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Article

Temporal and Spatial Analysis of Deformation Monitoring of the Ming Great Wall in Shanxi Province through InSAR

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Abstract: Influenced by geological, climatic, and natural weathering factors, the Great Wall heritage is susceptible to deformations, posing significant challenges to the comprehensive preservation of the Great Wall sites. To investigate techniques for monitoring deformations in extensive linear cultural heritage sites, such as the Great Wall, this study utilizes the SBAS-InSAR technique for deformation monitoring and analysis. A dataset comprising 161 Sentinel-1A images spanning from March 2017 to January 2022 was chosen for SBAS-InSAR processing, yielding a deformation velocity field. To verify result credibility, a typical mountainous segment spanning approximately 896.53 km within the Great Wall landscape corridor underwent analysis. The findings suggest that around 75.8% of the landscape corridor along the Shanxi section of the Ming Great Wall maintain relative stability, displaying deformation rates varying from -10 to 10 mm/year. The remaining 24.2% of the landscape corridor experiences notable deformations, including a maximum subsidence rate of 33.1 mm/year and a maximum subsidence of 148.6 mm. This study illustrates the potential utility of the SBAS-InSAR technique for monitoring and evaluating surface deformations in extensive linear cultural heritage sites.

Keywords: SBAS; InSAR; Great Wall; subsidence monitoring; heritage conservation

1. Introduction

The Great Wall in China is a culturally, historically, scientifically, and artistically significant heritage site. It is expansive, culturally diverse, located in complex natural and human environments, and subject to various risk factors. Prolonged exposure has led to an increasing stability risk due to natural and human influences. In recent years, incidents of wall collapse resulting from deterioration, damage, and improper restoration have posed challenges to current conservation efforts.

The Ming Great Wall in Shanxi Province is a noteworthy segment of the Great Wall and faces difficulties in conducting extensive field observations due to the surrounding natural environment. However, Synthetic Aperture Radar Interferometry (InSAR) offers considerable advantages over traditional methods for monitoring deformation. Its wide coverage, high precision, high resolution, and all-weather capability make it a suitable tool for studying the Great Wall [1,2]. Nevertheless, conventional D-InSAR techniques face limitations such as temporal and spatial decorrelation, as well as atmospheric phase delay, resulting in suboptimal performance when monitoring deformations in large linear structures. Recent research has paid attention to linear structures, prompting the use of time series InSAR techniques like Small Baseline Subset (SBAS) and Persistent Scatterer (PS) analysis [3–7]. These techniques have gained prominence for their high accuracy and resistance to noise. Notable results have been achieved in studies involving linear features such as subways [8–10], bridges [11,12], and high-speed railways [13,14].

This study builds upon domestic and international research achievements [15], utilizing Sentinel-1A ascending orbit data in conjunction with the SBAS-InSAR technique to analyze the deformation velocity field of the Shanxi section of the Great Wall. The goal is to assess the trend of

deformation development in significant sections of the Ming Great Wall in Shanxi Province. This analysis aims to establish a theoretical foundation and offer technical support for the monitoring and preservation of other similar large linear cultural heritage sites.

2. Study Area and Data Sources

2.1. Overview of the Study Area

The Ming Great Wall in Shanxi Province extends for a total length of 896.53 kilometers and encompasses 6 cities and 25 counties. It consists of three sections: the Outer Great Wall, Inner Great Wall, and Riverside Great Wall, as shown in Figure 1. The Outer Great Wall (segment k1) originates from Huai'an in Hebei Province and stretches westward to Tianzhen, passing through Yanggao, Xinrong, Zuoyun, and Youyu, before reaching Piankou, spanning approximately 380 km. The Inner Great Wall (segment k2) commences in Pingshan, Hebei Province, and enters Fanzhi in Shanxi Province. It traverses Hunyuan, Ningwu, and Shencheng, before turning towards Piankou, covering a distance of about 400 km. The Riverside Great Wall (segment k3) is constructed along the Yellow River. The westernmost segment, at the junction between Shanxi Province and Shaanxi Province, spans around 70 km from Piankou to Hequ.

