Accuracy detection of Satellite and InSAR Technology in the Deformation Monitoring in Civil Engineering

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Abstract. This paper focuses on the application of Satellite Navigation Positioning System (such as GPS and BeiDou Navigation Satellite System) and InSAR technology in healthy monitoring in civil engineering. Considering the high cost of Satellite Positioning measurement and blind spot of InSAR measurement, it is reasonable to combine both technologies for accomplishing regionally area and focused points monitoring. During the study, the control network points were positioned with GPS measurement technique and height differences were supported with precise levelling measurements. As the result of measurement campaigns, the height differences were determined from the GPS measurements and InSAR measurements respectively. Later on, deformation analysis using the height differences according to provided data from the GPS and the data from the InSAR system were carried out separately. The comparison between GPS and InSAR results will be shown in the paper.

1. Introduction

In these years, a lot of deformation monitoring systems were adopted and investigated for determining and analyzing different kinds of engineering structures. Monitoring is important for assessing the stability of structures and for confirming the validity of the design during the construction and operation stages. During these studies, the used measurement techniques and systems, which could be geodetic or non-geodetic, are determined considering the type of the structure of which deformations will be monitored, its environmental conditions and expected accuracy from the measurements. The ideal monitoring system for large scale projects such as highway and rock engineering should be able to continuously and automatically monitor the behavior of an extensive area in real time and with high accuracy. In addition, the low costs and easy handling would be an advantage.

There are various types of instruments for monitoring deformations or displacements in Civil Engineering, such as extensometers, inclinometers, laser distance meters, etc. Although they all have advantages and are useful for health monitoring, they generally cost a lot of labor, time and other resources. In addition, for the extensive area monitoring, the accuracy will decline. The results may become not sufficient.

In order to overcome such problems of conventional or traditional methods, modern satellite technologies such as, Satellite Navigation Positioning System and Interferometric Synthetic Aperture Radar (InSAR) system, have begun to be used in Civil Engineering field, especially in the Rock Engineering field and Geotechnical Engineering field.

BeiDou Navigation Satellite System (BDS), similar with GPS, is a Chinese space-based satellite system for navigation and long baseline surveys which can provide the three-dimensional coordinates
of certain locations on or near the Earth\cite{1}. InSAR is a kind of radar which is used to create images of a landscape; these images can be two- or three-dimensional representations of the object. Both technologies can be applied to monitor the displacement/deformation of the ground and the surfaces of structures\cite{6}.

Compared with InSAR, BDS was said to have a higher accuracy at around 1-2 millimeter\cite{11}. However, Satellite Navigation Positioning System performs well at point to point monitoring, while InSAR system is good at large area monitoring. If Satellite Navigation Positioning System is used for a large extensive area, the cost will be very high for setting the base points. InSAR can reduce the cost for the large area monitoring, but sometimes we cannot achieve the accurate information for the special points sometimes\cite{12}. Therefore, this study combines there two technologies together to investigate whether we can get a better result on the deformation monitoring.

A case study that is about implementing the deformation analysis of a large railroad using BeiDou Navigation Satellite Positioning System and InSAR measurements will be discussed here. At the same time, the Precise Levelling measurement was adopted as the reference measurement to adjust and correct the data measured through Satellite Positioning System. The dynamic deformation of measurement points and a reference point was observed to examine the accuracy of BDS. Then, a 3.1 Km railway was monitored for the further discussion.

2. Measurements

2.1. BDS measurements

There are two methods for using BDS. One is point positioning for navigation. Latitude, longitude, and height, three-dimensional absolute coordinates of a measurement point, could be obtained instantaneously. The accuracy of the point positioning method is approximately a few meters\cite{13}.

Here we used the second method, which is relative positioning as shown in Figure 1. Compared with previous method, relative positioning method need an extra reference point. It provides the three-dimensional relative coordinates between two points with the accuracy of millimeters. By continuously observing the coordinates of measurement points, the displacements are obtained as changes in the coordinates. The standard deviation of the measurement can be a few millimeters, but it depends on the length of baseline and the data correction.

