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ORIGINAL PAPER

Real-time landslide monitoring of Pubugou hydropower resettlement zone using continuous GPS

Ruya Xiao · Xiufeng He

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Abstract The rapid growth of hydropower in China raises concerns about the related resettlement issues. In order to obtain the real-time surface displacement data of the potential landslides, a continuous GPS observation network is established in new Hanyuan County where more than 100,000 people are resettled due to the Pubugou hydropower engineering in southwest China. GPS multi-antenna switch devices are used to reduce the hardware investment, and the results show that the RMSs of the two horizontal components are 2 and <4 mm for the vertical component. This level of accuracy is comparable to the conventional "one antenna with one receiver" GPS observation mode. The comparison between the displacements evaluated by GPS monitoring method and digital inclinometer shows consistency, and this indicates that GPS could be a reliable complement to traditional ground movement monitoring methods. No catastrophic landslide failures happened since the resettlement was completed. We captured a remarkable movement in August 2011, and this proves that the continuous GPS monitoring system could be used to detect early indications of rapid displacement and for disaster warning.

Keywords Resettlement zone · Landslide · Real-time monitoring · GPS multi-antenna · Digital inclinometer

1 Introduction

China has committed to cut carbon dioxide emissions per unit of gross domestic product (GDP) by 40–45 % of 2005 levels by 2020 (Yi et al. 2011). To achieve the target of

R. Xiao · X. He (✉)
Institute of Satellite Navigation and Spatial Information System, Hohai University, Nanjing, China
e-mail: xfhe@hhu.edu.cn

R. Xiao
e-mail: ruya.xiao@hhu.edu.cn

increasing the share of nonfossil fuels in primary energy consumption to 15 %, renewable energy development is encouraged.

By the end of 2010, there are thousands of hydropower stations in China that are always located in gorges accompanied with geological hazards such as landslides and mudslides. However, active landslides are always hazardous to work on, and traditional field monitoring, even if taken regularly, might not be able to detect signs of impending failure. Moreover, catastrophic movements often occur during heavy rainfalls with poor visibility. Real-time (or actually near-real-time) monitoring can provide insight into and help us better understand the dynamics of landslide movements which may be critical to protecting lives and properties.

To study and predict the dynamic behavior of landslides as well as to avoid casualties due to sudden failures, continuous monitoring is indispensable. The simplest way is to measure surface movements and analyze the kinematics of landslides. Global positioning system (GPS) can provide 24-h continuous readings on position, velocity in nearly all weather conditions (He et al. 2007). Practice in the past decades showed that GPS may be the most suitable technique for measuring surface displacements in unstable areas with high accuracy, which is comparable to conventional survey techniques. The usefulness of GPS in continuous landslide monitoring has been confirmed. Gili et al. (2000) applied GPS to monitoring the displacement of landslide whose result was compared with the classical surveying methods (theodolite, electronic distance meter (EDM)). They pointed out that a direct line of sight is not necessary in GPS survey, which can work in all weather conditions. Besides, it allows a larger coverage with similar accuracy. Moss (2000) found that the rapid-static GPS can provide a new quick method to determine the 3D map of landslide. The study showed that a field accuracy of approximately 10 mm can be achieved. Malet et al. (2002) attempted to measure the displacement of the landslide with GPS for a long time and determined the experimental accuracy. They found that the accuracy can reach 2.7 mm (north–south) and 2.2 mm (east–west) for horizontal and 5.0 mm for vertical components for 1-h sessions. Thus, GPS is applicable to the continuous monitoring landslides or man-made structures with small and slow displacements ($\sim$5 mm per day). Coe et al. (2003) studied a very old landslide, the Slumgullion landslide, and found that in the 3.5-year GPS observation period, the landslide was continuously moving, but the velocity varied on a seasonal basis. The GPS result offered new knowledge for the landslide research. Squarzoni et al. (2005) demonstrated the capabilities of low-cost single-frequency GPS equipment for the landslide monitoring, and the results are validated with EDM measurements. Besides, the GPS data analysis provided precise mapping of the boundaries of the landslide area and the distinct zones. Bruckl et al. (2006) utilized photogrammetric, GPS and geophysical data to derive a constraint on the kinematics of the sagging process, and the displacements observed have shown a uniform movement of the whole slope. A research project aimed at assessing the landslide hazard and susceptibility in Italy was implemented by Tagliavini et al. (2007). The accuracy of the new values was verified using GPS and inclinometric measurement in the high Cordevole river basin. Peyret et al. (2008) quantified the spatial and temporal evolution of the deformation of Kahrod landslides in Iran. A time series of GPS recordings is presented, and differential InSAR results spanning the same period were analyzed. Three-dimensional deformation can be got from rapid-static GPS surveys, and the InSAR deformation amplitude is in complete consistency with the one estimated by GPS. In the study of Hastaoglu and Sanli (2011), the landslide monitoring using rapid-static GPS was investigated. They processed the data using both rapid-static and static methods, and the results indicated the biases occurring on GPS rapid-static vertical velocity estimates. Wang (2012) employed both campaign rapid-static and continuous static GPS to monitor a creeping landslide movements in Puerto Rico. The relationship between the deformation and rainfall was also discussed. Calcaterra et al. (2012) reported experimental data in two landslides in the Italian Southern Apennines. The surface and deep displacements were evaluated by means of GPS stations and inclinometers, respectively. Results showed that surface displacement measured by GPS is consistent with the surface displacement evaluated by means of inclinometer measurements.

