Accuracy detection of Satellite Technology in the Deformation Monitoring of Slope

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Abstract. Recently, the use of Global Navigation Satellite System (GNSS) in slope deformation monitoring has received great attention in the world. However, the high expenses of the setup, especially different kinds of receivers for various monitored points, and the accuracy has limited the application of GNSS in health monitoring. This study focuses on the application of Satellite Navigation Positioning System (BeiDou Navigation Satellite System) in healthy monitoring in slope. During the study, the control network points were positioned with GNSS measurement technique and height differences were supported with precise levelling measurements. Later on, deformation analysis using the height differences according to provided data from the GNSS and the data from the Total Station were carried out separately. The comparison between GNSS and the Total Station results will be shown in the paper.

1. Introduction

In these years, health monitoring plays a key role in disaster prevention, construction and maintenance project. The Global Navigation Satellite System (GNSS) provides a well understood, widely deployed and accepted way to accurately determine precise location. The positioning service quality assurance, expressed in terms of accuracy, integrity, availability, and continuity of the localization service help GNSS technology fast expansion in geo-localization applications and services in Civil Engineering[1-5]. GNSS positioning makes us possible to use known coordinates of satellites to calculate the distances from satellites to receivers then using the distances to calculate the unknown coordinates. Time domain measurements can determinate the pseudo range from satellites to receivers, and phase ambiguity measurement can determinate the distances that carriers passed by[6-8].

Even though GNSS (Global Navigation Satellite System) positioning technology has been utilized for surveying engineering, satellite geodesy and navigation for decades. Much more satellites are in view, transmitting navigation data at more frequencies as during the past years with the dual-frequency system GPS only. However, the performances of GNSS receivers need to correspond with the accuracy. In order to ensure the positioning precision and to correspond the international standard requirement, the calibration of GNSS receivers are becoming more important.

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[9]. According to its functional designation, the system is able
to provide continuous positioning, navigation and timing (PNT) services and short message communication services already. Thanks to the completion of the constellation of the BeiDou regional system and the establishment of several ground tracking networks, BeiDou precise point positioning (PPP) and relative positioning have been investigated recently [10-15]. With the development in advance GNSS receiver technology and relative positioning methods, many of the errors sources in GNSS carrier-phase measurements have been drastically reduced. Such as atmospheric delays, orbital and clock errors are spatially correlated through different process.

In this contribution, we present a BDS system for real-time PPP project on site to improve the health monitoring and hazard prevention of slope. 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 accuracy and continuous positioning, navigation and timing (PNT) services was investigated in this work to implement the deformation analysis of a long baseline slope in geotechnical engineering.

2. BDS measurements

BDS supports two different methods on navigation positioning. The first one is point positioning for navigation. Latitude, longitude, and height, three-dimensional absolute coordinates of a measurement point, could be obtained instantaneously [16]. However, the accuracy of the point positioning method is approximately a few meters.

For the second method, it 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 [17]. The deformation information can be recorded as changes in the coordinates by continuously observing the coordinates of measurement points. The standard deviation of the measurement can be a few millimeters, but it also depends on the length of baseline and the data correction [18-20]. Generally, the longer of the baseline, the larger the system error measured in the test.

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.

3. System Overview

BDS sensors, composed of an antenna and a terminal box, are set on measurement points and a reference point. To achieve high accuracy result, using dual frequency receivers are recommended in
slope deformation monitoring. In view of which model of receiver should be chosen, this depends on the purposes of the survey and location of the site. 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.

To ensure the system can be capable of continuous operating, a continuous power supply should be provided. Therefore, it is suggested that solar panels and the rechargeable battery have to be used to power all the electronic devices on site.

4. System calibration

Reliability refers to the consistency of the results provided by a system; internal and external reliability are, respectively, the ability to detect gross errors and the effect of an undetected blunder on the solution[21]. 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 is 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[22]. In order to decrease noises, the distances between measurement points and interference sources selected here were all greater than 200 meters.