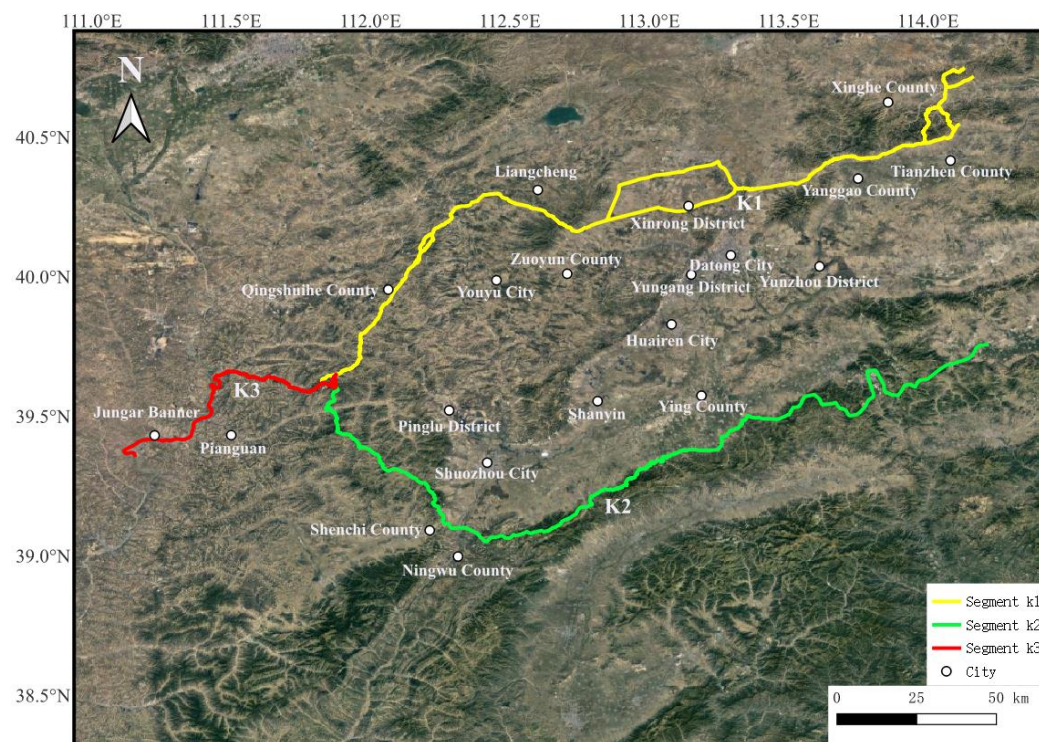


Figure 1. Route map of the Ming Great Wall in Shanxi Province.

Figure 2 illustrates the coverage area of the Sentinel-1A images used in the study. The study area is outlined in yellow, while the red markings indicate the ascending orbit image range of Sentinel-1A.

