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REVIEW

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GNSS techniques for real-time monitoring of landslides: a review

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Abstract

Currently, Global Navigation Satellite System (GNSS) Real-Time Kinematic positioning (RTK) and Precise Point Positioning (PPP) techniques are widely employed for real-time monitoring of landslides. However, both RTK and PPP monitoring techniques have their limitations, such as limited service coverage or long convergence times. PPP-RTK technique which integrates RTK and PPP is a novel approach for monitoring landslides with the advantages of rapid convergence, high-precision, and a wide service area. This study summarizes the limitations of RTK, PPP, and PPP-RTK monitoring techniques and suggests some improved strategies. Their performances are compared and analyzed using real monitoring data. The experiment results demonstrate that RTK is the best option for small-scale (the baseline distance < 15 km) and real-time landslide monitoring without considering the cost. PPP technique converges to centimeter-level accuracy in tens of minutes, only suitable for the stability analysis of reference stations. Over a large area (the baseline distance < 100 km), PPP-RTK can provide excellent horizontal accuracy and adapt the service range in response to the demand for monitoring accuracy, as the vertical accuracy is significantly impacted by the service range and elevation difference. Finally, the characteristics of three techniques are integrated to form a comprehensive landslide monitoring technique that considers intelligence, robustness, and real-time.

Keywords Landslide geohazards, RTK, PPP, PPP-RTK, Monitoring

Introduction

Under the joint action of internal and external factors, including gravity, earthquake, rainfall, and human activities, the rock-soil mass on a slope slides down in whole or in part along a specific sliding surface and direction, called landslide (Hungr et al., 2014; Huo et al., 2015). Since many countries are affected by landslide geohazards, their monitoring and early warning are crucial for preventing and controlling the casualties and property losses. Due to its advantages, including high-precision, all-weather, continuous three-dimensional positioning, and no requirement for communication, the Global Navigation Satellite System (GNSS) has been successfully applied in landslide monitoring since the 1990s. (Li, 1996; Gili et al., 2000; Matsushima and Takagi, 2000; Malet et al., 2002; Abidin et al., 2008; Wang et al., 2011). The two most common approaches for real-time landslide monitoring are the Real-Time Kinematic positioning (RTK) and Precise Point Positioning (PPP) technologies. RTK can achieve high-precision positioning by using the differential method to remove most errors with the assistance of a single station or regional multi-stations, which is particularly effective for the slow-varying landslide monitoring in real-time, but the cost is high and the operating distance is limited (Eyo et al., 2014). While the more affordable PPP does not require the support of a reference station and is often employed for deformation monitoring with centimeter-level accuracy, but needs external products and long convergence time (Zhang et al., 2017a).

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Wabbena et al. (2005) first proposed the PPP-RTK in 2005, which is based on the PPP model and utilizes precise atmospheric products to speed up the Ambiguity Resolution (AR). It takes full advantage of both PPP and RTK to accomplish real-time, wide-range, fast convergence, and high-precision positioning. It can provide users with a unified and seamless positioning service and offer a novel ideal for landslide monitoring.

This study first reviews the principles and application traits of RTK, PPP, and PPP-RTK techniques. Then, the monitoring performance with three techniques is analyzed using real monitoring data, and their advantages and disadvantages are summarized. Finally, an intelligent and robust real-time landslide monitoring system is proposed by integrating three techniques.

Methodology and application

RTK monitoring technique

RTK adopts the Double Difference (DD) model to eliminate most of the errors in the observations, leaving only the coordinate and ambiguities parameters to be estimated in a short baseline, as shown in Eq. (1).

$$\begin{cases} P_{rb,k}^{ij} = \rho_{rb}^{ij} + e_{rb,k}^{ij} \\ L_{rb,k}^{ij} = \rho_{rb}^{ij} + \lambda_k \cdot N_{rb,k}^{ij} + \epsilon_{rb,k}^{ij} \end{cases} \tag{1}$$

where P and L are the code and phase observations (m), respectively; i and j represent the non-reference and reference satellites, respectively; r and b represent the rover and reference stations, respectively; ρ denotes the geometric distance between satellite and receiver (m); k denotes the signal frequency; λ_k denotes the wavelength of the k-th signal frequency; N denotes the integer ambiguity in cycles; e and ϵ represent the sum of the measurement error, multipath error, and residual model error for the code and phase observations, respectively.

