Research review of large deformation monitoring of rock and soil

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Abstract. Landslide is a kind of extremely harmful global geological disaster, which often cause serious property losses and casualties. Therefore, scientific and effective landslide monitoring is of great significance for disaster prevention and mitigation. This article introduces the status quo and development trend of landslide deformation monitoring technology in the form of a review. Firstly, the deformation monitoring technologies about rock and soil are summarized and evaluated from three aspects: air (GNSS technology, InSAR technology), sky (UAV technology, 3D laser scanning), and ground (MEMS and Optical fiber technology). Then, the article focuses on ground (deep inclinometer) of the above three aspects, mainly talks about some advanced monitoring technologies used in inclinometer such as fiber Bragg grating and MEMS. The research results show that the inclinometer based on fiber Bragg grating has high monitoring accuracy with 1 με, and the data can be transmitted in time without electromagnetic interference. The MEMS-based inclinometer can measure the vertical tilt angle and horizontal torsion angle, which can realize the three-dimensional deformation monitoring in space. The above research and development of the novel inclinometer provide an effective mean for rock and soil deformation monitoring. Finally, the article summarizes the realization of accurate and reliable monitoring of landslide deformation.

1. Introduction
As a mountainous country, China's mountains account for about two-thirds of the country's area. The mountainous terrain is complex and prone to landslides[1–5]. China is one of the countries in the world with extremely frequent collapse and landslide disasters. According to the 2020 National Geological Disaster Bulletin, a total of 7,840 geological disasters occurred in China in 2020, of which landslide disasters were the most serious, with 4,810 occurrences.

Landslide is a manifestation of the instability of a rock-soil mass with a certain inclined surface, that is, a phenomenon in which a part of the rock-soil mass slides relative to another part of the rock-soil mass. Landslides are a kind of geological disasters, causing huge losses to industrial and agricultural production as well as people's lives, and sometimes even cause devastating disasters. For example, on December 20, 2015, a large-scale landslide occurred in Hengtaiyu Industrial Park in Guangming District, Shenzhen, Guangdong. The accident caused 73 deaths and 4 missing, and the economic loss was as high as 880 million yuan. On June 24, 2017, a large-scale landslide occurred in Xinmo Village, Maoxian County, Aba Prefecture, Sichuan Province. The landslide body was about 18 million square meters, which blocked the river for 2 kilometers and caused 118 people to lose contact. On July 23, 2019, a landslide occurred in Shuicheng County, Liupanshui City, Guizhou Province. The accident caused 21 houses to be buried, 42 people were killed and 9 people lost contact. Once these
engineering problems occur, they will cause heavy casualties and economic losses, and engineering repairs are also costly. Therefore, before an accident occurs, it is very important to monitor the deformation of the rock and soil structure to ensure the safety and stability of the rock and soil engineering structure[6–11].

2. Research status of landslide deformation monitoring methods

Since the middle of the 20th century, humans have begun to conduct research on landslide monitoring technology. With the continuous advancement of science and technology, a series of effective methods for monitoring large deformation of landslides have been developed. This paper proposes that the early identification of major geological hazards can be carried out by constructing a multi-source three-dimensional observation system based on space-borne platforms (GNSS, InSAR)[12,13], aviation platforms (UAV, 3D laser scanning)[14,15], and ground platforms (slope surface and internal observation)[16–22]. Firstly, with the help of high-resolution optical images and InSAR to identify areas that have undergone significant deformation and destruction in history, a regional and general survey of hidden dangers of major geological disasters can be realized. Then, with the help of LiDAR and UAV, detailed surveys of topography, rock mass structures, and hidden hazards can be conducted, so as to realize detailed investigation of hidden hazards of major geological hazards. Finally, through the review of the ground survey and the observation of the surface and the interior of the slope, the results of the general survey and detailed survey are confirmed or excluded, and the verification of the hidden dangers of major geological disasters is realized. The whole process is shown in Figure 1.

2.1. Landslide deformation monitoring based on space satellite remote sensing technology

2.1.1. GNSS monitoring technology.

GNSS is the abbreviation of Global Navigation Satellite System and the collective name of all satellite navigation systems[23]. GNSS technology has the powerful functions of all-round and real-time positioning and navigation in the air, sky and ground. It has high flexibility and meets different accuracy requirements[24,25]. With the adopting of carrier waves, the positioning accuracy of phase difference technology can reach mm-level or even better than mm-level. The GNSS receiver can obtain longitude, latitude and elevation information, and use the difference between the real-time
value and the initial value to reflect the displacement of the target point, so as to realize the measurement of rock and soil mass\cite{26}. As the number of satellites continues to increase, the accuracy of observations will continue to improve\cite{27}. GNSS monitoring technology will be of great benefit to the early identification of hidden geological hazards.

2.1.2. InSAR technology.

Synthetic aperture radar technology (SAR technology)\cite{28,29} is a high-performance radar monitoring device using microwave as the medium. The data collected by Synthetic Aperture Radar Interferometry (InSAR) can be used to generate three-dimensional terrain information on the earth's surface. Xu et al\cite{30} focus on using multiple remote sensing datasets to monitor movement of the Gold Basin landslide, the monitoring results of InSAR are shown in Figure 2. This technology has the advantages of all-time, all-weather, wide coverage, and high spatial resolution. InSAR can measure small ground motions in principle, and the measurement range covers a continuous large area, so it can be considered as a potential ideal tool for studying the deformation of geotechnical engineering\cite{31,32}. The time series InSAR technology can be effective capturing the surface deformation before the occurrence of the landslide, especially capturing the large-area deformation and the accelerated deformation signal before the landslide losing stability\cite{33,34}. This provides a very effective means for identifying and discovering the hidden dangers of the landslide in the slow creep deformation in advance.