![Figure 2. Accuracy examination system of BDS. The right sensor is appearance of fixed stations (reference point); The left sensor is appearance of pillars of calibration base points (measurement point).](image)

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 identified. After 24 hours installation, the BDS deformation monitoring system started to record data from measurements points. Due to the fact that, the baseline used in this experiment is relatively short, the most of the GPS errors such as ionospheric delays, orbital errors and clock errors are very small compared to multipath effect.
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:

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

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

5. Baguang slope project

Baguang slope is located at K28+220.0~K28+885.0 of Shenzhen City, China, as shown in Figure 3. It situates at mountainous area with terrain variation more than 665 meters, and the maximum excavation depth is 32.2 meters. Thus, the landside was construct with five-grade platforms to reduce the slope. The first-grade platform adopted the inclined retaining wall; the secondary platform adopted the anchor-bar frame; the third grade and the fourth-grade platforms adopted the anchor cable; the fifth-grade platform adopted the nets and grasses to protect the soil. There are 2 meters gap between each curve.

![Figure 3. The Baguang slope](image)

In March 2018, the construction of cutting slope of Baguang was completed. Findings obtained during fieldwork indicate that there are frequent mass movements such as landslides and rock falls in the area. The traces left by these natural disasters on the topography are visible to the naked eye, and these natural phenomena continue to alter the topography. In May 2018, due to its geological stability is low, a landslide had induced by a heavy rainfall event and cause the bottom of retaining wall displaced more than 20 mm. At June 9, 2018, the displacement of the retaining wall increased a lot. At June 14, 2018, the anchor beam of the secondary platform appeared landslide. At June 18, 2018, both the secondary and the third platform started collapse and the slope appeared cracks on its surface. Figure 4 shows the retaining wall of Baguang slope.

![Figure 4. The retaining wall of Baguang slope](image)
Considering that the slope of Baguang station was currently continuous deforming. Many deformations have exceeded the warning value. Once the slope occurs, the landslide must be harmful. In order to make sure the slope would not collapse in the future, it is necessary to reinforce the slope and monitor the deformation. Beidou navigation satellite system was adopted to guide the design and construction of retaining wall, anti-slide piles and lattice beams. In Figure 5, we can clearly see the anchor beam appeared sliding and broken.

![Figure 5. The anchor beam appeared sliding and broken](image)

5.1. Installation process

Choose the location K28+500 for installing the set of Beidou navigation satellite system. The base station was installed on a rock 210 meters away from the slope. The installation process including: column installation, Beidou positioning system installation, Solar panel installation and testing. The installation of BDS system was shown in Figure 6.

1. Column installation: Place the column at the planned location. Mark the location of the expansion bolt with a marking pen, then drill the hole with the electric hammer and the corresponding drill. After drilling to the intended depth, install the collision bolt and column.

2. Beidou positioning system installation: Install Beidou positioning system on the top of the column and adjust it with a horizontal ruler.

3. Solar panel installation: Assemble the solar panel and battery on the Beidou column, and place the solar panel toward the sun direction.

4. Testing: Connect the power cord and check the measurement points for 10 minutes.
Figure 6. Beidou Navigation satellite system on different positions of the slope of Baguang. There are retaining wall, anti-slide pile and lattice beam, respectively.

5.2. Accuracy estimate
In order to estimate the monitoring accuracy of the Beidou Navigation satellite system, an accuracy test was conducted at the site of the Baguang slope. The length of baseline is 210 meters, which is similar with the length of other baselines at Baguang slope. The Location diagram was shown in Figure 7. Fig 8 is the setup of Beidou checking point.

Figure 7. Location diagram of Beidou Navigation satellite system accuracy test.
Figure 8. Beidou checking point

The testing process can be divided into 3 trails. The horizontal and vertical displacements of checking point were listed in the table Table 1.

| Tests   | Time   | Displacement of checking point (mm) | Weather Condition |
|---------|--------|-------------------------------------|-------------------|
|         | Horizontal | Vertical | Horizontal | Vertical |                        |
| Trail 1 | 23-11-2018 14:20 | 23-11-2018 14:20 | 1 | 1 | Sunny |
| Trail 2 | 24-11-2018 17:23 | 24-11-2018 17:23 | 3 | 3 | Sunny |
| Trail 3 | 26-11-2018 10:55 | 26-11-2018 10:55 | 5 | 5 | Rainy and Cloudy |

(1) For trail 1, both horizontal and vertical displacement are 1 mm

Before the accuracy test, after the initial setting of the system, the original horizontal coordinate was changing between 0.4 to 0.7 mm. And the original vertical coordinate was changing between -1.7 to -1.9 mm. After setting the trail 1, the coordinate results of measurement point was shown in Figure 9. We can see that the horizontal results are vibrating from 0.9 to 0.2 mm. After 1 day, the recorded horizontal displacement is stable at 0.2 mm, which is 0.8 mm away from the real result. The error of vertical results are larger than horizontal results. The horizontal results are vibrating from -2.3 to -0.9 mm. The vertical error can be as large as –3.3 mm. After 1 day, the vertical error is -1.9 mm.
(2) For trail 1, both horizontal and vertical displacement are 3 mm.
For trail 2 as shown in Figure 10, when the horizontal and vertical displacement were set at 3 mm, the error between measured horizontal value and the real horizontal value is -0.5 mm. The error between measured vertical value and the real vertical value is -2.9 mm.

