Millimeter-Level Precision Deformation Monitoring Algorithms and Implementation of Beidou Satellite Navigation System

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Abstract: The millimeter accuracy deformation monitoring algorithm of the Beidou satellite navigation system is studied. Firstly, Turbo Edit method is improved to detect the cycle slip of one week. A more efficient independent double difference observation search method is proposed for BDS constellation structure. For the fixed ambiguity, a combination of decision function and sequential ambiguity is used. On this basis, BDS deformation monitoring software is developed. Finally, using the measured data of the deformation monitoring test platform, the feasibility of BDS in deformation monitoring is analyzed from the aspects of constellation distribution and calculation accuracy. The results show that BDS and GPS are basically the same in the geometric distribution of satellites in the test area. The short baseline accuracy of BDS is slightly lower than that of GPS, but it can still reach the accuracy level of 1 mm in plane and 2 mm in elevation.

1. Introduction

With the emergence of large-scale structures and frequent occurrence of geological disasters such as landslides and debris flows, the importance of deformation monitoring research has become increasingly prominent, and the theory and technology of deformation monitoring are also developing rapidly. Global Satellite Navigation System (GNSS) has the advantages of all-weather and high precision. As early as the mid and late 1980s, it was used as a deformation monitoring technology. Since 1995, GNSS has been used to monitor the slow deformation of landslides and dams, such as the GPS deformation monitoring system established in Pacoima and Gehemony dams of Qingjiang River. The feasibility of GPS for high-precision deformation monitoring has been analyzed, and the accuracy reaches millimeter level. The results show that the deformation calculated by GPS is highly consistent with the reservoir water storage [1]. In order to reduce the construction cost of the deformation monitoring system, a multi-antenna deformation monitoring system is proposed in reference [2]. The time-division single-pass connection between a receiver and multiple antennas is realized by using an additional multi-antenna switching switch. At the same time, considering the monitoring characteristics (such as the coordinates of monitoring stations are known), the deformation monitoring method of "no cycle jump and no
“ambiguity” is proposed in reference [3]. For the dynamic deformation of bridges, tall buildings and other structures, real-time monitoring system is suitable. Reference [4] developed GPS deformation monitoring data processing software, GPSMON, with positioning accuracy of sub-centimeter level. Reference [5] integrated GPS, accelerometer, pseudo-satellite technology, and established a real-time monitoring system for bridge deformation. At the same time, Geo++, Leica, Trimble and other measuring instruments companies have developed GPS deformation monitoring system, which has been widely used.

Beidou system has been developed in China since the 1980s, and the "three-step" plan for system construction has been implemented. At the end of 2012, the spatial signal interface control document of Beidou Satellite Navigation System was officially published, marking the formal completion of Beidou Regional Navigation and Positioning System. At present, there are 16 BDS satellites in orbit, including 14 working satellites, including 5 GEO satellites, 5 IGSO satellites and 4 MEO satellites. It is expected that Beidou Satellite Navigation System will be built around 2020. Previous studies have shown that the satellite clock performance and ranging accuracy of Beidou II system are basically at the same level as GPS [6].

In deformation monitoring, especially for landslides, dams and other deformation bodies, due to the limitation of observation environment, the observation stations are often seriously shielded, which affects the geometric configuration of satellites and reduces the accuracy and reliability of deformation monitoring. Because of its special constellation design (the existence of five GEO satellites and five IGSO satellites), BDS has larger satellite visibility than GPS and other systems in most regions of China even though the global network has not been completed. With the gradual entry of BDS satellite into orbit, this advantage will be more obvious. Although BDS is similar to GPS, its signal structure, satellite distribution and satellite type are quite different [7]. At the same time, the accuracy and reliability of monitoring results can also be improved by using a variety of monitoring systems. In addition, the research on the application of BDS deformation monitoring can also expand the application space of Beidou system in China, and verify the availability of Beidou system in the field of high precision navigation and positioning. Therefore, it is of great scientific and practical significance to study and use BDS and other systems for deformation monitoring.

