IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

Research, development, and field trial of the universal Global Navigation Satellite System receivers

To cite this article: W Y ZHAO *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **570** 062048

IOP Conf. Series: Earth and Environmental Science **570** (2020) 062048 doi:10.1088/1755-1315/570/6/062048

Research, development, and field trial of the universal Global Navigation Satellite System receivers

W Y ZHAO, M Z ZHANG*, J MA, G QI, S N ZHU and Z HUANG

China Institute of Geo-Environment Monitoring, 20 Dahuisi Road, Haidian District, Beijing, China, 100081

zhangmz@cigem.cn

Abstract. Global Navigation Satellite System (GNSS) can provide continuous, high precision, and absolute displacement information on landslides. It can thus be used in landslide monitoring applications. However, the cost of high-precision GNSS is too high for large-scale deployment. From an application perspective, we reviewed the status and challenges of applying GNSS technology to landslide monitoring. We then investigated the data specification for a landslide monitoring GNSS receiver to better meet specified engineering requirements. We further developed prototype universal GNSS monitoring devices and deployed them in the Heitai area for testing. Approximately two months of testing indicated that the prototype universal GNSS devices well meet the engineering requirements, and the tested GNSS data are in good agreement with the crack data. The hourly monitoring GNSS solution achieves sub-millimeter level accuracy and can be used for extracting landslide information.

1. Introduction

One of the most direct and effective means of avoiding casualties and reducing economic loss during landslides is monitoring and issuing early warnings. Surface displacement is usually monitored to study the movement and state of landslides. The Global Navigation Satellite System (GNSS) is a space-based radio navigation and positioning system [1] that has been widely used in landslide monitoring. It can provide global, real-time, 3D coordinates and speed with millimeter-level accuracy; and it is operational in all-weather conditions [2-4]. However, some limitations still exist in conventional landslide monitoring using GNSS. In this study, the application status of conventional GNSS in landslide monitoring was analyzed, and its limitations summarized. In view of the existing problems and application requirements for large-scale monitoring, future research and development directions and the main technical parameters to be considered for universal GNSS monitoring devices are proposed. Results of a field trial of the deployment of universal GNSS devices to study the Heitai landslide are analyzed and summarized.

2. Application and Problems of conventional GNSS in landslide monitoring

2.1. Application of GNSS in landslide monitoring

The rapid development of GNSS has promoted its application in landslide monitoring. At present, more than 100 navigation satellites of the four GNSSs coexist and are mutually compatible. Abundant satellite navigation information can greatly improve the availability, accuracy, completeness, real-time speed, and reliability of satellite positioning [5].

In GNSS monitoring, the double-differential carrier phase observation mode between satellites and stations is usually adopted. This observation mode can eliminate receiver error, satellite clock difference and most of the ionospheric and tropospheric delay errors that can occur over a short baseline (<10 km) [6-8].

Depending on the deformation stage of a landslide, periodic static solutions and continuous real-time dynamic solutions are necessary [9]. In the static solution mode, millimeter-level monitoring accuracy can be horizontally achieved. In the vertical direction, millimeter-level accuracy can also be achieved over a short baseline, provided there are good observation conditions and a long observation time. Real-time dynamic solution precision is generally at centimeter-level. According to the Saito curve, the deformation process of a typical landslide is generally divided into three stages, namely, the initial deformation stage, uniform deformation stage, and accelerated deformation stage [10]. In the initial deformation stage, the long-period high-precision static solution model can be adopted. In the uniform deformation stage, the high-precision static monitoring period should be shortened, and observation should be intensified in the rainy season. However, in the accelerated deformation phase, the continuous real-time dynamic solution mode is usually adopted to encrypt data observation and transmission to obtain real-time deformation information.

At present, the joint observation mode of multiple satellite systems is usually adopted in landslide monitoring. Since most landslides are located in areas with poor geological conditions, few satellite signals will be received and the geometric distribution configuration of satellites will be poor if only readings from the satellites of a single system such as GPS or BDS (BeiDou Navigation Satellite System) are received. Multi-system joint positioning will provide higher reliability, stronger continuity, and higher accuracy of location services [11]. In addition, the BDS, GPS, and Galileo systems all adopt code division multiple access technologies, which makes it more compatible and easier to achieve joint positioning.