RTK has been widely used in landslide monitoring. For example, Squarzoni et al. (2005), Rawat et al. (2011), Wang et al. (2011), and Fastellini et al. (2011) used RTK to monitor and analyze different landslide areas, and the results showed that RTK can be utilized for real-time dynamic deformation monitoring in landslide geohazards under certain conditions. Meanwhile, Wang et al. (2015) investigated the combined BeiDou Navigation Satellite System (BDS) and Global Positioning System (GPS) RTK technique for land subsidence monitoring. The results showed that the accuracy of the BDS/GPS results is greatly improved compared to that of the BDS results. Zhang et al. (2017b) indicated from their tests that the static mode of RTK can obtain the millimeter-level positioning accuracy in an open environment with the horizontal and vertical positioning accuracy better than 5 mm and 10 mm, respectively, which means RTK can monitor and give an early warning of landslides (Han et al., 2018a; Gumüş and Selbesoglu 2019; Liu et al., 2022). But the distance between the monitoring station and reference stations must generally be within 15 km to enable real-time and high-precision monitoring (Zhang et al., 2022), which increases the operation cost somewhat. Additionally, it will lead to consequences, such as miscalculations (Du et al. 2020) when the reference station is changed.

The Network RTK (NRTK) was proposed to tackle the short-range problem of RTK, whose service range can be expanded from less than 15 km to hundreds of kilometers (Rizos and Han, 2003; Aponte et al., 2009; Gumüş and Selbesoglu 2019). The application of NRTK in landslide monitoring is still in the development stage. It has not been effectively applied due to the issues with the current NRTK, including inconsistent positioning accuracy over the monitoring region caused by tropospheric delay, which is one of the key factors for NRTK to achieve centimeter-level positioning accuracy, and difficulties in removing system differences between the monitoring station and reference station equipment.

Environmental occlusion, communication interruption, and signal interference are common in landslide monitoring scenes. The accuracy and reliability of conventional RTK technique cannot meet the needs of landslide monitoring, so it is necessary to improve the integrity and robustness of the positioning algorithm. The present improvement strategies of GNSS RTK landslide monitoring technique are summarized as follows:

(1) Complex environment modeling improves localization accuracy. Satellite signals are seriously affected in complex environments, therefore the traditional weighting method based on elevation angle is not feasible or even unavailable. The Azimuth-Dependent Elevation Weight (ADEW) model can be established based on navigation satellite observations, which can significantly improve the RTK ambiguity fixing rate and positioning accuracy (Han et al., 2018b). To solve the short-time signal interruption of some BDS Geostationary Orbit (GEO) satellites, the carrier phase double difference observation compensation algorithm of GEO satellites can be used to reduce the influence of the excessive positioning deviation caused by state changes (Du et al., 2019). For anomalies and gross errors in the observations, the anomaly detection method based on the prior information on the Signal-to-Noise Ratio (SNR) can be used for real-time detection (Liu et al., 2022). Tests show that the above strategies can achieve the monitoring accuracy of RTK fixed

solution better than 4mm in the east and north direction and 9mm in the up direction.

(2) Stability detection and correction of reference station. GNSS RTK technique relies on a stable reference station to obtain continuous and reliable monitoring sequence. When the reference station is unstable, its offset should be compensated or another stable reference station should be selected to obtain a continuous and reliable monitoring sequence. In real-time monitoring, synchronous RTK and asynchronous RTK algorithms can first be used to jointly monitor the stability of the reference station. After calculating the offset, the monitoring sequence can be corrected to avoid false early warning caused by the instability of the reference (Du et al., 2020). When the reference station has a large deviation or a long interruption, it can be switched to another reference station to ensure the continuity and reliability of monitoring results. Meanwhile, the offset caused by switching can be compensated and repaired according to the motion state of the new reference station (Wang et al., 2022).
(3) Communication delay and interruption compensation. Due to the delay generated in the process of data transmission, the data of RTK stations will not be synchronized. The asynchronous RTK algorithm can be used to reduce the impact of the base station delay on the whole monitoring results (Du, 2021). For the data interruption problem of the reference station, the missing data of the current epoch at reference station can be effectively estimated, and the relative positioning model can be built for positioning solution (Du et al., 2019). The experimental results show that the precision of plane monitoring can still be maintained in the order of centimeters when the reference data is interrupted for 30 min.
(4) Deformation sequence noise extraction algorithm. Due to the influence of the multipath errors, there is significant system noise in the RTK monitoring sequence, which must be corrected further. Sidereal Filtering (SF) is an effective technique to weaken multipath errors. It can be used to extract GNSS error trends to correct the positioning errors of adjacent two-day results (Han et al., 2018a). In order to extract accurate deformation information from complex monitoring sequences, the adaptive sliding window method based on sample collapse points can be used to process GNSS landslide monitoring sequences (Huang et al., 2022). Both simulation and experimental results show that this method can provide more adaptive and reliable deformation information for landslide early warning.

The above algorithms have been applied in many landslide projects, and it is proved that they can effectively improve the accuracy and reliability of GNSS RTK landslide monitoring technique in a complex environment.