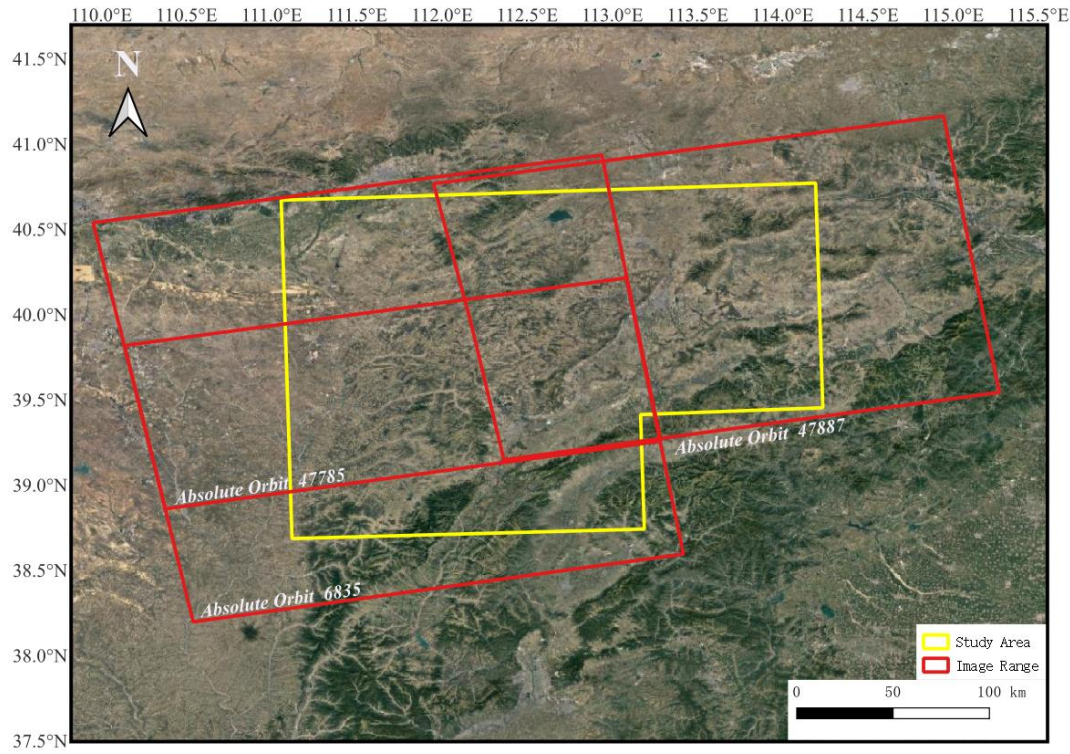


Figure 2. Illustration of the Study Area Boundary.

2.2. Overview of the Dataset

This study utilized single-look complex imagery data from the C-band of Sentinel-1A, covering a five-year period from January 2017 to January 2022. The imagery had a ground resolution of 5 meters by 20 meters and consistently employed VV polarization. Precise orbital data and a 30-meter resolution Digital Elevation Model (DEM) sourced from the NASA Space Shuttle Radar Topography Mission (SRTM) were used for satellite orbit refinement and terrain phase removal. The relevant parameters of the imagery data are presented in Table 1.

Table 1. Parameters of Sentinel-1A Image Data.

satellite	orbit	start date	Closing Date	Polarization	Number
S1-A	47785	20170319	20220121	VV	53
S1-A	47887	20170314	20220104	VV	57
S1-A	6835	20170313	20220110	VV	51

3. Research Methodology

3.1. Principle of Small Baseline Subset Time Series Analysis Technique

Acquire a set of $N + 1$ SAR images covering the same area, record the acquisition times $(t_0, t_1, t_2, \dots, t_N)$, register the images to a common coordinate system, and generate a series of M spatiotemporal differential interferograms with values below a specified threshold. The M following conditions should be met:

$$\frac{N+1}{2} \leq M \leq N \cdot \frac{N+1}{2} \quad (1)$$

The phase value of the pixel in the k -th interferogram is:

$$\delta\varphi_k = \varphi(t_n) - \varphi(t_A) \approx \frac{4\pi}{\lambda} [d(t_n) - d(t_A)] \quad (2)$$

In equation (2), $\varphi(t_i)$ represents the line-of-sight cumulative deformation relative to the initial time t_0 , and λ is the radar wavelength.

After correcting for terrain-induced phase errors, atmospheric delay phase, and noise phase in the obtained cumulative deformation variables, the transformed results yield the deformation rate v for high-coherence points in the study area:

$$Bv = \delta\varphi \quad (3)$$

In equation (3), B represents the coefficient matrix of $M \times N$, and $\delta\varphi$ is a matrix composed of phase values. The deformation rate v , therefore, can be expressed as:

$$v^T = \left[\frac{\varphi_1}{t_1 - t_0}, \dots, \frac{\varphi_N - \varphi_{N-1}}{t_N - t_{N-1}} \right] \quad (4)$$

When the coefficient matrix B is of full rank, the deformation rate v can be determined using the least squares method. If the matrix is not of full rank, the Singular Value Decomposition (SVD) method is employed to compute the deformation rate v .