In the second part of this paper, we briefly introduce the background of the hydropower station and study area conditions. Section 3 describes the GPS monitoring system established in Hanyuan. Section 4 presents the results obtained by conventional and GPS multi-antenna monitoring method. Comparison between GPS and digital inclinometers as well as a landslide case study is also shown. Finally, Section 5 concludes the paper.

2 Site conditions

Pubugou Hydropower Station is one of the large-scale hydropower projects located in southwest China, the middle reaches of Dadu River. As a symbol of China Western Development Project and key project of National Tenth-Five Year Plan, Pubugou Hydropower Station with a 186-m high core wall rock-fill dam was built for power generation, flood control and sediment retention.

The backwater length of Pubugou Hydropower Station is 72 km, and several towns are inundated. About 105,000 residents (92,500 from Hanyuan County) need to be relocated, which in resettlement scale is next only to the Three Gorges and Xiaolangdi in modern hydropower projects of China.

The main resettlement zone, new Hanyuan County, locates on Luobogang hillock (Fig. 1). Three ancient landslides, namely Luanshigang, Futang and Kangjiaping, were identified by geologists. The stability of the hill slopes is adversely affected by the water surface rising and fluctuation in the reservoir. The rise of the groundwater level results in the reduction in the effective stress of the soils and the loss of soil shear strength. Large-scale catastrophic movements may be triggered when the shear stress exceeds the shear resistance of the materials (Sassa et al. 2005a, b). During Wenchuan Earthquake in 2008, the resettlement zone suffered huge damage and the situation became more complicated and unforeseeable.

In 2009 and 2010, two landslide failures occurred in Hanyuan and caused great loss of lives and properties (Fig. 2a). Hundreds of retaining walls were built to minimize large

Fig. 1 Panoramic photograph of the new Hanyuan County on the hillock. The *blue lines* indicate the approximate boundary of the main landslides, and the *red lines* represent three ditches through the whole resettlement zone

Fig. 2 Landslide failure in 2010 and cracks observed on the retaining walls

movement of the landslides. But, cracks were soon observed on the retaining walls (Fig. 2b, c, d). The displacements of landslides cause continuous damage to buildings and infrastructures. Monitoring is essential to predict the behavior of landslides because it not only can determine the rate of landslide movement but also can detect early indications of catastrophic movements.