PPP monitoring technique

The dual-frequency Ionosphere-Free (IF) observation model is typically used for PPP in landslide monitoring to reduce or eliminate the influence of first-order ionosphere delay and can be expressed as:

$$\begin{cases} P_{r,\mathrm{IF}}^{s} = \rho_r^s + t_r - t^s + m_{r,w}^{s} \cdot Z_{r,w} + b_{r,\mathrm{IF}} - b_{\mathrm{IF}}^{s} + e_{r,\mathrm{IF}}^{s} \\ L_{r,\mathrm{IF}}^{s} = \rho_r^s + t_r - t^s + m_{r,w}^{s} \cdot Z_{r,w} + B_{r,\mathrm{IF}} - B_{\mathrm{IF}}^{s} + \lambda_{\mathrm{IF}} N_{r,\mathrm{IF}}^{s} + \epsilon_{r,\mathrm{IF}}^{s} \end{cases} \tag{2}$$

where r and s represent the receiver and satellite, respectively; t_r and t^s denote the receiver and satellite clock errors (m), respectively; $Z_{r,w}$ and $m_{r,w}^{s}$ denote the zenith tropospheric wet delay (m) and mapping function, respectively; $b_{r,\mathrm{IF}}$ and b_{IF}^{s} are the code IF hardware delays of receiver and satellite (m), respectively; $B_{r,\mathrm{IF}}$ and B_{IF}^{s} are the phase IF hardware delays of receiver and satellite (m), respectively, and the other parameters are the same as before.

Compared with RTK, the PPP can make up for the shortcomings of RTK in terms of range, cost, and receiver configuration. Numerous studies have shown that the PPP can be applied to landslide monitoring. Wang et al. (2014) processed and analyzed the monitoring data of several monitoring points in a landslide area. The results showed that PPP can be used for real-time dynamic monitoring and early warning of landslide geohazards. Huang et al. (2017) compared RTK and PPP for monitoring a large landslide area. The study demonstrated that the positioning accuracy of RTK is better than 3 mm, which can be used for real-time monitoring of landslides, while the positioning accuracy of PPP can reach around 6 cm, which can be used for the maintenance of deformation data. Lin et al. (2021) used the multi-system combination PPP to obtain the surface displacements in a landslide area. The experiment showed that the solution can be converged to the centimeter-level within about 30 min, and the average internal consistent accuracy was better than 1 mm while the average external consistent accuracy was better than 5 cm after convergence, which meets the requirement of centimeter-level accuracy for rapid landslide monitoring.

Unfortunately, the most challenging issues with PPP in real-time and high-precision landslide monitoring are positioning accuracy and convergence speed, which makes the PPP only applicable to quasi-real-time and low-precision landslide monitoring. Even in a good observation environment, PPP still takes tens of minutes to achieve cm or even dm positioning accuracy and also needs to converge again when the data is interrupted or disturbed. In the area of landslides, the position of the reference station may change during the monitoring process because of unstable soil conditions. Since stable and reliable reference stations are crucial for the RTK realization, the stability and reliability of those stations can be routinely checked through the absolute positioning of PPP.

In landslide monitoring, the application of PPP technology should focus on the following strategies:

(1) Improved initialization and positioning performance. Compared with the RTK and other relative positioning techniques, PPP positioning performance is more affected by the environment. In monitoring applications, a combination of multi-system and multi-frequency PPP technique can significantly improve positioning accuracy and convergence time in an occlusion environment (Huang et al., 2018). In addition, by predicting residual information, the adaptive factor of the coordinate component can be established to construct a dynamic PPP algorithm that considers real-time position prediction information, and improve the utilization rate of prior parameter information, thus improving the real-time PPP positioning accuracy and convergence speed (Du et al., 2018).

(2) Stability monitoring of the reference stations. PPP is an absolute positioning technique, which is not affected by other stations in the landslide area. It can be used as one of the main techniques for stability analysis of reference stations. The stability analysis of PPP can be combined with periodic solutions (such as hourly solutions, daily solutions, etc.), real-time solutions, and postprocessing solutions for comprehensive judgmen. When a reference station is unstable, the PPP results of reference station can also be used as effective compensation for the other monitoring stations results of RTK to realize the overall correction of the whole landslide deformation. The long-term PPP monitoring results can also be used as a basis for establishing stable regions (Wang et al., 2013; Wang, 2013).