After obtaining the deformation rate, a temporal integration is conducted to derive the deformation phase values over the specified time period. Multiplying the deformation phase values by the phase-to-deformation conversion coefficient $\frac{\lambda}{4\pi}$ yields the deformation time series on the ground's Line Of Sight (LOS) direction as seen by the radar.

Finally, the deformation component along the radar LOS direction d_{LOS} , is transformed into the vertical deformation d_v component on the Earth's surface, as follows:

$$d_v = \frac{d_{LOS}}{\cos \theta} \quad (5)$$

In equation (5), θ represents the satellite incidence angle, and d_{LOS} signifies the Line Of Sight (LOS) deformation component.

3.2 Data Processing Procedure

Figure 3 depicts the processing flow of the SBAS-InSAR method, which includes four main steps: data preprocessing, baseline estimation, differential interferometry, and phase unwrapping. Prioritization of interferometric pairs ensures adherence to spatiotemporal baseline conditions. This study used a spatial baseline threshold of 2% and a temporal baseline threshold of 40 days as standards. Interferometric processing was carried out on images obtained from three orbits, resulting in 126, 118, and 134 interferometric pairs. Coherence images with high quality were selected and, in conjunction with SRTM4 DEM and Ground Control Points (GCPs), two inversion procedures were performed to estimate deformation rates and residual deformations. To geographically reference the study area's SRTM4 DEM data, annual average subsidence rate maps for the Ming City Wall area in Shanxi Province were obtained for the period from 2017 to 2022. Since the three deformation fields shared the same GCPs, seamless mosaic and analysis were conducted using ENVI, resulting in a comprehensive deformation field. In order to reduce computational load and suppress noise, a multi-view approach of 2 looks in range and 10 looks in azimuth was applied to the interferograms. Furthermore, Goldstein filtering was employed to further eliminate noise from the multi-view differential interferograms, and the minimum cost flow method was used for phase unwrapping.