2.2. Problems of conventional GNSS in landslide monitoring

Landslide hazards often occur in areas with poor geological conditions, and these present challenges to conventional GNSS devices. Some of the challenges are summarized as follows:

(1) The conventional GNSS receiver is too expensive for large-scale installation and popularization. The price of the conventional GNSS positioning board is relatively high. With the addition of data storage, data processing, power supply, communication, and other application functional units, the cost of a single high-precision GNSS receiver becomes unattractive 12]. In addition, conventional GNSS installation is complicated and very expensive, thereby hindering the large-scale use of GNSS devices.

(2) Conventional GNSS has poor adaptability to geological conditions, and the following problems often occur. First, it has high power consumption requirements, usually more than 3 W. This makes the monitoring device, mainly powered by solar energy, inadequate and with poor endurance under continuous rainy weather. Second, satellite signal occlusion causes fewer satellite data to be received by ground devices, resulting in poor satellite geometry. Third, the reliability of devices is usually low. In harsh field environments, the device often needs on-site maintenance after operating for long periods.

(3) Obtaining monitoring results with high reliability and precision using conventional solution models is difficult. Moreover, GNSS is susceptible to multipath effects caused by the surroundings [13-14]. The multipath effect has always been a key factor restricting the application of GNSS in complex environment monitoring [15-17]. Therefore, establishing a fine observation environment model for denoising and error correction is necessary to solve the model.

(4) The wide use of new technologies in landslide monitoring and intelligence is not common. Lack of bi-directional control of monitoring terminals, remote parameter modification, self-

adaptive dynamic adjustment of monitoring frequencies, and other functions cannot meet the requirements of large-scale GNSS installation and its efficient management.

3. Development and field trial of universal GNSS receiver

3.1. Development of a universal GNSS monitoring device

Due to the application requirements of large-scale deployment and the problems associated with conventional GNSS devices in landslide monitoring, developing universal GNSS devices with large-scale deployment capabilities is necessary. A universal GNSS monitoring device should satisfy the following conditions: reliable operation, simple function, appropriate precision, high-cost performance, and convenient installation. 1) Reliable operation means meeting the requirements of continuous regular operation. 2) Simple function means that only data acquisition and transmission modules are kept at the device end, and cloud computing is adopted to significantly reduce the power consumption and cost of front-end hardware [18]. 3) Appropriate precision means meeting the accuracy requirements of landslide monitoring. 4) High-cost performance means reducing costs as much as possible while meeting functional requirements. 5) Convenient installation means to improve current device integration capabilities and the adoption of a convenient installation method. Improvement of device integration includes the integration of hardware within a device and integration across different devices.

A summary of the suggested parameters for universal GNSS is presented in Table 1. Note that the following criteria should be met for the development of a universal GNSS device. 1) It should have the ability to receive at least L1 and L2 of GPS and B1 and B2 of BDS. 2) It should meet the monitoring accuracy of different deformation stages of the landslide. 3) It should accommodate the use of Internet of Things (IoT) and 5G communications. Data transmission stability and communication power consumption should be balanced. 4) The average power consumption should be less than 2 W when the data sampling and upload interval is not less than 15 s. 5) Level of Protection is not less than IP67. 6) It should employ the use of steel structures and other new installation methods.

Moreover, exceptional observation environment models have been built to correct these errors. Optimization of the adaptive algorithm at different deformation stages and automatically triggering the switch of GNSS from static to real-time dynamic solution should be implemented to meet the requirements of intelligent monitoring for the accuracy from millimeter to centimeter in different deformation stages.

Table 1. Parameters of universal GNSS.