![Figure 1. The BDS displacement monitoring system. In this system reference stations conducted as the reference point for the positioning. User devices could be the devices for monitoring deformation of measurement points.](image-url)
In order to clearly identify the accuracy of BDS measurement, different lengths of baselines were selected. The baseline lengths were 10 m and 3800 m in this study.

The BDS adopts the static measurement method for the calibration. During the calibration test, the equipment of BDS and the measurements points were installed on the roof of high building, and there were no shields surrounding them. The data was collected for 24 hours for each point. The position change of measurement points was obtained based on the reference point. The accuracy of BDS was determined by comparing the measured data with the calibrated data.

In order to ensure the effectiveness of data collected through BDS, the locations of measurement points and reference point of BDS should be far away from high-power radio transmitting sources and high-voltage wires. In order to decrease noises, the distances between measurement points and interference sources selected here were all greater than 200 meters.

BDS sensors, composed of an antenna and a terminal box, are set on measurement points and a reference point. They are connected to a data center into which a computer, a data memory, and a network device are installed. The data emitted from the satellites are received at the sensors and then transferred to the data center through cables. The server computer automatically controls the entire system to acquire and then analyze the data. Then, the three-dimensional displacements at all the monitoring points are obtained. The monitoring results are provided to users on the web through the Internet in real time. For Figure 2, the measurement point sensor was installed on a deformation platform. The horizontal and vertical position of measurement point could change slightly via the deformation platform. In this way, the accuracy of BDS deformation monitoring system could be indentified.

After 24 hours installation, the BDS deformation monitoring system started to record data from measurements points. For 10 meters baseline situation, the position of measurement point changed 4 times. The Figure 3 shows the deformation results of the 10 meters baseline measurement point. After correction by theodolite, the horizontal deformation of the measurement point was set at 0.53 mm, 2.53 mm, 1.03 mm and 30 mm, respectively. The vertical deformation of the measurement point was set at 0 mm, -1 mm, -3 mm and 30mm, respectively. Here illustrate the results of 0.53 mm horizontal deformation. Based on the results, for the horizontal measurement, the maximum horizontal deformation value is 1.3 mm, which is 0.77 mm different from the original point. The minimum horizontal deformation value is almost 0.53 mm.
For the deformation at 30 mm, as shown in Figure 4, the horizontal deformation values observed were even and very close to 30.8 mm. On the contrary, the vertical deformation values were not so closed to the original value. The maximum vertical deformation value is 28.2 mm. The minimum vertical deformation value is 27.8 mm, which is 2.2 mm away from the original value.

The Figure 5 shows the deformation results of the 3.8 km baseline. After correction by theodolite, the horizontal and vertical deformation of the measurement point were both set at 8mm. Based on the results, for the horizontal measurement, the maximum horizontal deformation value is 8.1 mm. The minimum horizontal deformation value is 7.3 mm. The average horizontal deformation value is 7.6 mm. The mean square error of horizontal deformation measurement value is 0.5.

At the same time, it is clear to find that the maximum vertical deformation value is 10.9 mm. The minimum vertical deformation value is 10.4 mm. The average vertical deformation value is 10.9 mm. The mean square error of vertical deformation measurement value is 2.6.
Figure 5. The 3800 meters baseline measuring results of the measurement point (8, 8).

Then, use theodolite to set the deformation of the measurement point at 22mm and 50 mm, the results is almost same with the 8 mm deformation results. It can conclude that, for the 3.8 km baseline, the accuracy of horizontal deformation is 0.5 mm and the accuracy of vertical deformation is 2.6 mm.

2.2. Influence of typhoon
By the end of 2018, there was a strong Typhoon Yutu attacking South China. The maximum speed of Typhoon Yutu reached 72 m/s, which is the strongest typhoon in year 2018. The lucky thing is that when Typhoon Yutu passing through Shenzhen, China, the maximum moving speed has reduced to 20 m/s. A test was finished to evaluate the accuracy of BDS under attacking of Typhoon Yutu.