PPP-RTK monitoring technique

It is clear that RTK and PPP are not the best options for real-time and high-precision landslide monitoring when considering their limitations. According to the NRTK concept, the precise atmospheric products are extracted and modeled from the ground-based reference network to accelerate the AR for the Undifferenced and Uncombined (UDUC) PPP model. The fast convergence and high accuracy PPP-RTK will be realized in the real-time, high-rate, and high-dynamic scenario, providing a new method for landslide monitoring. Therefore, the precise tropospheric and ionospheric products are introduced into the UDUC PPP model as pseudo-observations, and the PPP-RTK model can be expressed as:

$$\begin{cases} P_{r,k}^{s} = \rho_r^s + t_r - t^s + \gamma_k \cdot \widehat{I}_{r,1}^s + m_{r,w}^s \cdot Z_{r,w} + b_{r,k} - b_k^s + e_{r,k}^s \\ L_{r,k}^{s} = \rho_r^s + t_r - t^s - \gamma_k \cdot \widehat{I}_{r,1}^s + m_{r,w}^s \cdot Z_{r,w} + B_{r,k} - B_k^s + \lambda_k N_{r,k}^s + \epsilon_{r,k}^s \\ \Delta T_r = Z_{r,w} - \tilde{Z}_{r,w} \\ \Delta I^s = \widehat{I}_{r,1}^s - \tilde{I}_{r_1,1}^s \end{cases} \tag{3}$$

where γ_k denotes the ionospheric mapping factor at the k-th frequency ($\gamma_k = f_1^2/f_k^2$); $I_{r,1}^s$ denotes the slant ionospheric delay at the frequency 1 (m); $\tilde{Z}_{r,w}$ and $\tilde{I}_{r_1,1}^s$ denote the tropospheric delay products and the ionospheric delay products for each satellite (m), respectively; ΔT_r and ΔI^s represent the difference between the estimated values and products' values for the troposphere and ionosphere, respectively.

The PPP-RTK has attracted the attention of many scholars. Teunissen et al. (2010) and Li et al. (2010) built the PPP-RTK model of regional atmospheric augmentation to achieve fast PPP-AR positioning services. Li et al. (2020) and Ma et al. (2020) conducted multi-system PPP-RTK experiments using a CORS reference network in a European region, respectively, and the results showed that PPP-RTK with various system combinations could conduct the PPP-AR within several epochs and significantly increase the positioning accuracy in East, North, Up (ENU) components. Real-time dynamic PPP-RTK tests were done by Wu et al. (2020) in a region of China, and the results demonstrated that the first fixed time was only approximately 36 s while Three Dimensions (3D) positioning accuracy was better than 3.3 cm with the horizontal positioning accuracy of 1.13 cm. With the progress in theoretical research, the PPP-RTK service systems start to be rapidly constructed and promoted, such as the Centimeter Level Augmentation Service (CLAS) provided by Quasi-Zenith Satellite System (QZSS) in Japan (Inaba et al., 2009), the CenterPoint RTX service by Trimble, the TerraStar-X service by NovAtel, the Marinestar G4+service by Fugro, and the SSRPOST service from GEO++, etc. All the above results demonstrate that PPP-RTK has the potential to provide real-time and high-precision landslide monitoring services.

At present, the global PPP-RTK technique is in the stage of research and development. There are some application issues to be addressed, such as complex algorithms, high hardware requirements, and lack of monitoring standards. There are no examples of successful applications. But we believe that PPP-RTK technique has good potential in real-time landslide monitoring. However, the following technical problems need particular attention:

(1) Fast and reliable transmission of regional corrections. The performance of PPP-RTK is much related to the data quality and data sampling rate provided by the server (Zhang et al., 2020). How to build a high-precision atmospheric model and control the data transmission volume are the important problems to be solved. Fortunately, a new fifth generation of mobile technologies (5G) assisted GNSS PPP-RTK system is designed, which is expected to meet the demands for rapid transmission of massive and high-precision atmospheric error corrections and other corrections in the PPP-RTK monitoring application (Asari et al., 2020).

(2) Landslide monitoring integrity technique. GNSS landslide monitoring and early warning are concerned with life safety, so the reliability of monitoring results must be guaranteed. However, the influencing factors of PPP-RTK correction data are complex, and the errors of any visible satellite observations and its correction data may have a great impact on the final positioning results. At present, PPP-RTK service providers have no mature definition and products for integrity monitoring. In order to apply the universality to landslide monitoring, it is urgent to carry out research on GNSS PPP-RTK monitoring integrity technique.

The advantages and disadvantages of various GNSS high-precision monitoring techniques are given in Table 1 (Zhang et al., 2020; Zhang et al., 2022). It is apparent that RTK has the shortest response time and is usually applied to capture the sudden deformation of landslides in real-time. As for the NRTK, it is more suitable for monitoring large areas where there are a number of reference stations. In contrast, PPP is frequently used to periodically check the stability of reference stations because it requires a considerable convergence time to get high-precision absolute coordinates. PPP-RTK is not limited by the baseline distance and can be used to monitor wide landslide areas, but the monitoring accuracy is lower than that of RTK.