Parameter type	Values	
Monitoring accuracy	Static solution accuracy(1 h)	Horizontal: 5 mm+1 ppm RMS
		Vertical: 10 mm+1 ppm RMS
	Dynamic solution accuracy	Horizontal: 10 mm+1 ppm RMS
		Vertical: 20 mm+1 ppm RMS
Output signal	NB-IoT/LoRa/4/5G	
Receiving satellite signals	At least GPS: L1 and L2; BDS: B1 and B2	
Power consumption	When the data sampling and upload interval is no less than 15 s, ≤2 W	
Level of protection	No less than IP67	

Based on the technical parameters of universal GNSS, a series of prototypes have been developed. The cost of the prototype is about 10,000 yuan, and the average power consumption is less than 2 W when the data sampling and upload interval is no less than 15 s. Meanwhile, the improvement of hardware integration makes the equipment more portable.

3.2. Field trial of the universal GNSS receivers

To test the performance of the universal GNSS receivers, some field trials were conducted on slopes in Gansu province. The universal GNSS receivers installed on Heitai landslide in Yongjing County, Gansu Province were taken as an example for analysis.

Heitai landslide is located in Yanguoxia Town, Yongjing County, Gansu Province. The shape of the front area of this landslide is an irregular arc. The landslide is characterized by a back of 40 m high, and an elevation of 1580 m in the front and 1708 m in the back, with a relative elevation difference is 128 m. A series of arc-shaped cracks are present parallel to the rear wall. Numerous cracks provide good channels for surface water, especially irrigation water, to infiltrate. The stability of the slope is easily damaged. The main sliding direction of the landslide is 150° and is southeast trending, and the main threat objects include the residents at the foot of the slope and national highway 309.

The three universal GNSS devices installed on the landslide can all receive GPS (L1 and L2), BDS (B1 and B2), and GLONASS (L1 and L2) satellite data. Only data acquisition and transmission modules are present in the devices, and the computing is completed in the cloud. The monitoring terminal can realize bidirectional control, remote parameter modification, and self-adaptive dynamic adjustment of monitoring frequency. GNSS reference station is within 1 km from the three monitoring stations with GNSS01, GNSS02 and GNSS03 as the identity of the device, respectively. The device layout is shown in Figure 1. The data sampling interval and uploading interval of three devices are all 15 s, and the static solution was completed once based on the observation data of each hour. Furthermore, one crack gauge is present.

Figure 1. The layout of GNSS and Crack gauge

The monitoring data distribution of the three devices from 0:00, 15th April to 23:00, 15th June 2020, is shown in Figure 2. The X-, Y-, and Z-axis represent the north, east, and upward directions, respectively. The solid lines in Figure 2 are the linear trend lines corresponding to the monitoring data. As shown, in the X-axis direction, the three devices all showed a noticeable trend of sliding southward. In the Y-axis direction, GNSS01 and GNSS02 present an apparent eastward sliding trend, while the motion of the GNSS03 is less apparent. In the Z-axis direction, all three devices showed a significant downward trend. Based on the monitoring data of X, Y, and Z, GNSS01, GNSS02, and GNSS03 all showed a southeastward sliding trend, which is consistent with the conclusion of the actual southeastward sliding direction.