3 GPS monitoring system

Because of its highly automated and less labor intensive than traditional geodetic survey techniques, GPS is considered as one of the best techniques for deformation monitoring (Mora et al. 2003; Psimoulis et al. 2007; Stoica et al. 2008; Su et al. 2009; Yin et al. 2010b). It provides a 3-D displacement vector at the specific point where we set up the antenna (Guglielmino et al. 2011). The spatial resolution depends on density of the antenna and thus is always low. Therefore, GPS does have disadvantages, the major drawback being the high cost associated with placing a permanent GPS receiver at each monitoring point. The GPS multi-antenna switch (GMS) is a dedicated electronic timed switching device connecting one receiver with several antennas mounted at different monitoring sites, which significantly reduces the number of receivers required (He et al. 2004). The receiver makes standard pseudo-range and carrier-phase observations for each antenna (Chen et al. 2000; Ding et al. 2003; He et al. 2011).

Nevertheless, real-time landslide monitoring system requires not only selecting reasonable monitoring methods and installing effective monitoring networks, but also high-grade hardware and software supports (Yin et al. 2010a). These include automated

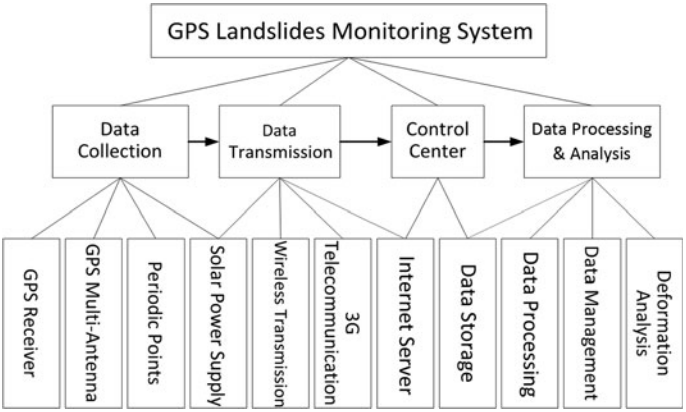

Fig. 3 GPS landslide monitoring system

monitoring and data acquisition instruments, means of efficient and high-speed data transmission, automatic data processing, large central data storage and distribution of monitoring information. As shown in Fig. 3, the GPS landslide monitoring system established in Hanyuan resettlement zone includes four elements: data collection, data transmission, control center, and modeling and analysis.

3.1 GPS data collection

Twenty-eight continuous and about 90 periodic monitoring stations are installed in the whole county. The continuous monitoring stations operate 7×24 h, and engineers will periodically check the other stations. Considering the distance between the monitoring stations, we choose 10 continuous monitoring stations to link up with two multi-antenna controllers.

The layout scheme of the GPS monitoring stations was carefully designed based on field investigation before implementation. Generally, we place the monitoring stations on the retaining walls where the observation conditions are suitable. In Fig. 4 and Table 1, we can see the distribution profiles. In key areas with more buildings, the density of GPS monitoring stations is also higher. The pin and triangle marks (Fig. 4) represent continuous and periodic monitoring stations, respectively; meanwhile, we make distinctions in colors (Table 1) among different profiles. The underlined station names in Table 1 represent the multi-antenna stations, and the italic ones mean that on these sites 3G technology is used for data transmission.

3.2 Data transmission

Each site needs to transfer massive amount of data in real time to the control center that is always located within a town area. A public wireless phone network or other media may be used. In this case, we chose the wireless transmission and third-generation telecommunication technologies.

The wireless transmission system possesses higher power, and the transmission range covers more than 50 km. Wireless transmission is the most preferred option when there is direct line of sight. The receiver at the control center will store all the data simultaneously