Experiments and results analysis

Data description and processing strategy

To evaluate the monitoring performance of the three techniques, a monitoring station and 15 reference stations from the ground-based augmentation network in a landslide region of Shaanxi Province, China, on June 6, 2021, were chosen. The distribution of those stations is shown in Fig. 1, where the triangular symbols denote the monitoring station, and the circles denote the reference stations. There is a self-built reference station near the monitoring station, about 800 m away, which is convenient for the RTK experiments and is not shown in Fig. 1. This study designed three PPP-RTK service solutions to provide precise atmospheric products for adequately reflecting the service range of PPP-RTK, as shown in Table 2. All ground-based augmentation stations are jointly calculated for the AR products while considering the integrity of the AR products. The parameter strategies of the three techniques in this experiment are shown in Table 3.

Table 1 Advantages and disadvantages of several high-precision GNSS monitoring technologies

Type	Accuracy range (mm)	Time	Applicable landslide scenarios
RTK	Horizontal: $\pm(3-8)$ Vertical: $\pm(5-15)$	≤ 10 s	It is suitable for real-time and high-precision monitoring of landslides within one area, but the baseline distance is less than 15 km and reference stations are necessary
NRTK	Horizontal: $\pm(5-10)$ Vertical: $\pm(8-20)$	≤ 10 s	It is suitable for real-time and high-precision monitoring landslides in multiple areas. The baseline distance is less than 100 km, and independent reference stations are unnecessary
PPP	Horizontal: $\pm(20-50)$ Vertical: $\pm(50-100)$	≥ 30 min	It is suitable for the stability monitoring of reference stations without the distance limitation, but precise products are necessary
PPP-RTK	Horizontal: $\pm(5-10)$ Vertical: $\pm(8-20)$	≤ 10 s	It is suitable for monitoring large landslide areas, and the service is more flexible

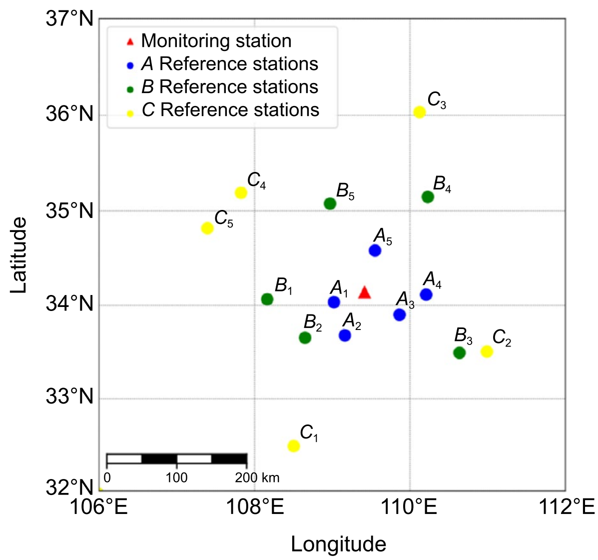

Fig. 1 Distribution of the landslide monitoring station and reference stations

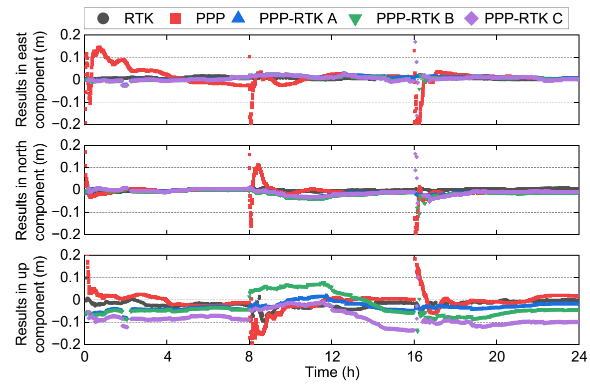

Fig. 2 Positioning errors in ENU components for the three techniques

Monitoring performance

The convergence of the real-time positioning is achieved when the positioning errors in the east (E), north (N), and up (U) components become smaller than 10 cm for ten consecutive epochs. After convergence, the Root Mean Square (RMS) of the ENU components represents the positioning accuracy. What is required for landslide monitoring is displacement information. The coordinates at the time when the monitoring station was set up are utilized as references in this study. The parameter filter is reset every 8 hours to directly reflect the monitoring performance of each technique, and Fig. 2 illustrates the positioning errors in ENU components for RTK, PPP, and PPP-RTK at the landslide monitoring station. Due to the atmospheric parameters being highly correlated with spatial distance, the ionospheric and tropospheric delays in the short baseline can be eliminated, making the AR faster. As a result, the RTK positioning results are almost fixed at the first epoch, and the positioning accuracy in ENU components is at millimeter-level after convergence. In contrast, the PPP takes almost tens of minutes to converge to the centimeter-level in ENU components, making real-time and high-precision monitoring difficult. The PPP-RTK, based on the UDUC PPP model, uses precise atmospheric products as the constraints to accomplish a quick AR comparable to the RTK. In Fig. 2, the

