Land Subsidence Monitoring System Based on BeiDou High-Precision Positioning

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Abstract. Land subsidence is a geological disaster caused by natural or human activities. The rate of change in early settlements is often extremely small and presents a challenge to monitoring. This experiment includes BeiDou positioning, multiple antenna, and high-precision baseline solution. It developed the BeiDou deformation monitoring system and used static relative positioning for high-precision land subsidence monitoring. We have adopted integrated hardware design, equipped with a variety of communication modules, satellite receivers, and embedded module in one. In addition, we have developed the corresponding communication protocol for data transmission. Finally, a corresponding monitoring interface software was designed on the client to intuitively reflect the settlement process in a graphical manner.

Keywords: Land subsidence · Baseline solution · High-precision positioning

1 Introduction

Since entering the twenty-first century, China has made remarkable achievements in the process of modernization. However, in the process of rapid development, many potential hidden dangers are often ignored by people. Land subsidence is one of them, which is a kind of local subsidence movement caused by the loosening of underground structures and stratum crushing due to human engineering activities, resulting in the reduction of the elevation of the upper crust.

The secondary consequences of land subsidence have caused heavy casualties and loss of social wealth. In order to avoid or reduce the disasters caused by land subsidence, it is necessary to carry out effective monitoring in the early stage of land subsidence.

Current monitoring methods are mainly divided into traditional manual monitoring and automatic monitoring systems. In the last century, land subsidence monitoring has been dominated by traditional methods which is often difficult

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to meet the monitoring needs due to the poor accuracy. With the development of information, communication, and automation technology, automatic monitoring system has been rapidly developed in recent years. Compared to traditional methods, the automatic monitoring system has advantages such as real time, accuracy, and stability.

2 Measurement Technology

There are many ways in traditional geodesy, such as leveling, GNSS, InSAR, and layerwise mark [1]. Among them, GNSS measurement technology has been developed rapidly in the past decades. It may provide high-precision three-dimensional coordinate which can be widely used in land subsidence monitoring. The relative baseline precision of GNSS can achieve 110^{-7}.

Current GNSS measurement technology mainly includes precise point positioning (PPP), differential positioning, and network real-time kinematic (RTK).

2.1 Precise Point Positioning

Precise point positioning, also called as absolute positioning, uses single receiver for positioning. GNSS performances are optimal in an open sky when many satellites are in view and the signals are uncorrupted [2]. After years of development, PPP has been widely used in high-precision measurement, satellite orbit determination, aeronautical measurements, and surface deformation monitoring. The system architecture of PPP is relatively simple, while precise satellite orbit and clock products required by it always suffer a latency [3].

Traditional precise point positioning using undifferenced and ionosphere-free pseudo-range and phase combination measurements can obtain positioning results of centimeter level [4].

2.2 Differential Positioning

Differential positioning, also known as relative positioning, places some GPS receivers as reference station for observation. Based on the known precise coordinates of the reference station, the distance correction to satellite is calculated, and the reference station sends data continuously. After years of improvement, real-time differential positioning technology has been well developed which can significantly improve the positioning accuracy and reliability [5].

2.3 Network RTK

Network RTK is a new technology based on continuous operation reference station (CORS) network and conventional RTK technology which have been widely used in real-time high-precision navigation, survey, and mapping [6].

3 Land Subsidence Monitoring System

For a real-time precise positioning service, at least three components including precise orbit determination (POD), precise clock estimation (PCE), and precise point positioning (PPP) are necessary.

Multi-global navigation satellite system (GNSS) combined positioning [7] has become an inevitable trend in GNSS-based navigation. In addition to BeiDou as the main reference, the system also introduced GPS, GLONASS, and GALILEO auxiliary navigation systems.

3.1 System Schematic

The automatic land subsidence monitoring system mainly includes data receiving system, communication network, and monitoring center as Fig. 1 shows.

The receiving system consists of several GNSS stations, and satellite raw data will be transmitted to communication modules and then be forwarded to communication network to the cloud server.

Data of all the station will be transmitted to the solution terminal. When completed, results will be uploaded to the cloud server and broadcast to the monitoring center.

