Research on the analysis of factors affecting the deformation of the Great Wall in multimodal synergy

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Abstract

This study is dedicated to the conservation of the Ming Great Wall in Beijing, and adopts a multi-integrated monitoring method aimed at monitoring and evaluating the impact of environmental vibration hazards on the deformation of the Great Wall. By coupling remote sensing technology and ground monitoring data, integrating multiple sources of data, including ground displacement monitoring system based on inertial measurement unit and global navigation satellite system, as well as synthetic aperture radar interferometry technology, we obtain high-precision vibration data and displacement information for comparison and analysis, and reveal the potential impacts of environmental factors on the Great Wall's legacy, so that we can realize continuous and dynamic monitoring and control on the Great Wall's structural stability and its surrounding environment. It also reveals the potential impacts of environmental factors on the Great Wall heritage and realizes the continuous dynamic monitoring of the Great Wall's structural stability and its surrounding environment. The results of the study show that this comprehensive monitoring method can efficiently identify and warn of vibration sources that may cause damage to the Great Wall, providing scientific basis and technical support for the protection of the Great Wall.

1. Introduction

The Great Wall is the largest and most widely distributed cultural heritage in China, and was inscribed on the World Heritage List in 1987. The Juyongguan Great Wall is part of the Ming Great Wall, with a total length of 4,142 meters, located in Changping District of Beijing. Currently, the Great Wall is facing serious damage problems. Due to long-term erosion by wind and rain, destruction by plants and animals, and human activities, the Great Wall, especially the rammed-earth wall, has suffered serious diseases, such as cracks, collapses, and spalling, and some sections have even disappeared without a trace (Yang Jie et al, 2021; Du Yumin et al, 2016; Gu Haiping, 2021; Yuan Zhongxia et al, 2023). These damages not only affect the integrity and authenticity of the Great Wall, but also bring great challenges to the conservation work (Du Yumin et al, 2016). Therefore, it is necessary to adopt preventive protection for the Great Wall, and the preventive protection strategy emphasizes taking measures before the damage occurs, of which environmental vibration hazard monitoring is a key part (Yuan Zhongxia et al, 2023). In complex terrain and bad weather, traditional monitoring techniques are difficult to implement, while GNSS technology is preferred because of its stability and accuracy, especially in the early warning and assessment of major disasters. In addition, GNSS can directly obtain the 3D vector deformation of the landslide surface, which provides accurate results for the monitoring of large-scale linear cultural heritage such as the Great Wall (Zhao Yousong, 2011).
Although the monitoring technologies are constantly advancing, such as 3D laser scanning, long-distance crack observer, "UAV+satellite remote sensing technology", and InSAR technology (including the MTInSAR method) have been applied to the Great Wall monitoring (Zhang Qin et al, 2022; Guan Haiping, 2021; Liu Junjun et al, 2016), and these technologies provide new paths to analyze the deformation factors of the Great Wall, they are still facing challenges, such as monitoring lag, monitoring range cannot cover the whole area and other problems (Sun Chenhong et al, 2020; He Haiying et al, 2021; Hang X et al, 2021). In this paper, we will introduce a multi-integrated monitoring method, which integrates multiple monitoring techniques to realize the analysis of the influence factors of the Great Wall deformation.

2. Method

The deformation monitoring of the Great Wall integrates InSAR, GNSS and accelerometer technologies to achieve real-time and efficient monitoring. By installing accelerometers at key points of the Great Wall, the vibration frequency and amplitude characteristics of the Great Wall can be monitored in real time; at the same time, GNSS receivers are used to obtain millimeter-level positioning accuracy and track the three-dimensional displacement changes of key points; combined with InSAR technology to extract the phase information of satellite radar images and generate large-scale deformation time series maps. Through a multi-source data fusion framework, the spatio-temporal characteristics of the three technologies are complementary: accelerometers, GNSS and InSAR form a "high-frequency - continuous - wide-area" monitoring system.The specific technology roadmap is shown in Figure 1.