Table 2 Three PPP-RTK service solutions

Solution	Stations	Average distance to the monitoring station
A	A_1 to A_5	About 45 km
B	B_1 to B_5	About 75 km
C	C_1 to C_5	About 190 km

Table 3 Parameter strategies for three techniques

Parameter items	Strategies		
	RTK	PPP	PPP-RTK
Observations model	DD	IF	UDUC
Frequency	GPS dual-frequency		
Observation weighting	0.3 m and 0.003 m for code and phase		
Sampling rate	30 s		
Cutoff angle	15°		
Orbits and clocks	Broadcast ephemeris	Real-time products from CNES	
Zenith wet tropospheric delay	No	Estimated	Atmospheric products
Ionospheric delay	No	Estimated	Atmospheric products
Satellite hardware delay	DD	AR products	AR products

Table 4 Positioning accuracy statistics for the three techniques

Technology	Results in east component (cm)	Results in north component (cm)	Results in up component (cm)	Results in horizontal component (cm)	Results in 3D component (cm)
RTK	0.95	0.32	1.99	1.00	2.23
PPP	3.15	0.61	1.83	3.21	3.69
PPP-RTK A	0.73	0.40	4.34	0.83	4.42
PPP-RTK B	0.65	0.40	4.33	0.76	4.40
PPP-RTK C	0.63	0.38	9.38	0.73	9.41

PPP-RTK for three service solutions (45 km to 190 km) can reach convergence in several epochs, and the accuracy in the EN components after convergence is almost the same as the RTK, whereas the accuracy in the *U* component decreases significantly as the range increases but remains at the centimeter-level.

The positioning accuracy statistics of the daily solution for the three techniques are listed in Table 4. The horizontal accuracy of RTK and PPP-RTK is better than 1 cm, whereas that of the PPP without AR is about 3 cm due to the *E* component absorbing more ambiguity residuals. In the *U* component, the accuracy of both RTK and PPP is better than 2 cm, while the accuracy of PPP-RTK decreases from 4.3 to 9.3 cm as the service area increases.

To further find out the reasons for the decrease of PPP-RTK in vertical accuracy with the service range, the atmospheric bias between the products and "real" values is shown in Fig. 3, where the atmospheric "real" values are derived from the monitoring station using the PPP-AR with the forward and backward filters. With the service range increasing from 45 km to 190 km, the tropospheric accuracy shows a decreasing trend, but its overall accuracy is maintained within 3 cm, while the ionospheric accuracy drops from 1–2 to 4–10 cm, indicating a stronger correlation between ionosphere delay and distance. The *N* component is primarily influenced by the satellite's planar geometric distribution, which tends to have higher accuracy, whereas the *E* component is strongly constrained by AR to improve accuracy significantly, so that the *U* component is forced to absorb most of the atmospheric products' residuals, resulting in a decrease in vertical accuracy as the service range increases. In this research, the traditional weighting method based on the inversed distance is employed to generate atmospheric products, and the empirical variance thresholds are used to constrain the atmospheric products, introducing the atmospheric products' residuals into the *U* component. It is worth noting that the ionospheric accuracy of the three PPP-RTK solutions from hours 13 to 19 has a relatively large bias, which can be attributable to ionospheric anomalies in the area at that time of day and reduce the PPP-RTK positioning performance in the same period.

The first convergence time is one of the most crucial indicators for monitoring techniques. The parameter filter is reset every 5 min for the monitoring station. The atmospheric anomalies data from hours 13 to 19 are excluded, and a total of 216 data samples are collected and scaled with the convergence of various periods, as shown in Fig. 4. RTK can reach the first convergence time with 100% in less than 2 min and 88% in less than 1 min. As can be seen from the percentage of the first convergence time within 1 min (82.4%, 73.1%, and 29.6%) and over 2 min (6%, 9.3%, and 44%), the convergence performance of the three PPP-RTK service solutions (45, 75, and 190 km) is also closely related to the service range, which is consistent with the conclusion about positioning accuracy. From this experiment, the horizontal accuracy of PPP-RTK can match the same millimeter-level as RTK regardless of the service solutions, while the vertical accuracy decreases noticeably with the increase of the service range but also maintains at the centimeter-level. The percentage of the first convergence time within 1 min in the service range of 100 km can reach about 70%.