From November 2nd to November 5th, during the typhoon period, the position of sensors was adjusted for 4 times as listed in Table 1. The maximum vertical adjustment was 10 mm, which is because the deformation of rock or bridge under attacking of typhoon should be slightly, unless there is a landslide or collapse. From the table, we can find that the accuracy of BDS was slightly influenced by typhoon. However, for 10 mm vertical adjustment, the difference between the real test results and the original value was smaller than 1.3 mm. As we can say, for the accuracy of BDS, it is not necessary to consider the influence of ordinary weather condition.

Table 1. Accuracy of BDS under attacking of Typhoon

| Date  | Weather   | Vertical adjustment | Real test results | Error |
|-------|-----------|---------------------|-------------------|-------|
| Nov.2 | Moderate rain | 3 mm               | 2.4 mm            | 0.6   |
| Nov.4 | Cloudy    | 5 mm                | 2.0 mm            | 3.0   |
| Nov.5 | Sunny     | 7 mm                | 4.6 mm            | 2.4   |
| Nov.6 | Sunny     | 10 mm               | 8.7 mm            | 1.3   |

2.3. InSAR measurements
InSAR is a SAR-based technique used to obtain the deformation of the land surface. It is a method that makes two SAR observations from the same orbit at different periods and identifies the differences in phase between them\(^{[14]}\). SAR is also mounted on BD satellite. It can create high-resolution radar images of the Earth’s surface. It uses microwaves to irradiate objects on the earth’s surface and observes the objects by analyzing the reflected signals. The advantage of BD based InSAR is that it can provide centimeter-scale deformations of the surface of the earth over an extensive area, 40 km * 40 km, and achieve a spatial resolution of 3 m * 3 m\(^{[15]}\). To avoid the impact of the running of train and make sure the stability of data collection, the InSAR equipment was installed on the fence position of the railway bridge.
Because the radar of InSAR system is also carried by Beidou satellite, so the BDS navigation satellite system and InSAR system were integrated on the same sensors as shown in Figure 6.

Figure 6. Beidou positioning sensors and the corner reflector

Figure 7. Size of Beidou antenna

Figure 8. Size of corner reflector

Figure 9. Data collector
There are three 100 W solar panels to support energy to each sensor. Because that place is suffering the storm every year, so the solar panels should be locked on the ground by expansion bolts. Assumed the wind speed is 32.6 m/s. The area of solar panel is 1.2 m×0.55 m.

The maximum wind force on the solar panels is:

\[ F = S \times \frac{w^2}{1600} = 0.66 \times \left( 32.6 \times 32.6 \right) / 1600 = 0.438 \text{ kN} \]

As a result, each solar panel is fixed by 6 M10 × 120 expansion bolts. The length of the screw is 120 mm, the length of the expanded rod is 90 mm, the drilling diameter is 14 mm, the drilling depth is 80 mm, and the pulling force is 3.9 KN.

2.4. Data collection and transmitting

The InSAR system is also connecting with BDS. Therefore, there are two methods for InSAR data transmitting 4G and lora (broadband satellite). 4G network is used for data transmission in areas with communication signal coverage. For the area without 4G network coverage, InSAR system can automatically switch to broadband satellite mode for data transmission. These two methods can promise that data is not missing during the whole testing process, and ensure the validity and continuity of data. The data collection frequency of BDS is 1Hz.

3. Railway project

There is a railway connect Shenzhen City and Xiamen City in China. The railway bridge was built in 2010. All the piles are friction pile with the diameter of 1 and 1.25 meters. After running several years, the deformation of bridge pier appeared very serious deformation. In years 2010 to 2013, it was found that the deformation of Baima Bridge reached up to 243.1 mm, which exceeds the upper boundary of deformation limitation. Therefore, a 3.1 km long railway was studied in this project. Both BDS method and InSAR method were adopted in this study. We used these two methods not only wanted to measure the deformation of this slot of railway, but also want to figure out the accuracy of them in the real project.
4. Data analyzing

Data of InSAR monitoring system were observed for one year. The current InSAR results are shown in the Figure 12. In order to compare the test result of BDS measurement and InSAR measurement, 8 points were selected to show the comparison between BDS and InSAR.