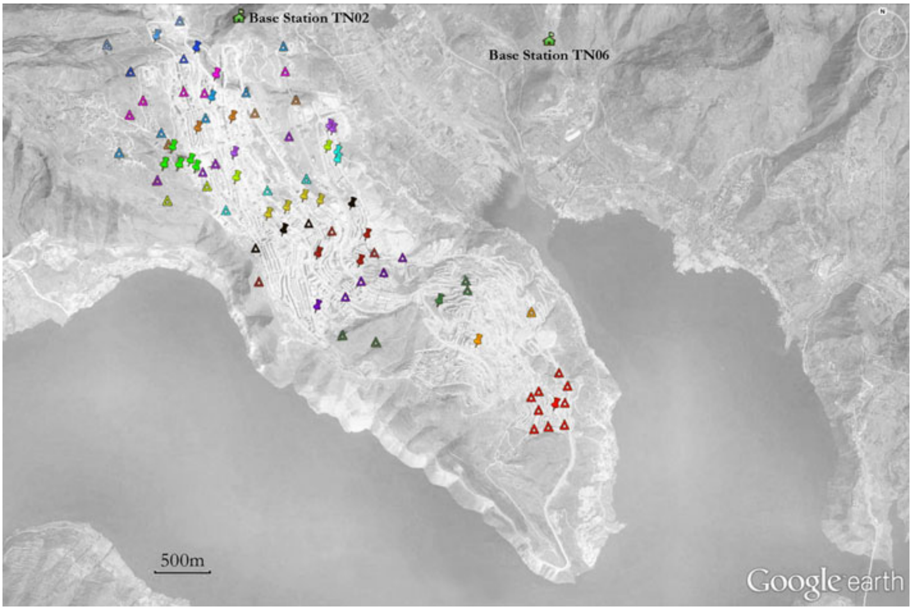

Fig. 4 Distribution of the GPS monitoring stations in new Hanyuan County, Luobogang. Detailed information for different *colors* and *marks* was shown in Table 1 below. The map comes from Google Earth™

Table 1 Detailed information for the monitoring stations

Profile	Approximate Trend (North by East, Degree)	Continuous Monitoring	Mark	Periodic Station	Mark
1	62.77	TP1-2 TP1-4		TP1-1 TP1-3	
2	64.54	TP2-2 TP2-3 TP-2-4 TP2-5		NONE	---
3	68.09	TP3-5 TP3-6		TP3-1 TP3-3 TP3-4	
4	68.09	TP4-2 TP4-4		TP4-1 TP7	
5	68.09	TP5-3 TP5-5 TP27		TP5-1 TP5-2 TP5-4 TP6	
6	68.09	TP6-1 TP6-3		TP6-4 TP5 TP28	
7	58.28	TP7-3		TP7-1 TP7-2 TP7-5 TP4 TP30	
8	68.12	TP8-4		TP8-1 TP8-2 TP8-3 TP3 TP29	
9	79.99	TP9-3		TP9-2 TP2	
10	50.4	TP10-1		TP10-3 TP1	
11	118.3	TP11-1 TP11-2 TP11-3 TP11-4 TP11-5		NONE	---
12	58.03	***TP12-2*** TP12-4 TP12-5		TP12-1 TP12-3 TP26	
13	44.52	TP13-2		TP13-3 TP13-4 TP13-5 TP13-6	
14	53.21	***TP14-2***		TP14-3 TP14-4 TP17 TP18	
15	52.88	***TP15-2***		TP24	
16	57.44	***TPSR-5***		TPSR-1 TPSR-2 TPSR-3 TPSR-4 TPSR-6 TPSR-7 TPSR-8 TPSR-9 TP23	

and check for the data integrity. The data will be saved at the site when the transmission device is down.

The power to the GPS receivers and data transmission devices is supplied by the uninterruptible power system (UPS) at the monitoring sites. Although solar panels are all

Fig. 5 Photographs of continuous monitoring sites

employed at each site, power from the city electricity grid is always the preferred option when it is available. The UPS will warn the CPU when the voltage is too low, and the data in transient memory will be saved in local computer hard disks immediately (Fig. 5).

3.3 Control center

The central servers housed inside the control center are connected with a local area network (LAN). The control center serves two main functions: Firstly, it receives the monitoring data, verifies the integrity of the data, assesses the status of all the devices and issues control commands to the field stations. Secondly, the control center is responsible for data analysis, storage of processed data, deformation modeling, forecast and transmission of information.