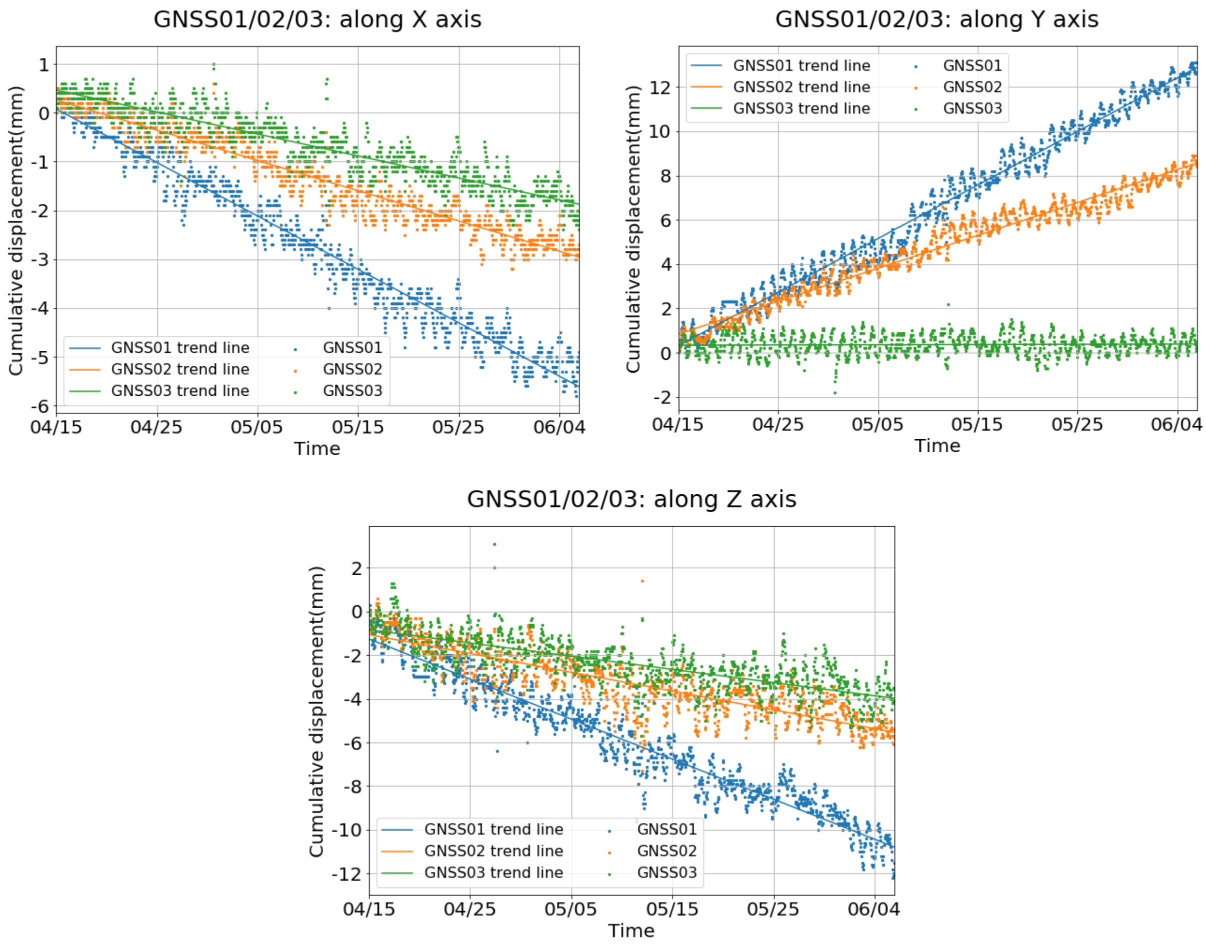


Figure 2. GNSS01/02/03: cumulative displacement along X-/Y-/Z-axis

The root mean square error (RMSE) between the actual monitoring values of the three devices and the corresponding linear trend line were calculated, as presented in Table 2. The RMSE corresponding to the three devices in X-, Y-, and Z-axis directions is similar, and the monitoring data fluctuates within 1 mm. In addition, the RMSE in the X- and Y-axis directions is less than the corresponding value in the Z-axis direction. This is related to the fact that the vertical observation error of GNSS monitoring is larger than the horizontal one.

Table 2. RMSE between the monitoring values and the corresponding linear trend line

IOP Conf. Series: Earth and Environmental Science **570** (2020) 062048 doi:10.1088/1755-1315/570/6/062048

Device No.	X:RMSE (mm)	Y:RMSE (mm)	Z:RMSE (mm)
GNSS01	0.31	0.44	0.78
GNSS02	0.28	0.46	0.83
GNSS03	0.33	0.52	0.74

The 3D displacement of the three devices; GNSS01, GNSS02, and GNSS03 and crack data were also calculated, and its distribution is shown in Figure 3. The figure shows that the three GNSS devices and the crack gauge showed a significant trend of increasing displacement, and the changing trend was consistent. Since the three GNSS and crack gauge were installed at different locations of the landslide, a certain difference in deformation was observed.