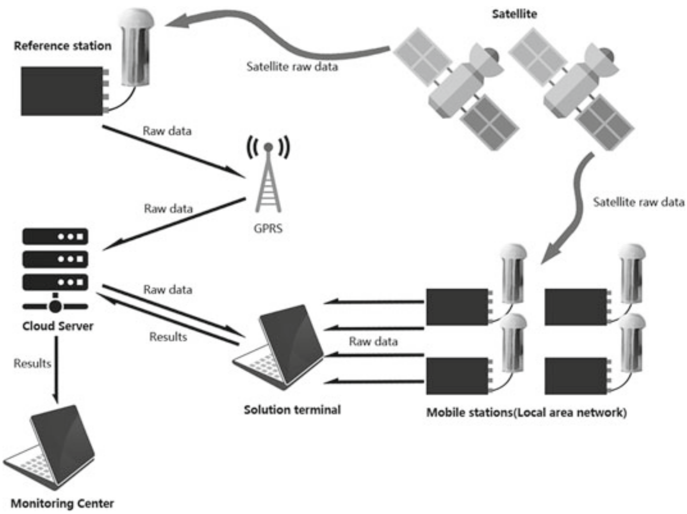

Fig. 1. Land subsidence monitoring system

3.2 Receiving System

In order to obtain data in a specific format and verify it, commands need inputting to the serial port of GNSS receiver. As for stability and safety, and relatively low real-time requirements, ARM embedded modules are recommended to be applied in the subsystem.

The GNSS receiver and ARM embedded module together form a receiving system. Orbit and ephemeris parameters will be transmitted to the GNSS receiver through high-frequency (HF) antenna. ARM embedded module is responsible for messaging with the receiver and as the controlling core.

3.3 Communication Network and Monitoring Center

In actual situations, the reference point of geological stability often exceeds the distance of the monitoring point beyond the scope of the general local area network, so that the cloud server will play the role of forwarding data.

4 Data Processing

The processing of GPS measurements adopts GAMIT/GLOBK, which is a comprehensive GPS analysis package developed by MIT, Scripps Institution of Oceanography, and Harvard University [8]. IRTF2000 is adopted as reference frame, and the model is set to the baseline solution (detailed in Fig. 2) with an interval of 24 h.

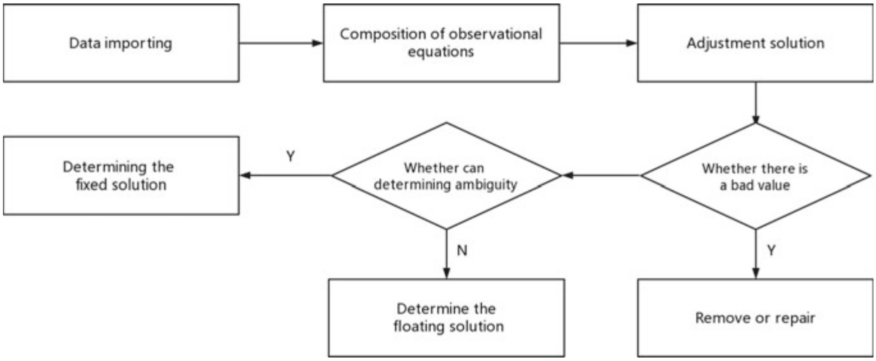

Fig. 2. Process of baseline solution

4.1 Basline Solution

The principle of the baseline solution can be summarized in the following steps:

(1) Adjustment initialization: Uncertain parameters can be solved based on the double-differenced observables, and the error equation is as follows.

Undetermined parameters:

$$\widehat{X} = \begin{bmatrix} \widehat{X}\ C \\ \widehat{X}\ N \end{bmatrix} \tag{1}$$

Cofactor matrix of the undetermined parameters:

$$Q = \begin{bmatrix} Q_{\widehat{X_C}\widehat{X_C}} & Q_{\widehat{X_C}\widehat{X_N}} \\ Q_{\widehat{X_N}\widehat{X_C}} & Q_{\widehat{X_N}\widehat{X_N}} \end{bmatrix} \tag{2}$$

After initialization, the variable of integer ambiguity is obtained.

(2) Determination of ambiguity: There are many ways to confirm the ambiguity. Now, a more reliable and reliable way is based on the search method which takes each ambiguity as the origin and then uses the error as a radius to confirm the integer solution of all the ambiguities.

(3) Determination of baseline fix solution: When confirming the integer solution of ambiguity, baseline integer solution [9] that the integer ambiguity located can be obtained. The integer solution can be used as a reference, which is helpful to the subsequent baseline solution, and to evaluate the quality of baseline.

4.2 Kalman Filtering

The essence of GLOBK is a Kalman filter, which makes the best estimate of the system state by analyzing the input and output observation data [10].

The Kalman filter estimates the process through a form of feedback control: The filter estimates the process state at a certain time and then obtains the feedback as a measurement. Therefore, the Kalman filter equations are divided into two groups: time-updated and measured equations, which can be expressed as follows:

$$\widehat{x_k}^- = A\widehat{x_{k-1}} + B\widehat{u_{k-1}} \tag{3}$$

$$P_k^- = AP_{k-1}A^T + Q \tag{4}$$

$$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1} \tag{5}$$

$$\widehat{x_k} = \widehat{x_k}^- + K(z_k - H\widehat{x_k}^-) \tag{6}$$

$$P_k = (I - K_k H)P_k^- \tag{7}$$

The schematic diagram of Kalman filter is detailed in Fig. 3.