![Figure 2. Monitoring results of InSAR\cite{30}](image)

2.2. Landslide deformation monitoring based on aerial observation technology

2.2.1. UAV technology.
UAVs can be equipped with laser scanning systems, camera systems, infrared camera systems and other equipment for high-altitude operations. The three-dimensional space distance relationship between two points in the monitoring area can be arbitrarily measured[35]. In order to ensure the integrity of the final measurement results, the vertical scanning data is fused with the UAV scanning data, and the relevant auxiliary software is used to filter the point cloud to quickly classify ground and non-ground points. After manual classification, the high-precision DEM model is built according to ground point data. Based on the DEM model, the landslide body can be extracted at any vertical and horizontal sections, the area and volume of landslide body can be calculated, and the data can be compared with early data to realize regional change monitoring[36–39]. Our team used UAV to construct three-dimensional topographic map in the Three Gorges reservoir area, and the results are shown in Figure 3. The cost of this technology is low, and the 3D point cloud model of the scene can be automatically restored directly from the 2D image without relying on the prior information of any ground control points.

![Figure 3. (a) Route planning (b) UAV aerial survey terrain construction](image)

2.3. Landslide deformation monitoring based on ground measurement method

2.3.1. MEMS-based tilt angle monitoring technology.

MEMS technology is a 21st century cutting-edge technology based on micro/nanotechnology. It refers to the design, processing, manufacturing, measurement and control of micro/nano materials. It can integrate mechanical components, optical systems, drive components, and electrical control systems into a micro system. It has the characteristics of miniaturization, diversification, stabilization and integration. It is widely used in the monitoring of landslides[1,40–42].

The MEMS-based high-sensitivity inclinometer sensor has a resolution of 0.0025°, a sensitivity of 0.0085°, and can sense a tilt movement of 0.01°. Equipped with a wireless modem, it can reach a maximum of 600m wireless communication in an open area with good conditions. The MEMS inclinometer sensor and wireless communication instrument are low-energy-consumption equipments, four dry battery power supply can achieve continuous work for 12 months (measurement interval: 10 minutes). To a certain extent, it can greatly reduce on-site maintenance work. As shown in Figure 4(a).

The team installed the MEMS surface inclinometer at 30°57′44.8″N 109°21′19.6″E in the Xinpu area of the Three Gorges Reservoir. The installation of the inclinometer is shown in Figure 4(b). Firstly, inserting a 1m long pole into the ground with an insertion depth of about 60cm. Then, installing the MEMS surface inclinometer on the pole, and collecting the value of inclination of the ground. Finally, the collected signal is transmitted to the host through the wireless modem, and the host transmits the data to the user remotely through the 4G gateway, realizing remote real-time online monitoring.
3. Some advanced monitoring technologies used in inclinometer

Summarized technologies above are GNSS, InSAR, UAV, three-dimensional laser scanning, surface tilter, inclinometer etc, which are important means of slope deformation monitoring. Among these technologies, inclinometer is an effective mean of underground monitoring, which is of great significance for judging slope instability. The following will focus on several types of inclinometers.

3.1. FBG inclinometer

Based on the FBG technology, the inclinometer is designed. A PVC rod with a cross-sectional diameter of 20 mm and a length of 1000 mm was used to carve a groove with a depth of 2 mm on the bus, and the fiber was drawn straight into the groove in advance, and then pasted with epoxy resin glue to make the inclinometer. The inclinometer is shown in the Figure 5(a) below.
Figure 5. (a) Schematic diagram of inclinometer (unit: mm) (b) Installation of the inclinometer

The epoxy resin can bond the optical fiber and the PVC well, so that the optical fiber can measure the strain distribution on the surface of the PVC rod well. When monitoring the slope, drill holes in the corresponding positions of the slope in advance and insert the PVC rod vertically into the hole, as shown in Figure 5(b). When the slope slides under the action of load, the PVC rod has good elastic property and can deform well with the soil. According to the strain measured by optical fiber, the displacement of the PVC rod can be calculated to reflect the deformation of the slope. The monitoring accuracy can reach a micro strain.

3.2. MEMS inclinometer
A new type of inclinometer integrating inclination and torsion measurement. The inclinometer is composed of multiple measuring units, which are composed of a package protective layer, a MEMS micro-electromechanical system, a pulley, a connecting device and an articulating device. The multiple measuring units in the inclinometer can rotate with each other, and they can also twist themselves. The MEMS microelectromechanical system is placed inside the encapsulation protection layer to form the basic form of the measurement unit. Four pulleys are installed through the connecting device and the hinge device. When in use, the pulley is fitted on the sliding track of the inclinometer tube to realize the up and down movement of the inclinometer. The inclinometer device can simultaneously measure the deep displacement of the rock and soil body and the torsion angle of the inclinometer. Through an iterative algorithm, the torsion and tilt of any inclinometer unit can be obtained, and the deep deformation of the rock and soil body can be accurately calculated. The device has a simple structure, it is easy to use and has good application prospects.

4. Conclusions
There are many factors leading to landslides, multiple monitoring methods are required to be performed simultaneously. This article sorts out various methods currently used in landslide monitoring. The main conclusions are listed in the following aspects:

1. GNSS and InSAR technologies have the characteristics of wide monitoring range, which can be used to realize the general survey of regional scanning.
2. UAV can realize the construction of three-dimensional topographic maps, so it is applicable for the detailed investigation of the high-risk landslide.
3. On-site investigation, ground and internal monitoring are used to understand the evolution and stability of landslides. As a result, it can be used to finally confirm major landslide hazards.
4. Through the coordinated use of multiple monitoring methods, a hierarchical comprehensive early warning system is established to achieve the purpose of monitoring and early warning of landslides.

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