Summary

According to the experiment results, RTK can be used extensively in small-scale landslide monitoring because it can quickly and accurately obtain positioning results with accuracy at millimeter-level. But it cannot independently determine absolute coordinates and must rely on a reference station, which is relatively expensive. PPP can directly get absolute coordinates without a reference station, but PPP is only useful for slow-varying and near real-time landslide monitoring because the monitoring accuracy can be achieved at centimeter-level after tens of minutes. PPP-RTK can adjust the service range based on the monitoring precision required to control the costs, but the service range has a greater impact on its vertical accuracy. In response to the above limitations, we propose a combined PPP-RTK monitoring technique

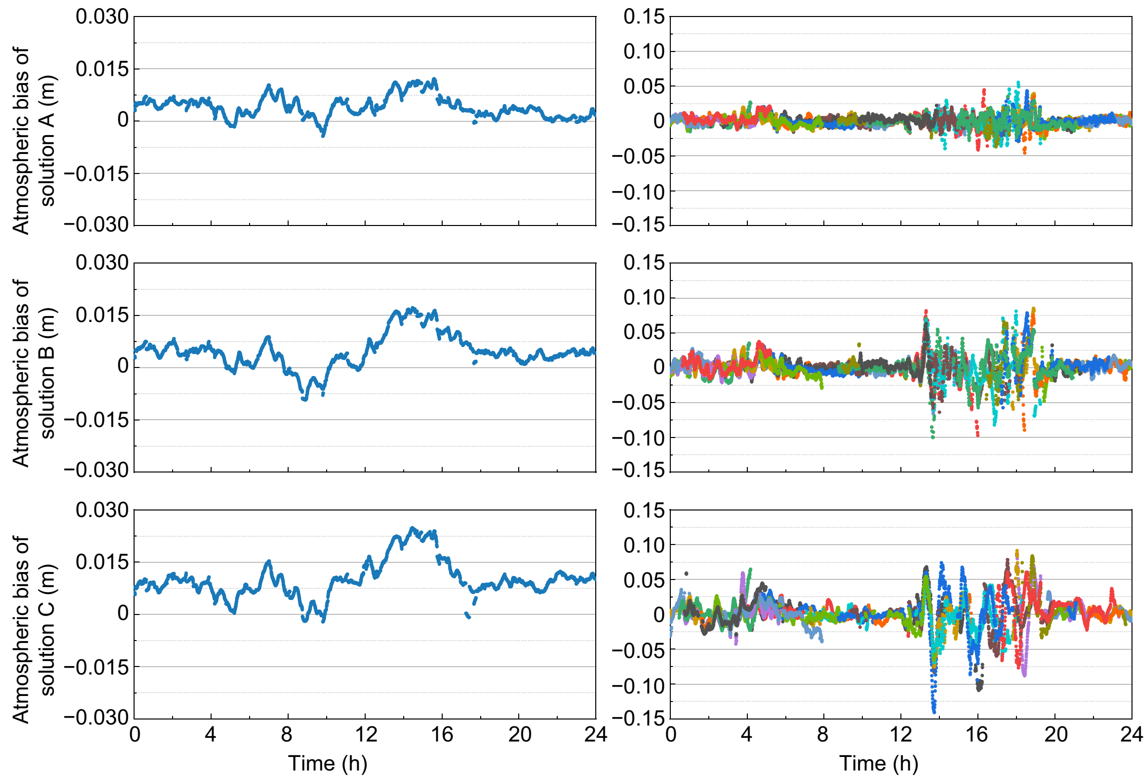

Fig. 3 Atmospheric bias of the three PPP-RTK solutions (left column: troposphere; right column: ionosphere)

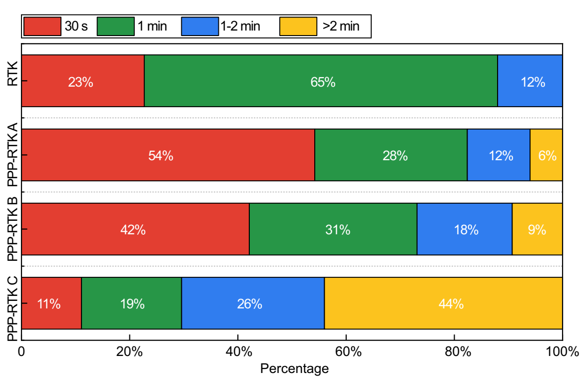

Fig. 4 Ratio of 216 samples for RTK and three PPP-RTK solutions

that considers intelligence, robustness, and real-time. The main ideas of the proposed technique are as follows, and the corresponding data processing steps are shown in Fig. 5.

(1) Data preprocessing. The cloud platform receives and synchronizes the data streams from the monitoring area in real-time, organizes and classifies the data for storage, and simultaneously performs real-time quality control for the data.

