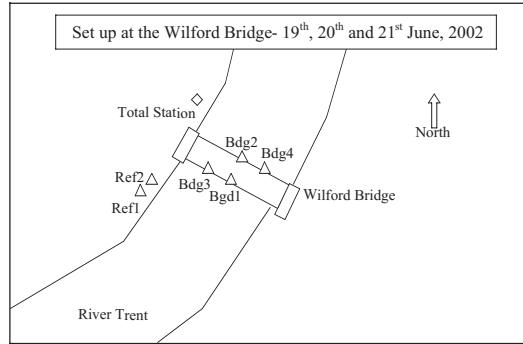


Figure 1 The layout of the GPS receivers and total station for the bridge trial in June, 2002 (not to scale)



Figure 2 The total station 360° prism located next to the GPS antenna



Figure 3 The total station with the Wilford Bridge in the background

The bridge was made to move and vibrate by staff and students from the IESSG who passed across the bridge in different ways (marching, running etc.). Measurements from the total station were collected on all three days of the trial only during these periods of highest activity (the amount of time varied from day to day). On the first day of the trial the circular prism was used and also the retro tape was tested. It was not possible to pick up a signal from the retro tape. On the other two days the 360° prism was used. This paper will compare and discuss the results shown by the total station and GPS data. Results from the accelerometer will be discussed in another paper.

## 6. Bridge Trial Results

Calculations of the movement of the prism, from the angles and distances taken from the total station were performed. Figure 10 shows the height displacement as recorded by the total station for the last day of the bridge trial. The Leica dual frequency GPS data from point Bdg2 was processed using Ski-Pro with Ref1 as the reference station, and the height displacements calculated can be seen in Figure 11. The GPS data is at a 10 Hz data rate, while the total station data rate is 1 Hz.

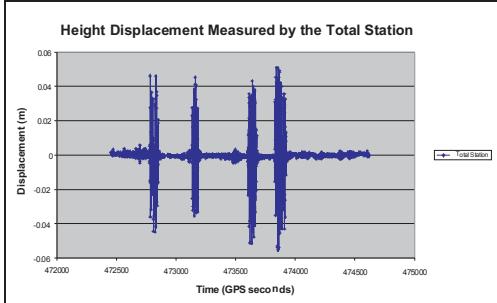


Figure 10 The height displacement measured by the total station on Friday 21st June.

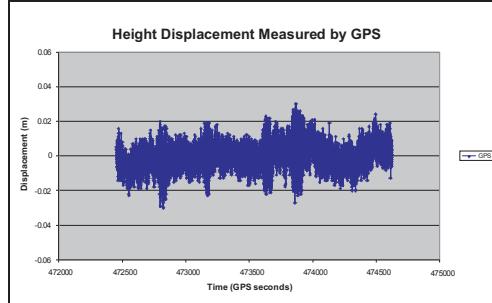


Figure 11 The height displacement shown by GPS at Bdg2 on Friday 21st June.

Four very distinct peaks of movement can be seen in Figure 10. The amplitude of these movements is at the highest peak approximately 0.1m. The same peaks of movement can be seen (if a little less clearly) in Figure 11, however the amplitudes of these movements are very much smaller with the peak only being about 0.05m, which is half that shown by the total station. It was encouraging that the total station had picked out all the peaks of movement in this case, but why were the amplitudes so different? For a long time the reason for the difference in amplitude calculated from the two systems was not known. In this situation it was difficult to ascertain which system showed the ‘truth’, although as GPS has been used for many years for dynamic monitoring perhaps this system should be more trusted. It was, however, suggested that the GPS data could go through some filtering during the processing or even in the receiver itself. The GPS data was reprocessed in two other pieces of software, GrafNav and Kinpos (the software developed at the UoN), and the results were similar to those from Ski-Pro.

Recently it has been suggested that the 360° prism could be to blame. 360° prisms have a face error of about 6mm which is constant on each face, but is opposite on adjacent faces. It is possible that the total station could have been measuring to the prism in such a way that it was hitting the corners and swapping between the faces as the bridge moved. If this is the case then the GPS data shows the correct amplitude.

Results from the first day of the bridge trial, when the circular prism was used, were also processed and these can be seen in Figure 12. As it can be seen from this Figure there is a difference in the amplitude of movement calculated by each system here too. However, in this case the GPS shows a much higher displacement. The total station is only measuring a displacement of 8mm at maximum. This cannot be correct as from observing the movement of the bridge it was apparent that it was moving much more than 8mm. Comparing Figure 12 and Figure 13, the difference shown in displacement measured by the total station on the two different days is quite striking. The amount of bridge movement on the third day of the trial was indeed greater than on the first day, but the difference was not of this magnitude. On the first day the circular prism was used and on the third it was the 360°, suggesting that some sort of face changing error could have caused larger displacements than were actually occurring to be recorded. The reason that such small displacements were recorded on the first day of the trial is still not known.