Firstly, based on the double-difference model, this paper studies the high-precision baseline solution method of BDS. According to the characteristics of deformation monitoring, a deformation monitoring software platform based on BDS is developed by using a reliable data processing strategy. At the same time, based on the deformation monitoring test platform equipped with three-dimensional precision testing system, this paper discusses and analyses the usability of Beidou system in deformation monitoring from the aspects of satellite distribution, internal and external coincidence accuracy of calculation results and so on, using the measured data collected in a certain area of central China, and advances it with GPS calculation results. Comparisons were made.

2. System Algorithms and Implementation

In order to explore the feasibility of using the existing Beidou constellation for deformation monitoring, this paper develops a deformation monitoring software. The software aims to realize the quasi-real-time (time resolution mode) and high-precision processing of BDS deformation monitoring data, so the software uses broadcast ephemeris to solve. Previous studies have shown that under the condition of short baseline, the broadcast ephemeris error has little influence on the baseline calculation results, and can be neglected, not counting [8]. At the same time, the software has the ability of BDS-GPS joint solution, but the existing research shows that there is a systematic deviation between BDS and GPS high-precision solution results due to antenna phase center correction, etc. [9]. Therefore, this paper only analyses the single-mode results of BDS.

The software includes the whole process from data processing to result output, including data preparation, normal equation formation and superposition, ambiguity fixing, time series result analysis and so on.
(1) Data preparation mainly includes two aspects: one is to calculate the satellite position according to the broadcast ephemeris; the other is to detect and mark the cycle slip of the observed data. The improved Turbo Edit method [10] is used to detect cycle slips. The combined observations of MW, LG and LC are used to detect cycle slips respectively. The results show that the cycle slip detection strategy mentioned above is basically independent of ionospheric activity and observation conditions, and can detect a week's cycle slip, thus greatly reducing the workload of residual editing and shortening the data processing time. In order to avoid the disastrous consequences caused by cycle slip error repair, this paper adopts the strategy of only detecting, marking and not repairing cycle slips, and estimates the ambiguity parameters of all cycle slips.

(2) Forming double difference observation equation, superimposing normal equation and mapping ambiguity to double difference ambiguity [11]. Reference station-reference star and global search are used to select double difference observation values. If a reference station or a reference star exists in an epoch observation, the reference station-reference star method is used. Otherwise, the global search method is used to search the double difference observation values with independent function in the maximum extent among all the current epoch observations. Considering the particularity of BDS constellation, GEO satellite is the first choice when choosing reference satellite. If any GEO satellite is not a reference satellite because of environmental occlusion, IGSO and MEO satellites are chosen as reference satellites in turn. According to the baseline length, the first-order effects of ionospheric errors can be eliminated by using either single-frequency observations or double-frequency observations to form a non-ionospheric combination. The main errors to be considered in the formation of the normal equation are tropospheric correction, earth rotation correction, antenna phase center correction [20], tidal load correction and so on. Other errors are considered to be eliminated in the process of double difference. Saastamoinen model is used for tropospheric correction, and piecewise linear model is used for estimating residual tropospheric effects. The phase center of BDS satellite antenna adopts the model published by MGEX (multi-GNSS experiment). The phase center correction model of receiver antenna is unknown and replaced by 0 in the system. After solving the normal equation, the floating-point solution is obtained. At this time, residual editing is needed to mark the possible cycle slips and bad values, and then the normal equation is reconstructed until the residual editing has no cycle slips or bad values.

(3) Fuzziness fixing is carried out by combining decision function and sequential fuzziness fixing. Firstly, the probability that each ambiguity can be fixed is calculated, and the ambiguity corresponding to the maximum probability is fixed. Then the normal equation is updated, and the above procedure is repeated until the ambiguity is fixed or no ambiguity can be fixed. The results show that in the application of deformation monitoring, because the baseline is generally short, the ambiguity fixing strategy can basically fix all the Beidou double-difference ambiguities. Fixed ambiguity solutions are obtained by solving the integer ambiguity back to the normal equation.

(4) Time series analysis is carried out in frequency domain and time domain. Frequency domain analysis mainly studies the geophysical effects in the original deformation signal and the effects of GNSS technical errors, and extracts the true deformation information from the original results by designing filters. In time domain analysis, ARIMA is used to model the deformation time series to analyze the intrinsic relationship of deformation and predict the development of deformation.