Figure 6 demonstrates the automatic data processing flowchart. Raw data is backed up on the Internet server after being received at the control center. An additional data-splitting and reuniting process is required since the observations from sequential working GPS multi-antenna stations are continuously recorded in the receiver. The coordinates and the deformations of the monitoring points are determined with respect to the reference station. Thus, simultaneous data from both base and monitoring stations is required for data processing. The deformation surveying system is regarded as a slowly moving kinematic problem, and the initial coordinates of the monitoring points with centimeter accuracy between two observation sessions can be used for rapid integer ambiguity fixing. Kalman filter is used as sequential adjustment algorithm, and more details of the data processing strategies can be found in the reference (Chen et al. 2000). The database is the key part of the data processing software, and all the results can be inquired and displayed for further analysis in the decision support module.

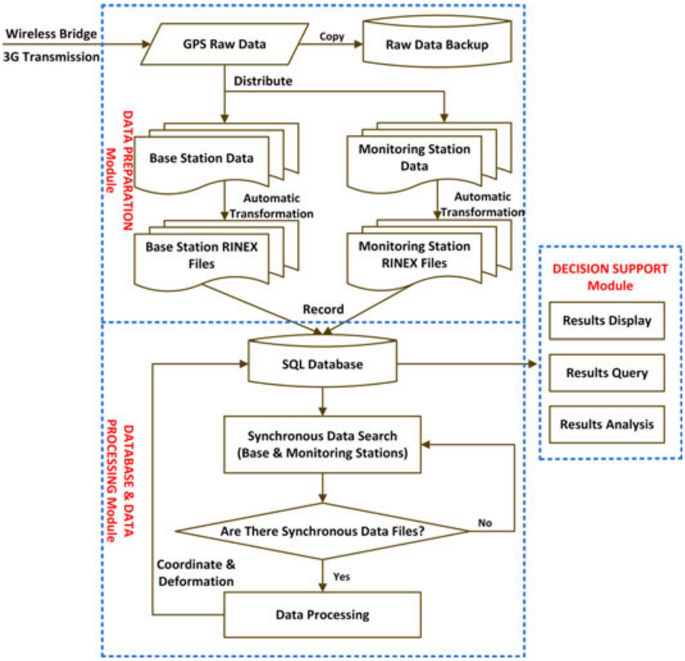

Fig. 6 Overview of the automatic data processing flowchart

4 Results and analysis

The system began trial operation and field testing in May 2011 when the conventional continuous GPS monitoring stations were established. The reliability and stability of hardware and software were tested; in the meantime, the data processing precision was analyzed. After troubleshooting and recalculating some initial coordinates, normal operation commenced at the end of December 2011. Meanwhile, the sites with multi-antenna receivers were put into practice. The performance of the conventional GPS monitoring and multi-antenna stations is shown here.

4.1 Conventional continuous GPS monitoring

The technology of utilizing conventional continuous GPS to monitor the landslide is mature. Changes in the baseline length between the stable base station TN02 and the monitoring station are calculated. All the deformations are transformed into local east, north, up coordinates with whose origin located at TN02 base station.

Here, we show the daily resolution results in Fig. 7 from typical monitoring stations during the period of June to October 2011. As the observation data are acquired at the control center per hour, the 24-h continuous session is split into hourly sessions. Three-component baseline lengths and coordinate changes in hourly resolution are automatically calculated, and the daily average of the hourly resolutions reduces random errors as well as thermal movements of the antennas and steel bolt. The maximum displacement variations in TP9-3 and TP7-3 were no more than ±2 and ±3 mm in the horizontal and vertical components, respectively. The readings illustrate there were no significant movements at