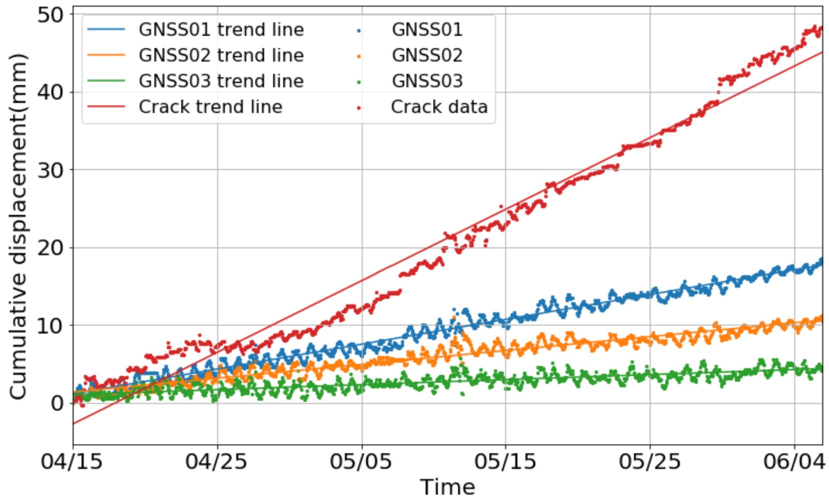
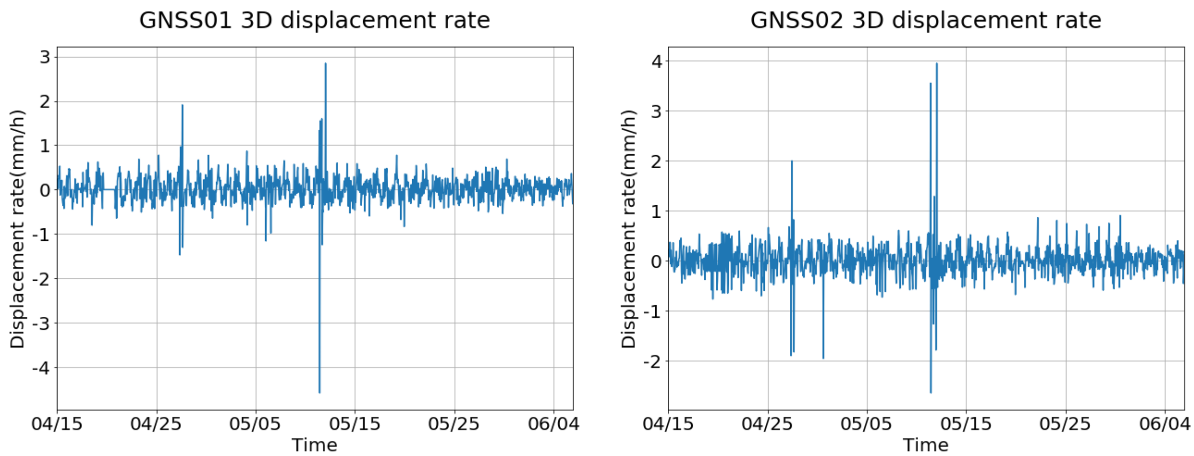


Figure 3. GNSS01/02/03 and crack cumulative displacement in 3D space

The 3D displacement rate of the three devices was also calculated. The results, as can be seen, presented in Figure 4 exhibit a great deformation on May 11th and 12th. This can be attributed to rainfall from 6th–9th May. Additionally, the crack gauge began to show large deformation on 10th May, which can be related to the rainfall from 6th–9th May. The above analysis shows that universal GNSS can effectively capture the deformation trend of the landslide.