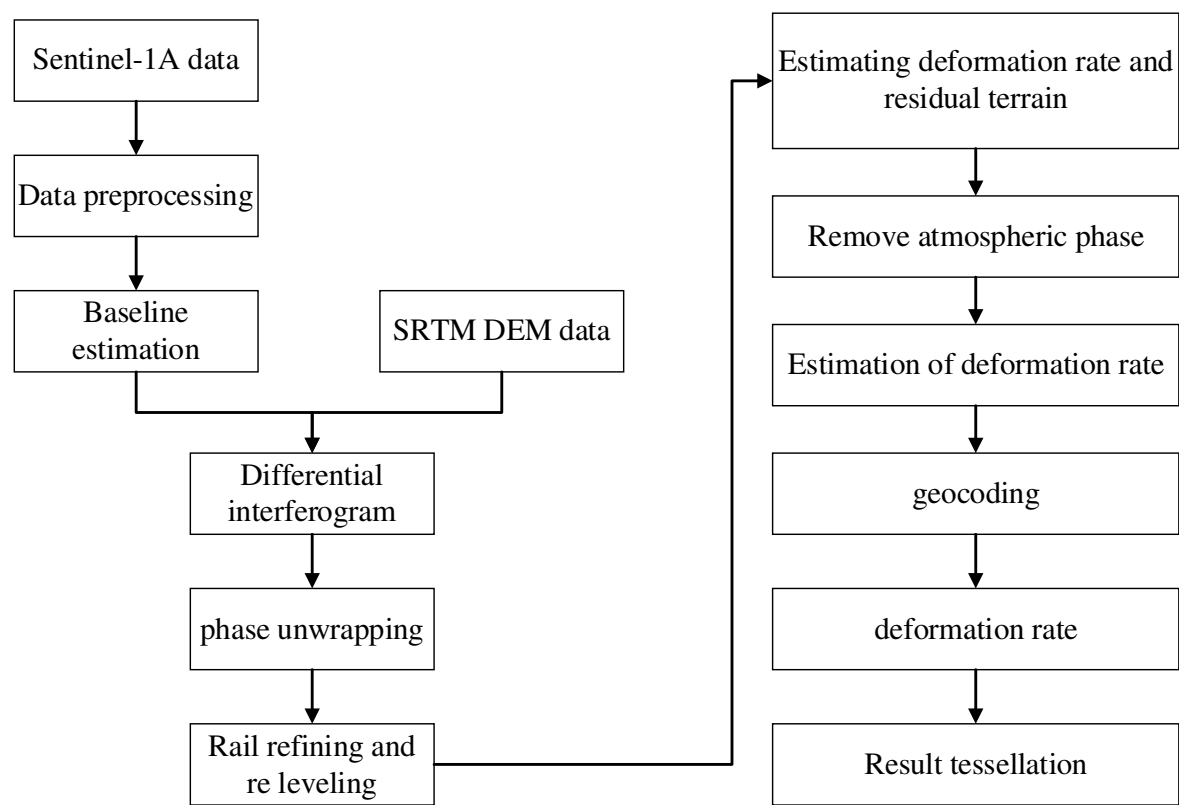


Figure 3. Flowchart of SBAS-InSAR Technique.

4. Analysis of Results

4.1. Analysis of subsidence monitoring along the Great Wall area

The primary focus of this study was the 250m buffer zone along the Ming Great Wall in Shanxi Province, with a reference point coordinates of (112.5°E, 39.8°N). Annual average rates of vertical ground deformation along this buffer zone were obtained and presented in Figure 4, while Figure 5 illustrates the corresponding components of vertical ground deformation. The analysis reveals that the majority of deformation rates for the Great Wall range from -10 mm/year to 10 mm/year, with deformation components concentrated between -60 mm and 40 mm. Notably, significant subsidence is observed in several segments, namely the Yulong Bay section (D1), the Shuocheng section (D2), the Youyu section (D3), and the Lierkou section (D4). Among these four key subsidence segments, the maximum rate of subsidence reaches -30.11 mm/year, with the maximum subsidence measured at -148.63 mm.