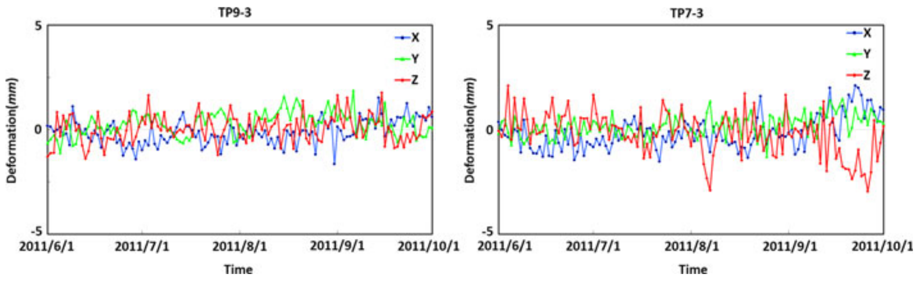

Fig. 7 Conventional continuous GPS monitoring results

the two monitoring stations during the entire time range. In other words, the areas these stations represent are quite stable without abnormal deformation. The fluctuation in the *Z* direction shown in Fig. 7 is more obvious than in the other two directions since GPS survey can generate more precise results in the horizontal component than in the vertical component.

4.2 GPS multi-antenna monitoring

Since the observations from sequential working GPS multi-antenna sites are continuously recorded in the receiver, an additional data-splitting procedure is required before normal data processing. Although the deformation readings obtained from these sites are not continuous as compared to the system operating under the "single-antenna" mode (due to less data points collected at these antennas), nevertheless, this system is capable of monitoring slow-moving ground mass.

Daily resolution results from TP4-4 and TP11-3 that belong to the two different multi-antenna controllers are plotted in Fig. 8. Generally, the distance between antenna on the monitoring site and multi-antenna receiver, always larger than that of the conventional method, ranges from hundreds of meters to several kilometers. To reduce attenuation in transmission, signal amplifiers are used on coaxial cable connecting antennas to the multi-antenna controllers. The displacement variations fluctuate from −3 to 3 mm in the horizontal components and −5 to 5 mm in the vertical components, revealing more obvious than the results from conventional continuous GPS monitoring mode. Although the amplifier will suppress noise and increase signal-to-noise ratio (SNR), the signal is still a little bit noisier than that of conventional method, which results in more obvious fluctuation (Fig. 8).

Root mean square (RMS) of the daily displacement time series can be considered as an index to evaluate the precision of the GPS measurements (Eckl et al. 2001; Soler et al. 2006; Dogan 2007). The maximum, minimum and average RMSs of the sites mentioned above are listed in Table 2.

The accuracy of conventional monitoring mode for daily resolution reaches <1 mm for horizontal and within 3.0 mm for vertical components. In terms of RMSs, there is no significant difference between the multi-antenna and the conventional single-antenna scheme. Accuracy of 2 mm horizontally and 4 mm vertically can be achieved through GPS multi-antenna monitoring. The slight loss of accuracy is attributed to the noisier signal recorded in the shared receiver. Since the same level of accuracy from conventional monitoring method can also be obtained via multi-antenna method, the latter is obviously a more economical and cost-effective solution in deformation monitoring.

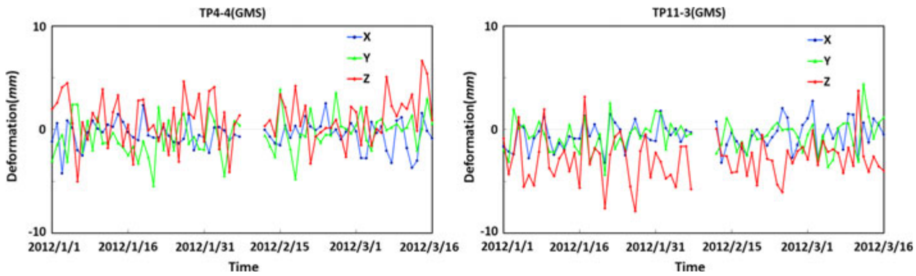

Fig. 8 GPS multi-antenna monitoring results. Regular device maintenance results in missing data

Table 2 Measurement error at each monitoring site

Monitoring sites	Max/Min/Average (mm)		
	X	Y	Z
TP9-3	1.38/0.73/0.91	1.29/0.69/0.85	3.20/1.78/2.25
TP7-3	1.76/0.75/0.99	1.87/0.72/0.93	4.26/1.84/2.45
TP4-4(GMS)	2.19/0.73/1.11	2.14/0.71/1.04	5.13/1.8/2.63
TP11-3(GMS)	4.31/0.82/1.26	3.09/0.72/1.21	8.27/1.94/3.04