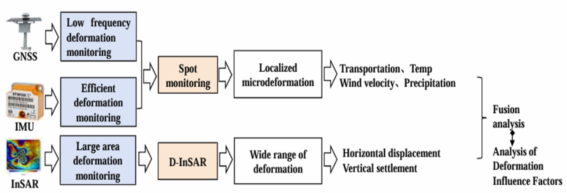

Figure 1. Overall technology roadmap.

2.1 Principles of D-InSAR technology

D-InSAR (Differential Interferometry) is a technique to obtain surface deformation information by comparing multi-scene SAR images before and after surface deformation. It removes the topographic phase and finally extracts the surface deformation phase, i.e., the surface deformation information, by differentiating the interferograms containing both topographic and deformation information from the interferograms containing

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only topographic information (Crosetto M et al, 2020). The overall interferometric phase of the interferogram can be expressed as follows:

$$\varphi_{\text{tol}} = \varphi_{\text{flat}} + \varphi_{\text{topo}} + \varphi_{\text{defo}} + \varphi_{\text{orbit}} + \varphi_{\text{atm}} + \varphi_{\text{noise}} \quad (1)$$

where φ_{tol} = overall interfering phase
φ_{flat} = flat earth effect phase
φ_{topo} = terrain phase
φ_{defo} = deformation phase
φ_{orbit} = phase due to orbital error
φ_{atm} = phase due to atmospheric delay
φ_{noise} = phase due to noise

2.2 Principles of environmental vibration monitoring technology

Environmental vibration monitoring of the Great Wall based on GNSS+IMU technology is mainly realized by fusing the high-precision positional information provided by the Global Navigation Satellite System (GNSS) with the high-frequency dynamic motion information provided by Inertial Measurement Units (IMUs).GNSS tracks the displacement of the Great Wall, while the IMUs capture the dynamic changes induced by vibration in real time. Although IMUs provide high-frequency data, their independent use over a long period of time can lead to error accumulation; GNSS, although highly accurate, is slow to update and may be affected by signaling problems (Gaoge Hu et al, 2018). By fusing the data from both, the advantages of each can be utilized to achieve more accurate motion monitoring of the Great Wall and timely detection and warning of possible structural risks.

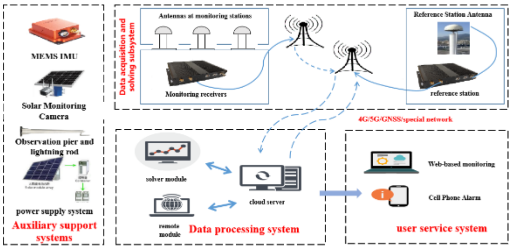


Figure 2. Schematic diagram of environmental vibration monitoring technology.

Accelerometers monitor the storage of raw data errors (correctable) and integration drift errors, commonly used frequency domain integration to avoid. Its data integration to get the displacement, divided into hardware and software method, hardware method accuracy is limited, software method contains time domain and frequency domain integration. Time-domain integration directly through the acceleration of two integrals to obtain the displacement results, generally using the trapezoidal formula to calculate, can be expressed in the following form:

$$a_m(t) = a_t + C + \varepsilon$$

The original acceleration observation contains interference errors where $a_m(t)$ is the original measurement value of the accelerometer; a_t is the true value of acceleration; C is the zero drift, which is related to the hardware performance of the sensor and ε is affected by the external real-time environment such as temperature; and refers to the random errors caused by the internal factors of the instrument, which usually include quantization noise, white noise and random wandering, etc. The following formula is shown below, where and are the initial values of velocity and displacement, and D is the unknown constant term of the integration result. The v_t velocity and displacement S_t are obtained by integrating the acceleration observations twice in the time domain as shown in the following equation, where v_0 and S_0 are the initial values of the velocity and displacement and D is the unknown constant term part of the integration result (Baiqiang Zhang et al, 2017).

$$v_t = v_0 + \int a_m(t)dt = v_0 + \int a_t dt + \int \varepsilon dt + Cdt + D$$

$$s_t = s_0 + \int v_t dt$$

3. Study area

3.1 Geographic overview

Juyongguan is located in Changping District, Beijing, about 15.5 kilometers northwest of Changping City. The location is shown in Figure 3.