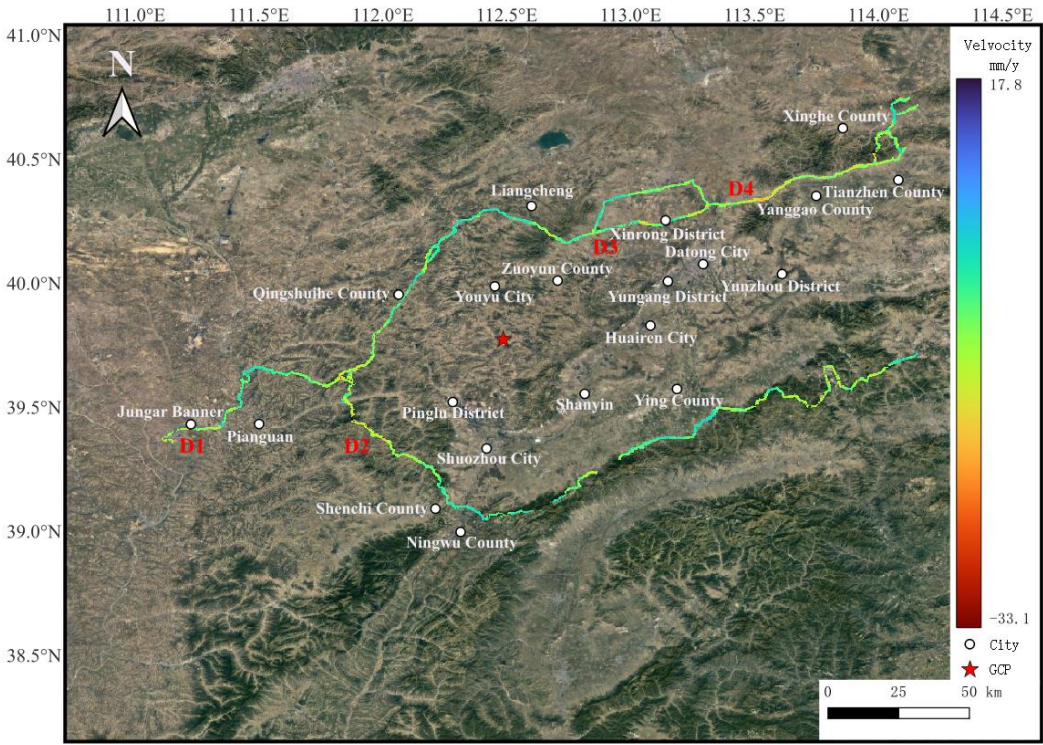


Figure 4. Ground Vertical Deformation Rates.

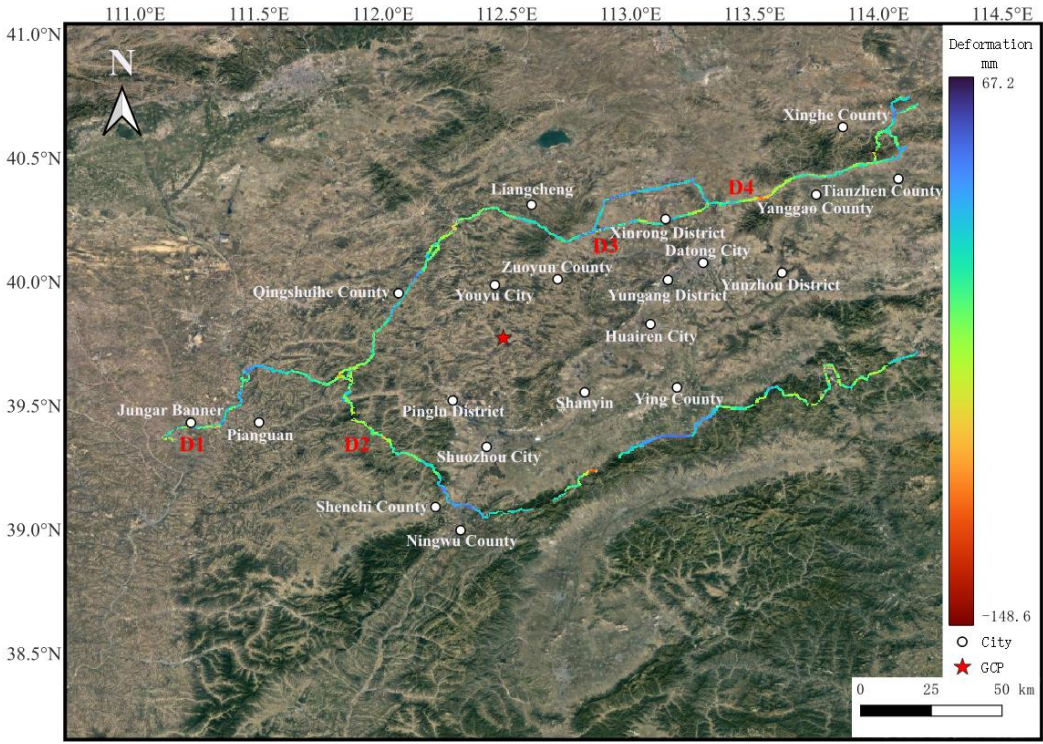


Figure 5. Ground Vertical Deformation Components.

4.2. Analysis of subsidence monitoring in the area along the Great Wall

An analysis of Figures 4 and 5 uncovers four noteworthy areas of subsidence. This study examines the risk factors for the Great Wall in these subsidence areas, using the classification of damage, causes of damage, and existing diseases of the Great Wall specified in the "Handbook for

Great Wall Resource Survey" released by the National Cultural Heritage Administration in April 2007 [16].