4.3 GPS results versus digital inclinometer data

The engineers also collected subsurface deformation data using RST MEMS digital inclinometer system periodically at GPS monitoring stations. Measurements were taken along two perpendicular directions, both A and B axes, from the depth of 0.5 to 28.5 m at 0.5-m intervals. Periodic measurements by inclinometer can provide us with the profile of relative displacements along the whole casing length. However, as the inclinometer readings are only taken at a specific time interval, variations in the rate of movements that might occur during this time interval cannot be recorded (Calcaterra et al. 2012). The total displacements at the depth of 0.5 m (which is the measurement point closest to the ground surface) were compared with the results obtained from two GPS stations, TP9-3 and TP7-3. The results are shown in Fig. 9.

It should be pointed out that the displacements derived from GPS and digital inclinometer should not be compared directly. GPS monitoring station measures the ground

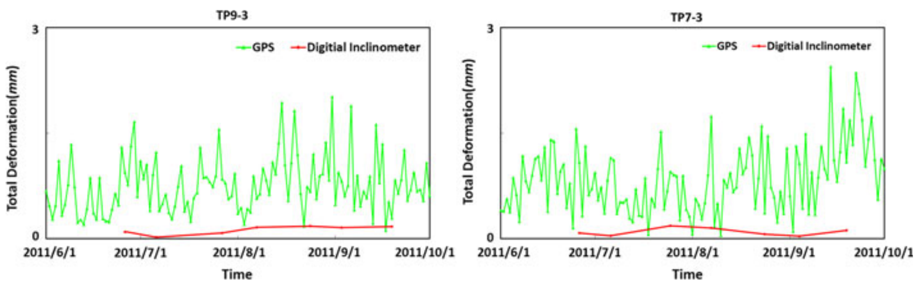

Fig. 9 The comparison between GPS and digital inclinometer results

surface movements, while the inclinometer measures the subsurface deformations. In addition, the two systems interact differently with the soil mass, and each system is also affected by its own systematic and casual errors (Gili et al. 2000; Calcaterra et al. 2012). Nevertheless, as evidenced from the monitoring readings of TP9-3 and TP7-3 shown in Fig. 9, displacement trends from the GPS monitoring station and digital inclinometer stations are highly consistent even though actual magnitudes are different. It can be concluded that the GPS monitoring system is capable of monitoring slow-moving ground mass.

4.4 Landslide case study

The GPS landslide monitoring system was designed to detect millimeter-level movements where antennas were placed. Figure 10 illustrates the movements on the three components captured by the system in August 2011.

The result for the site TP6-1 showed a significant displacement that occurred in August, and it became stable again in September. The site moves by almost 15 mm to the north (positive values on *Y* direction in Fig. 10) as well as 5 mm to the west (negative values on *X* direction in Fig. 10) within no more than 20 days.

Figure 11 shows the comparison between the GPS and digital inclinometer results on TP6-1 during the unstable period. Although the magnitude from digital inclinometer is smaller than that from GPS monitoring, the displacement trend and time of occurrence captured by both methods match well. Generally, the displacement amplitude on the ground surface will be larger than that in subsurface. Thus, the different results produced by the two methods revealing movement at different depths (0 m from GPS and 0.5 m from inclinometer) hold water.

Field investigations were conducted shortly after the displacement was discovered. Construction activities near the site TP6-1 influenced the stability of the local ground. A mound of soil heaped in the south results in much more load and pressure to the retaining wall. We believe this is the main reason for the monitoring site moving north. Later, we recalculated the coordinates of TP6-1 as the initial input for data processing. As can be seen from Fig. 12, the area regained stability in early 2012, which also reveals that the displacement on the monitoring site is only a temporary and nonpersistent phenomenon.