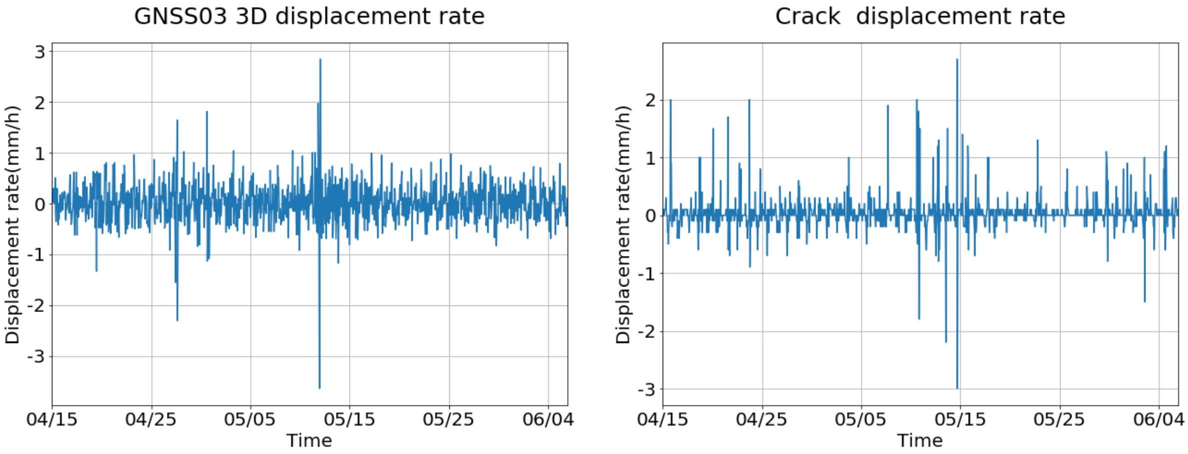


Figure 4. GNSS01/02/03 and Crack 3d displacement rate

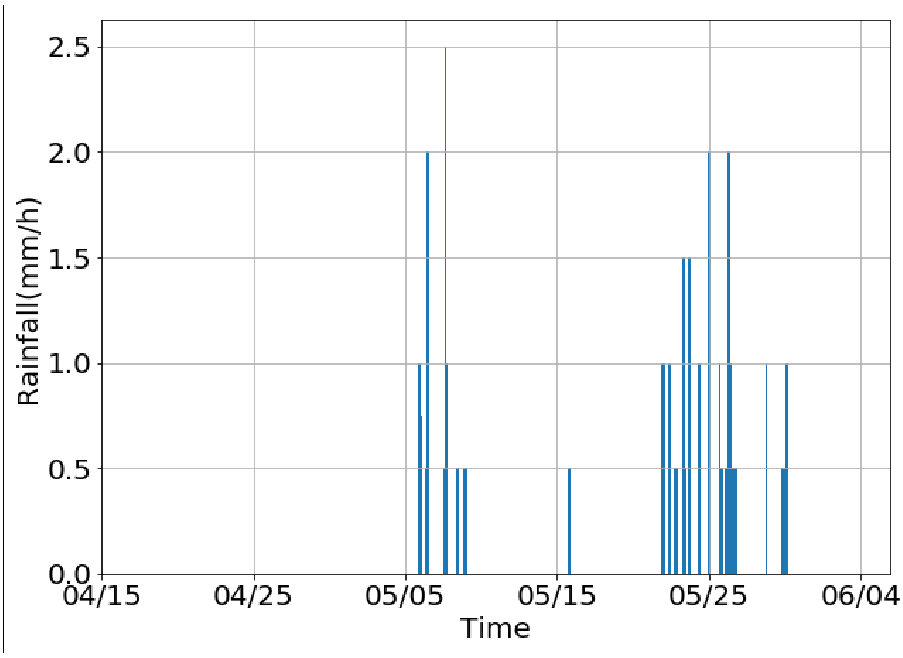


Figure 5. Rainfall per hour

4. Conclusion and Discussion

The challenges of conventional GNSS receivers in landslide monitoring applications were analyzed in this study. According to our survey, reasonable suggestions have been made for guiding the design of universal GNSS receivers. We also developed prototype universal GNSS receivers and tested them in the Heitai landslide. The testing data show that sub-millimeter precision is achievable with hourly solutions using the universal GNSS receivers. This is an indication that universal GNSS receivers are capable of capturing the trend of landslides. The tested GNSS time series also presented a good agreement with the crack gauge data. However, due to the limited field trial time, universal GNSS has not yet been tested for long-term deployment and complex environmental conditions. Further trials for long-term and complex environmental conditions will be conducted in future studies to improve and perfect the prototype.