Figure 3. Geographic location of Juyongguan.

3.2 Overview of equipment installation

Vibration disaster monitoring equipment for the Great Wall was installed at four locations of the Great Wall in Changping District, including one reference station and three monitoring stations.

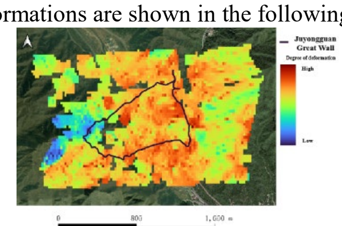
Figure 4. Installation of equipment at the reference station (left) and monitoring station (right).

Figure 5. Schematic diagram of the location of the Great Wall deformation monitoring station.

4. Analysis of results

4.1 Analysis of vehicle traffic factors

The Sentienl-1 images of the area around the Juyongguan Great Wall for the time period of 01/25/2023-06/06/2023 and 06/06/2023-03/12/2023 are selected to do two-period D-InSAR, and their deformations are shown in the following figures.



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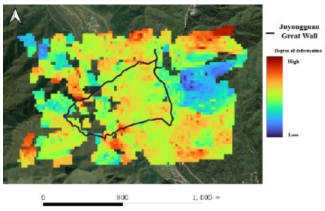

Figure 6. Deformation map of the area around the Juyongguan Great Wall (the upper sub-map is the first period data, the lower sub-map is the second period data).

One of the areas where significant deformation occurred is shown below:

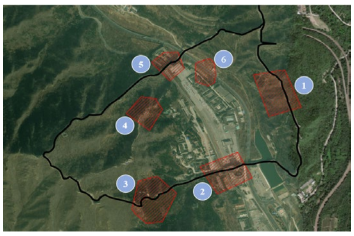

Figure 7. Labeling of areas with large deformation from January to June.

Figure 8. Labeling of areas with large deformation from June to December.

Combined with the information of traffic flow collected by the equipment installed in the field, the comparative analysis found that most of the locations with obvious deformation are located near the highway during the peak traffic flow period, and the rate of deformation in these three places is the most obvious among all the deformed areas, so it can be presumed that the vibration caused by the passage of vehicles has a greater impact on the deformation of the Great Wall, and the Great Wall in this area needs irregular inspection and a certain degree of maintenance.

4.2 Temperature factor analysis

In order to analyze the effect of temperature on the deformation of the Great Wall, the accelerometer data in hot weather and cold weather were selected for comparison and analysis. No. 4292 is used as a case study to analyze the effect of temperature on the deformation of the Great Wall. The selected dates are all windless and clear conditions to exclude the effects of rainfall and wind speed, and the IMU equipment used is equipped with a temperature compensation function, which attenuates the errors caused by temperature changes that result in different accuracy of the data collected by the IMU. The acceleration on August 18, 2023 (a hot day) and the acceleration on February 2, 2023 (a cold day) are shown below:

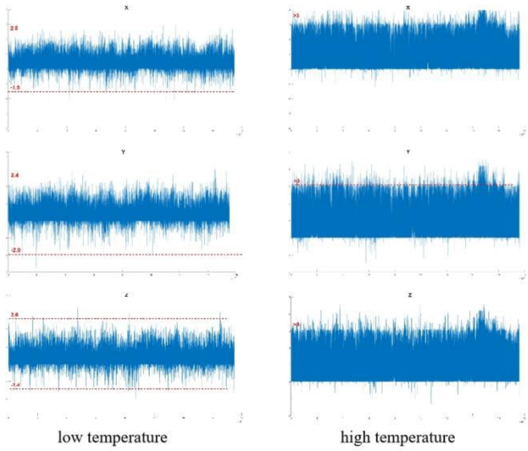

Figure 9. Schematic diagram of environmental vibration monitoring technology.