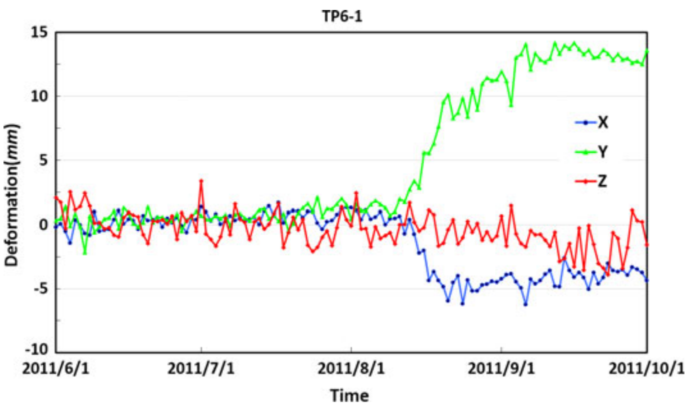

Fig. 10 The movements captured by the landslide monitoring system during August 2011

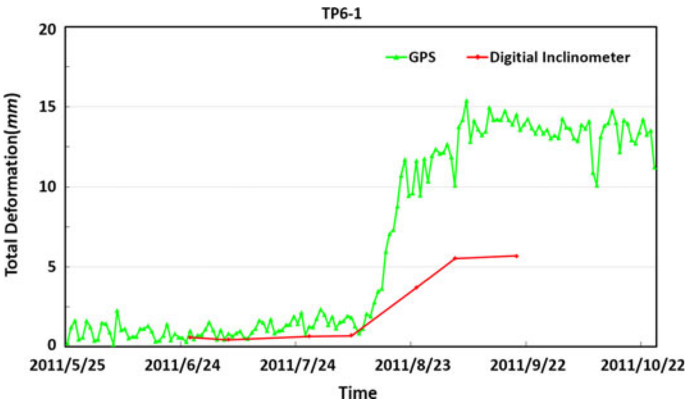

Fig. 11 GPS versus digital inclinometer results for the displacement on TP6-1 in August 2011

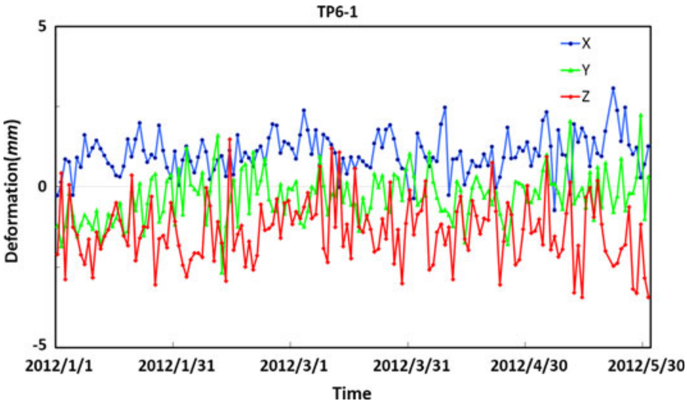

Fig. 12 GPS monitoring results on TP6-1 in 2012

5 Conclusions

The real-time measurement of ground surface movements over Hanyuan is one of the important field monitoring activities which would provide advance warning against sudden failures. The accuracy of conventional GPS monitoring stations established in Hanyuan reaches less than 1 mm horizontally and within 3.0 mm vertically. Accuracy of 2 mm for horizontal and 4 mm for vertical components can be achieved through GPS multi-antenna monitoring. Since there is no significant accuracy difference between the results from the two methods, the latter is obviously a more economical solution.

The comparison between GPS and digital inclinometer results shows a high consistency in respect of the displacement trend. This suggests that the GPS monitoring system can be employed as a complement to the traditional ground movement monitoring methods.

Fortunately, no catastrophic landslide failures happened since the resettlement was completed. The monitoring system can capture unusual movements and detect early indications of rapid displacement. Remarkable movements of ground surface could be reported to the responsible engineers immediately so that appropriate risk mitigation measures could be implemented as soon as possible.

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