Figure 10. The coordinate results of measurement point for trail 2

(3) For trail 1, both horizontal and vertical displacement are 5 mm.
For trail 3, the horizontal and vertical displacement were set at 5 mm. After 24 hours adjustment as shown in Figure 11, the measured horizontal cumulative displacement was 3.8 mm. The error between measured horizontal value and the real horizontal value is -1.2 mm. The measured vertical cumulative displacement was 4.6 mm. The error between measured vertical value and the real vertical value is -0.4 mm.

Figure 11. The coordinate results of measurement point for trail 2

When the displacement is 1 mm, the horizontal deviation rate is -80% and the vertical deviation rate is -190%. When the displacement is 3 mm, the horizontal deviation rate is -17% and the vertical deviation rate is -97%. When the displacement is 5 mm, the horizontal deviation rate is -24% and the vertical deviation rate is -8%. This proves the accuracy of BDS system is increase when the deformation of slope becomes more serious. For a slope displaces more than 100 mm, if we consider the system error is smaller than 5 mm, the deviation rate would smaller than 1/20. For an on-site health-monitoring project, this accuracy is accepted.
5.3. On-site monitoring
There are three sets of BDS system in Baguang slope. After 24 hours system initialization, the health monitoring started on August 4th, 2018. The health monitoring lasted for a year. Here chose one-month test results for analyzing.

Figure 12, Figure 13 and Figure 14 show the test results for three measurement points respectively. As we can see from the figures, as soon as the BDS system started, the deformation of measurement points was observed. And the deformation became larger and larger along with time increase.

In figures, the blue curves were represented the results recorded by the total station. The orange curves were represented the results recorded by the BDS system. By comparing test results of total station and BDS system, both curves show the similar behavior towards time. On August 18th, the deformation of measurement points shows dramatically increase in all three figures, which because there was a heavy rain on the same day. People on site can clearly see the cracks on the retaining wall. The intensively increase of cracks on the surface of retaining wall reflected the BDS system results can accurately and quantitatively indicate the deformation of slope, and guide the project maintenance and prevention.

The maximum difference between total station results and BDS system results in Figure 12, Figure 13 and Figure 14 is less than 5 mm, which also proves that the BDS system has the good ability for the long baseline and in-situ timely monitoring. In Figure 14, the results of total station results and BDS system results shows the huge difference, which may be caused by the influence of heavy rain on August 19th to the installation of total station. The accuracy of BDS results is in a few millimeters. For most hazard conditions, the deformations of slope are larger than tens or hundreds of millimeters, so the accuracy of BDS system is absolutely accepted.

After August 29th, the rain lasted for several days and the condition is not suitable for the operation of total station. So, the results of total station were missed after August 29th. The deformation trend of measurement points of BDS system reflected the influence of rainy days. The displacement of measurement points 2 reached up to 160 mm, twice of the value on August 19th.

Figure 12. Results comparison of measurement points 1 between BDS and Total Station.
6. 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 use 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 Total Station. At the beginning, we also used precise levelling measurements to help determining the position of sensors. After that, a deformation adjustment setup was adopted to adjust the position of sensors. So, it is possible to measure the accuracy of BDS method.

When the length of base-line is 210 meters, the accuracy of BDS method test of Beiguang on-site shows that the horizontal displacement accuracy of the BDS system is 1.2mm and the vertical displacement accuracy is 2.9mm. Generally, the hazard deformation of slope is usually more than 100mm. If we can control the accuracy in several millimeters, the deformation monitoring accuracy of Beidou equipment can satisfy the technical specifications.

The test result shows that the deformation of slope dramatically changed between August 18 and August 29, and the cracks were found on the retaining wall on the same day, which indicates that BDS measurement can reflect the deformation of the slope well.
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