![Figure 12. InSAR map of the railway](image)

4.1. BDS data analyzing

After installed the BDS sensors, collect the positioning value of measurement points for 5 times to calculate the mean square error. Based on the previous test results, the difference between each positioning value should be smaller than 5 mm. The mean square error was calculated as below:

$$\delta = \sqrt{\frac{\sum \Delta^2}{n-1}}$$

where $\delta$ is the mean square error; $\Delta$ is measurement error; $N$ is measuring times.

According to the measured data of this project, the mean square error of BDS is this project is drawn in the Figure 13. In the figure, the dots are mean square error measured through BDS, the horizontal axis represents the length of baseline. It is clear that the mean square error of BDS positioning measurement is increasing with the length of baseline, which is similar with the results mentioned above. From the results, when the length of baseline is 0.14 km, the mean square error is 1.1 mm. However, when the length of baseline increases to 3.1 km, the mean square error increases up to 3.4 mm. Generally, we can say the accuracy of BDS Navigation Satellite System is smaller than 3.4 mm when the length of baseline is 3.1 km.

A linear curve was drawn to simulate the relationship between mean square error and length of baseline. The fitting correlation coefficient is 0.9175, which means the accuracy of BDS and length of baseline is linearly related. It has guiding significance on the accuracy prediction of Navigation Satellite System.
4.2. Data comparison between BDS and InSAR

There are 8 measurement points to compare the results of BDS and InSAR. The results of 8 measurement points were traced for 3 months from September to December. The comparison results were shown in figures here.
Figure 16. Measurement point 02. The deformation results of BDS and InSAR methods.

Figure 17. Measurement point 03. The deformation results of BDS and InSAR methods.

Figure 18. Measurement point 04. The deformation results of BDS and InSAR methods.
From the comparison figures, BDS shows very close results with InSAR method. The deformation varied from -5 to 5 mm. Good news is that, in this period, the railway did not settle anymore. The
bridge is stable. Bad news is that the deformation results would not show a huge changing in this period.

Let see more details in the comparison. For Measurement points 01, 03, 74 and 77, the deformation of BDS is entangled with InSAR results. But, for measurement points 0a,02,04 and 76, the deformation of BDS looks a little bit smaller than InSAR. Especially for measurement points 76, the deformation results of BDS are negative, which means the point was settled down in these 3 months. However, the deformation results of InSAR is positive. The maximum difference between BDS and InSAR is less than 8 mm.

In these figures, another phenomenon is that the fluctuation of BDS results is severer than InSAR results. This proves that the BDS navigation method is more sensitive to the tiny deformation. As in all InSAR applications, displacement data are relative both in time and space. In time all data are referred to the unique master image. In space the data are relative to a reference PS supposed motionless. The variation of InSAR results looks more stable compared with BDS data.

5. Conclusion

As is very well known that, because of the weakness of geometric structure of Navigation Satellite System, the weakest component of a position obtained by Navigation Satellite System is the height component. Therefore, people uses precise levelling measurements in vertical positioning to support in determining vertical deformations.

This study outlines the basic research on the accuracy of both Beidou Navigation Satellite System and InSAR system. During the test, it is found that the accuracy of BDS method is decrease along the increase of the length of baseline, which is consistent with others test results. At the baseline length of 3.8 km, the mean square error of horizontal deformation measurement value is 0.5 mm. The mean square error of vertical deformation measurement value is 2.6 mm.

The accuracy of InSAR method is also studied in this work. Compared with BDS method, the fluctuation of InSAR results was smaller than BDS results. Even though the BDS method and InSAR method show different results, the difference between these two results were very small, less than 8 mm. Therefore, we can have a conclusion that they both have a very high accuracy for positioning test in Civil Engineering. The high accuracy and consistency of these two methods make them have the ability to be adopted in the same positioning project.

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