References

[1] Hofmann B, Lichtenegger H, Wasle E 2008 GNSS-Global Navigation Satellite Systems: GPS, GLONASS Galileo and More[M] Berlin: Springe

[2] Wu B, Li Z and Xu S 2001 Application of GPS Satellite Positioning Technique to Monitoring of Landslides in Three Gorges Dam Earth Science: Journal of China University of Geosciences[J] 26(6): 648-652

[3] Wang L. 2014 A Study on Key Technology of High Precision GPS Monitoring for Geological Hazard [D] Xi'an: Chang'an University

[4] Zhang Q, Huang G, Wang L, et al. 2007 GPS Monitoring and Surveying on Land Subsidence and Land Fissure in Xi'an City[J] Journal of Engineering Geology 15(6): 828-833

[5] Ning J, Yao Y, Zhang X 2013 Review of the Development of Global Satellite Navigation System[J] Journal of Navigation and Positioning 1(1): 3-8

[6] Brunner FK, Woschitz H and Macheiner K 2007 Monitoring of deep-seated mass movements[C]. In Proceedings 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure British Columbia Canada

[7] Hastaoglu K, Du S 2011 Monitoring Koyulhisar landslide using rapid static GPS: a strategy to remove biases from vertical velocities[J] Natural hazards 58(3):1275-1294

[8] Kaloop M, Kim D 2016 De-noising of GPS structural monitoring observation error using wavelet analysis[J] Geomatics, Natural Hazards and Risk 7(2) : 804-825

[9] Zhang Q, Huang G and Yang C 2017 Precision space observation technique for geological hazard monitoring and early warning[J] Acta Geodaetica et Cartographica Sinica 46(10): 1300-1307

[10] Saito M 1969 Research on forecasting the time of occurrence of slope failure[J] Soils and Foundations 17(2): 29-38

[11] WANG, L, FENG, Y and GUO J 2016 Reliability control of single-epoch RTK ambiguity resolution. GPS Solutions 21(2) 591-604

[12] Bai Z, Zhang Q, Huang G, et al. 2019 Real-time BeiDou landslide monitoring technology of "light terminal plus industry cloud" [J] Acta Geodaetica et Cartographica Sinica 48(11): 1424-1429

[13] FAN S, GUO J and PENG X 2004 Applications of TEQC to GPS Data Pre-processing[J] Journal of Geomatics 29(2):33-35

[14] WANG D, ZHOU H, ZHANG H, et al. 2014 Influencing Factors Analysis and Multi-path Effects of Different Plant Cover Types on GPS Positioning Accuracy for Forest Fire Control[J] Journal of Central South University of Forestry and Technology 34(11):46-51

[15] SHEN N, CHEN L, LIU J, WANG L, TAO T, et al. 2019 A Review of Global Navigation Satellite System (GNSS)-based Dynamic Monitoring Technologies for Structural Health Monitoring. Remote Sensing 11(9) 1001

[16] XIE S, Xi Y 2002 Characteristics and Error Analysis of RTK[J] Engineering of Surveying and Mapping 11(2): 34-37

[17] Yuan L, Huang D, Ding X, et al. 2004 On the Influence of Signal Multipath Effects in GPS Carrier Phase Surveying[J] Acta Geodaetica et Cartographica Sinica 33(3): 210-215

[18] Huang G, Huang G, Du Y, et al. 2018 A lowcost real-time monitoring system for landslide deformation with BeiDou cloud[J] Journal of Engineering Geology 26(4): 1008-1016