The sampling rate of the total station is approximately 1 Hz. As it has been mentioned earlier in this paper the natural frequency of the Wilford Bridge has been found to be 1.75 Hz. It has been suggested that the measurements of the total station are always taken at the same point of the bridge movement cycle, therefore showing no movement at all. On the third day of the bridge trial the periods of highest movement correspond to when the people on the bridge were ‘forcing’ the bridge to move at a certain frequency. This ‘forcing’ did not occur on the first day of the trial. It is thought that by changing the frequency at which the bridge moves it could have enabled movement to be observed by the total station that would not have been otherwise possible.

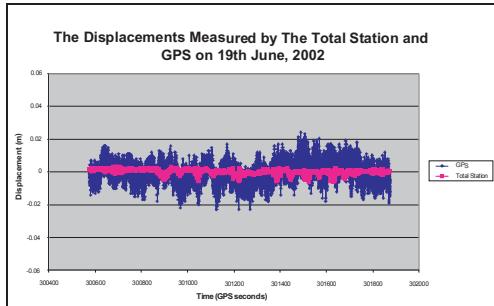


Figure 12 The displacement measured by GPS and total station on the first day of the bridge trial when the circular prism was used.

The results from the metronome suggested that for movement as fast as 1.75 Hz, it was not possible for the total station to measure all of the bridge movement. As it was seen with the data at 80 beats a minute not all oscillations were picked up, however a span of movement was shown. The results for the third also show a span of results (in this case the span is too high). It is not known why on the first day little or no movement was detected.

Other possible errors that could be associated with the total station are also related to the speed at which the bridge moves. It has been suggested that the angles and distances may not correspond to each other exactly. In the time it takes for the EDM signal to get to the bridge, be reflected by the prism and be recorded back at the total station, the bridge would have moved and so the corresponding angles recorded may not be correct. This could have affected the displacements recorded.

## 7. Conclusion

From the results presented it can be seen that measuring slow dynamic deformation is possible. The total station results from the trial with a moving monument matched well with the results that were obtained from GPS. However, the total station had many difficulties measuring the dynamic movement of very fast moving objects like the metronome and the bridge. Due to its slow data rate not all the oscillations were recorded and in the case of the bridge, very little movement was measured at all on the first day of the trial. For smaller bridges with a small amplitude and high frequency the total station can simply not measure fast enough. For longer bridges that move at slower frequencies the total station could be a possibility for monitoring.

On the third day of the bridge trial the amplitude of the structure measured by the total station was very large. It is thought that this was caused by face change on the 360° prism. Large amplitude were not seen when the circular prism was used, so this is likely to be the case.

A possible problem that has been identified is that, due to the speed at which the bridge vibrates the measurement of angles and distances may not correspond to each other.

## 8. Future Work

In the future it is hoped that experiments can be performed with two total stations on a fixed baseline measuring angles only. The advantages of this system are that angles can be measured faster than distances at a rate of four times per second and so a higher data rate can be achieved for the total station; and previously it has been stated that prior research by Radovanovic and Teskey (2001) has found that the main source of error with the total station is the EDM measurement. This would mean that more accurate measurements could be made at a quicker time interval. This could also lead to the total station being able to measure all the movement on

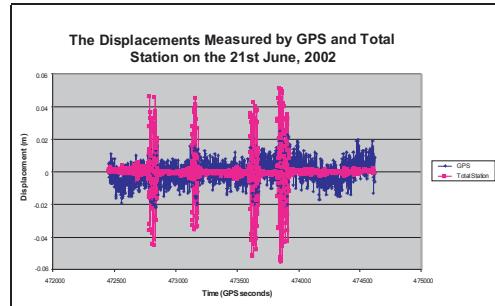


Figure 13 The displacement measured by GPS and total station on the third day of the bridge trial when the 360° prism was used.

smaller bridges and would also remove the possible problem of the angles and distances not corresponding to each other.

The main problem with the above method is whether the total stations are both measuring at the same time. Connecting the laptops to an external oscillator and/or a GPS receiver could be a solution to this problem. The uneven sampling rate of the total stations could cause problems for this method. Another problem is the accuracy to which the time can be known. At present it can only be known to the nearest second, which is not good enough for this application. Both these matters may be looked into in the future by the authors.

## Acknowledgements

This research is funded by the UK's Engineering and Physical Sciences Research Council (EPSRC), in collaboration with Cranfield University, Network Rail, WS Atkins, Pell Frischmann and Leica Geosystems Ltd. The authors would like to thank Mr Andrew Nesbitt for his help and advice during the trials mentioned in this paper. Gratitude is also expressed to staff from Leica Geosystems, particularly Steve Cooper, for their expertise and advice.

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