Accelerometer data on high-temperature days show higher acceleration dispersion and density than on low-temperature days, with peaks in the -2 m/s^2 to 3 m/s^2 range, exceeding the annual average, and peaks in the -2 m/s^2 to 2.5 m/s^2 range on low-temperature days, below the annual average. There is a correlation between temperature and acceleration that affects the vibration of the Wall.

4.3 Wind speed factor analysis

Wind speed is one of the important factors affecting the deformation of the Great Wall. The Great Wall at the three monitoring stations is located at the top of the mountain, with high altitude, and is subjected to wind blowing all year round. Due to the special characteristics of the architectural structure of the Great Wall, it will form a certain blockage to the incoming wind, which will lead to the slight deformation of the Great Wall under the action of the wind force.) and windy (NW wind 5, wind speed ⩾29Km/h) accelerometer data on March 28 are compared.

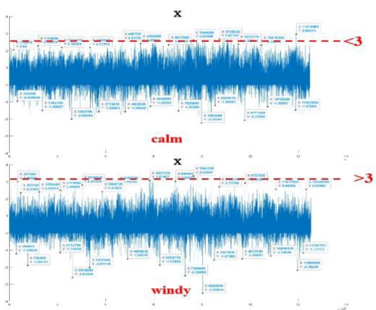

Fig. 10. Comparison of X-axis acceleration without and with wind at monitoring station 4292.

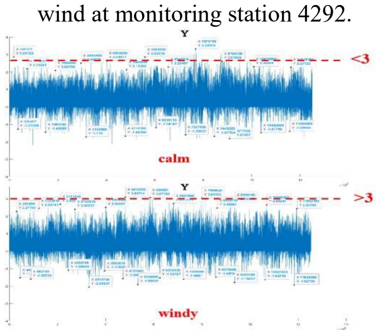

Figure 11 Comparison of windless and windy Y-axis acceleration at monitoring station 5916.

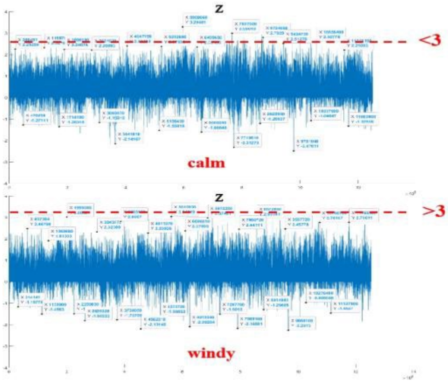

Figure 12 Comparison of Z-axis acceleration without and with wind at monitoring station 5857.

On March 25, when there was no wind, the acceleration was mostly concentrated in the range of $2\,m/s^2$-$2.5\,m/s^2$; on March 28, when there was high wind, the data extended to $2.5\,m/s^2$-$3\,m/s^2$, with some exceeding $3\,m/s^2$. Comparing the data in the deformation region, it can be judged that there is a certain correlation between the windy weather and acceleration, which has a certain effect on the vibration of the Great Wall.

5. Conclusion

Through in-depth analysis of the deformation monitoring data of the Great Wall, this study reveals the main factors affecting its stability, such as temperature fluctuations and wind action, and proposes corresponding protective measures. The study emphasizes the necessity of strengthening inspection, structural assessment and timely reinforcement, and suggests the classification of risks to optimize maintenance work. Meanwhile, the integration of multi-source technology realizes the organic combination of point monitoring and surface inspection for environmental vibration hazard monitoring of the Great Wall, which provides technical support for the protection of the Great Wall, which is a linear cultural heritage, and provides a reference for the protection of cultural heritage in the future.

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