3. Analysis of experimental data

(1) ANSYS model

Lijiaxia Hydropower Station is a large-scale hydropower project in the upper reaches of the Yellow River. The dam is a three-center circular double-curvature arch dam with a maximum height of 155 m, a crest elevation of 2185 m and a crest width of 8 m. In order to ensure the safety of dam operation, many (>3) GNSS observation stations are usually installed on the top of the dam, and the displacement changes of various parts of the dam are obtained at the same time, which results in a great waste of equipment resources. In theory, as long as the main deformation area of the dam is determined, only one clock synchronous dual antenna receiver is needed, the dam can be evaluated according to the measured
data. Operation status. In order to rationally use GNSS equipment and minimize cost, this section proposes using Ansys finite element software to predict the deformation of Lijiaxia dam, using Drucker-Prager criterion to carry out numerical simulation analysis, and determining key monitoring areas according to displacement changes and stress conditions. In order to simplify the calculation, structural materials are mainly divided into three categories: good rock mass, weak rock mass and concrete. The physical and mechanical parameters used in the calculation are determined through relevant literature. The specific numerical values are shown in the table. At the same time, the expansion coefficient of concrete is set at 1×10\(^{-5}\)/℃. The calculation model is shown in the figure. The geometric size is 480m×700m×305m (x elevation difference along the river x transverse river), the upper surface is unconstrained, and the normal constraints are applied to both sides of the dam and the bottom of the dam. According to the normal storage water level, the upstream water level is set at 2080m, the downstream water level is set at 2050m, the upper and lower intercept boundary is treated with impermeable boundary, and the left and right bank boundary is determined according to the known water head observed by the groundwater observation hole for a long time.

![Three-dimensional finite element model of Lijiaxia dam](image)

**Fig. 1 Three-dimensional finite element model of Lijiaxia dam**

(2) Determination of Key Monitoring Points

The three-dimensional finite element model is used to calculate the displacement and deformation of the dam. As shown in the figure, the dam is divided into 20 sections. The displacement information of key points in each section is extracted. According to the results of numerical simulation, the main stress position of the dam is judged. The average depth of water level in downstream corresponding dam section is about 30m, which is much smaller than that in upstream dam section. Therefore, only upstream water weight, hydraulic pressure and dam self-weight are considered in numerical simulation. The numerical simulation results show that the displacement mainly occurs in the horizontal direction of the dam, and the influence of the elevation direction is small. It can be used as the deformation characteristic constraint condition of IPARLAMBDC ambiguity fixing method.

Figure 2 shows that the numerical simulation displacement of each dam section is approximately proportional to the corresponding upstream water level depth, and the correlation coefficient reaches 0.99, which shows that upstream water pressure and water weight play a major role in dam deformation. As shown in the figure, the key points of the dam crest are extracted. Because the corresponding water level depth of section 11 is the largest, the deformation of section 11 in the middle of the dam is about 13.6 mm relative to section 1, which is much larger than that of other sections, i.e. section 11, which can clearly reflect the operation status of the dam. The GNSS 11 in the figure is taken as the monitoring point of GNSS. It can monitor the operation status of the dam in real time.
Fig. 2 Displacement variety of the key point of each dam section relative to No. 1 dam section in 2016

Fig. 3. Slope real map

4. Conclusion
This paper mainly analyses the feasibility of high precision deformation monitoring based on the current Beidou constellation. Through the analysis and discussion of the measured data, the following conclusions can be drawn: (1) In the test area (a city in central China), the visibility of BDS satellite is slightly larger than that of GPS. However, due to the special design of BDS constellation, its corresponding GDOP value is slightly worse than GPS. Secondly, by analyzing the measured data of deformation monitoring test platform, it is considered that BDS can reach the accuracy level of 1 mm in plane and 2 mm in elevation under the condition of short baseline, which can meet the needs of most deformation monitoring projects. In a word, the current Beidou satellite navigation system can meet the needs of high-precision deformation monitoring engineering, and can be popularized and applied in production practice.

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