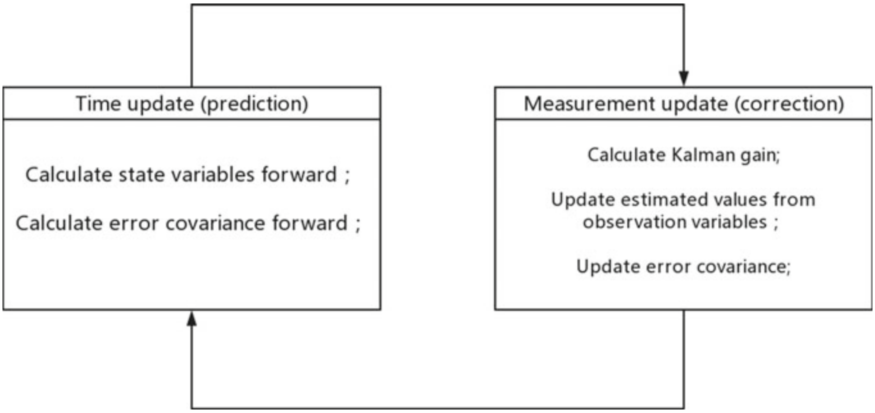

Fig. 3. Process of Kalman filtering

5 Results and Analysis

To simulate the actual settlement, observation antenna was placed on a precision mobile platform with an precision of 0.1 mm. The platform was moved in the vertical direction of 1.0 cm on March 24.

5.1 Results

Table 1 and Fig. 4 show the daily average observations from 23 to 28, which reflect the average change trend of the elevation. Compared with the actual adjustment, the absolute measurement accuracy has reached mm level.

Table 1. Daily average settlement data

Station	Date	Altitude (m)	Settlement (mm)
NJ-01	March 23	154.0375	0
NJ-01	March 24	154.0327	4.8
NJ-01	March 25	154.0275	10
NJ-01	March 26	154.0269	10.6
NJ-01	March 27	154.0273	10.2
NJ-01	March 28	154.0273	10.2

5.2 Error Analysis

The data of March 23 is taken as a benchmark to analyze the accuracy of the system.

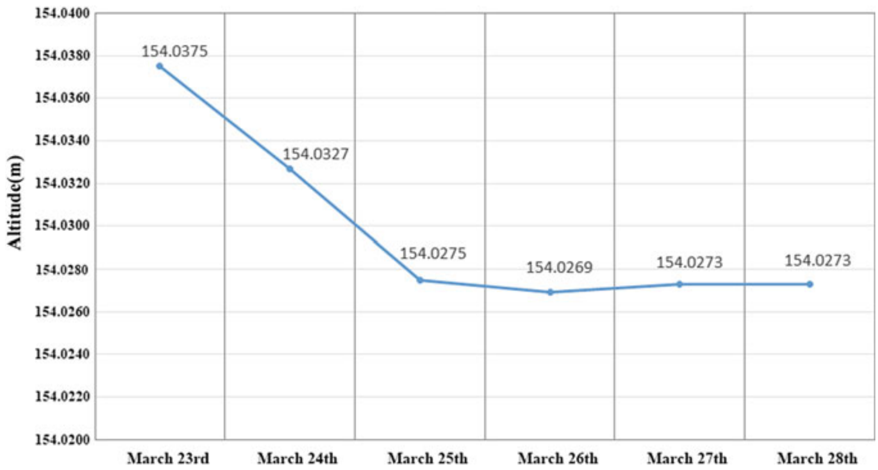

Fig. 4. Settlement curve

In order to quantitatively reflect the accuracy, it is necessary to introduce absolute difference and standard deviation which can be expressed as follows:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} \left(S_i - S_{avg}\right)^2}{N}} \tag{8}$$

According to the data in Table 1, substituting them into formula (8) respectively, the average absolute error and standard deviation can be calculated as 1.2 and 2.2 mm, having reached the mm level.

6 Conclusions

The chapter first introduced the current situation, background, and hazards of land subsidence in China. In order to take necessary measures in time for the hidden safety hazards of land subsidence, high-precision areas need to be monitored in real time. However, traditional monitoring methods have been difficult to meet the monitoring needs. Therefore, automated subsidence monitoring systems using modern communications, computer science, and satellite navigation technologies have emerged. With the completion of the BeiDou navigation system, more and more GNSS receivers are now beginning to be compatible with BeiDou Navigation Satellite System (BDS) information. Compared with other navigation systems, BeiDou provides unique short message communication means on the basis of ensuring safety, reliability, and high performance and can be used as an emergency communication method when a disaster occurs. Therefore, this experiment uses BDS as the main body and uses GPS, GLONASS, etc., as auxiliary references to establish a multi-mode fusion ground subsidence monitoring system to ensure the positioning accuracy in the case of real time and stability.

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