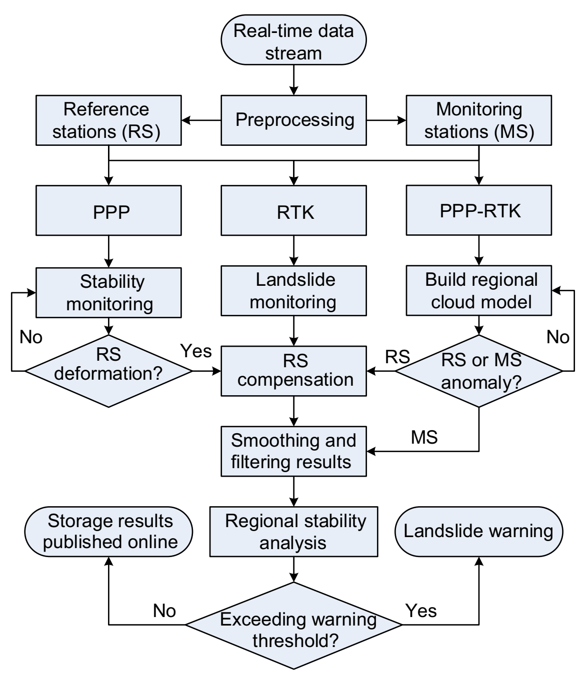

Fig. 5 Processing steps of a combined PPP/RTK/PPP-RTK monitoring technique for landslide geohazards

(2) PPP monitoring technique. Using real-time products from International GNSS Service (IGS)/ International GNSS Monitoring and Assessment System (IGMAS) and reference station data, the absolute positioning for various demands (real-time solutions, hourly solutions, and daily solutions) is conducted to check the coordinates of the reference stations, and instantly determine the corrections for the deformation of the reference stations.
(3) PPP-RTK monitoring technique. Based on the reference stations and stable monitoring stations in the monitoring area, building a landslide monitoring regional enhancement cloud model to generate multi-regional enhancement information, such as the a priori deformation and coordinate constraint information for monitoring station, the a priori water vapor constraint information, and so on.
(4) RTK monitoring technique. Combining environmental modeling and enhancement information, RTK monitoring with additional constraints is performed for each monitoring station. While the cloud platform performs real-time monitoring for the landslide region, the high-precision and quasi-static positioning service also updates the previous deformation data for each monitoring station.
(5) Real-time forecasting and early warning. The PPP-RTK monitoring results are used to supplement and enhance the integrity and reliability of RTK monitoring results, which will further improve the accuracy of the real-time forecasting values for the monitoring stations, and then realize real-time warning for the landslide area when the reliable forecasting values exceed the warning threshold.

Conclusions and outlook

This paper first introduces the principles and application traits of three monitoring techniques, i.e., RTK, PPP, and PPP-RTK in landslide geohazards. Then, the monitoring performance of three techniques is analyzed using real data. Finally, their advantages and disadvantages are summarized. The main conclusions are as follows:

(1) RTK in landslide monitoring mostly employs the short baseline mode, which can quickly obtain monitoring results with accuracy at millimeter-level under stable and reliable reference stations, but its service range is limited. Therefore, the short baseline RTK is the best option for real-time and high-precision landslide monitoring when the cost is not considered.
(2) Although the PPP needs tens of minutes to obtain stable centimeter-level monitoring accuracy, it has the advantages of no reference station required, low cost, and absolute coordinates, which is directly applicable to landslide monitoring in a large range, slow-variable, and near real-time. Meanwhile, PPP can assist RTK to check the stability of reference stations.
(3) PPP-RTK takes full advantage of both RTK and PPP, allowing users to select different service ranges per their specific needs for landslide monitoring accuracy. However, on a large-scale, its vertical accuracy decreases noticeably as distance increases due to the strong correlation between the atmosphere delay and spatial distance. It still faces many problems, especially about the atmosphere, that need to be solved urgently.
(4) In landslide monitoring, the advantages of the three monitoring techniques should be integrated. The PPP is used to monitor the deformation of reference stations, the PPP-RTK is employed to generate the regional enhancement information, and the RTK with additional constraints from the enhancement information is conducted to obtain real-time and high-precision results. By combing the above techniques, the reliability and accuracy of the results for monitoring stations will be maximized to ensure accurate landslide warnings.

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Author contributions
GH proposed the research, GH and SD developed theories and wrote the paper. SD conducted the computations. DW helped improve the manuscript. All the authors polished and approved the final manuscript.

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Availability of data and materials
Extended figures and results are available on reasonable request.

Declarations

Competing interests
The authors declare that they have no conflict of interest.

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