Segment D1 is located along the Yulong Bay shoreline in Hequ County, featuring a wall constructed from brick and stone. The topography of this area is defined by loess hills and gullies. Figure 6 illustrates the deformation rates of the D1 wall. Shanxi Province experiences significant annual variations in precipitation, characterized by uneven temporal distribution and frequent episodes of short-duration heavy rainfall. These heavy rainfall events have the potential to cause damage to the structure of the Great Wall [9,10].

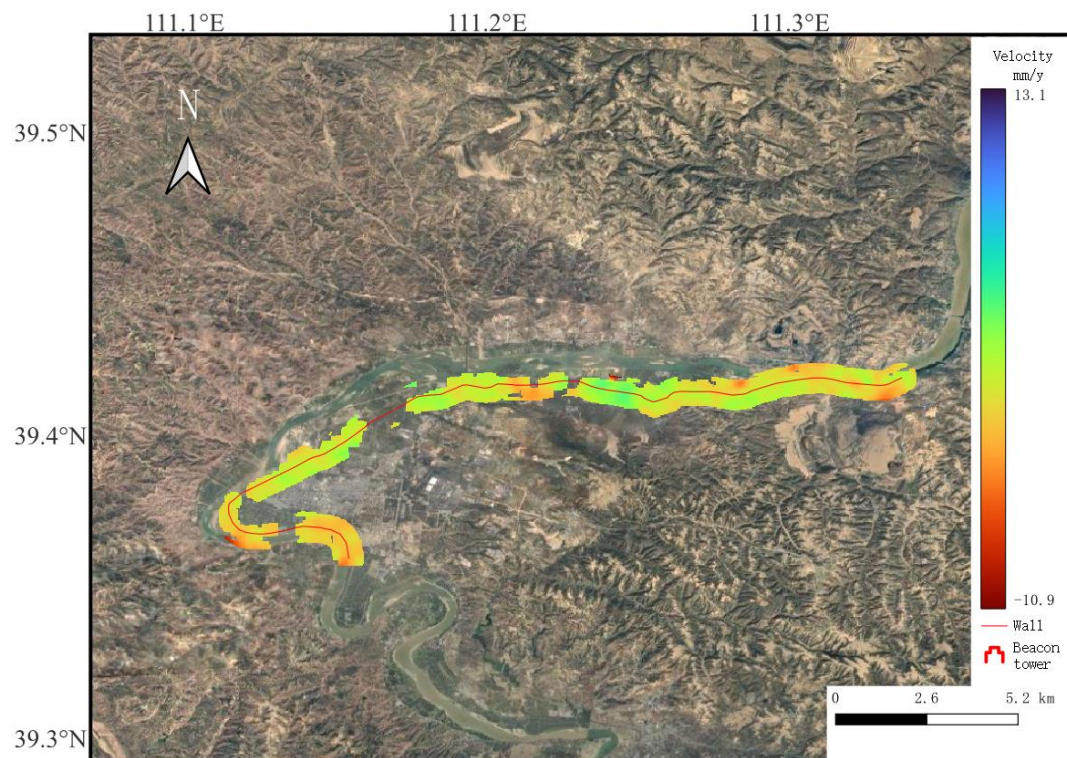


Figure 6. Deformation Rate Map of Great Wall Segment D1.

The temporal deformation characteristics are analyzed by focusing on the well-preserved No. 1 Watchtower of Luoquebao in Hequ County, Xinzhou City. Figure 7 presents the surface deformation at Shichengkou and the corresponding precipitation levels during different time intervals, combining historical precipitation data from meteorological bureau statistics. There is a strong consistency between the deformation patterns at Shichengkou and the monthly variations in local precipitation. During the flood season, which spans from June to September in the years 2017 to 2022, Shanxi Province experiences increased precipitation. Consequently, the Luoquebao No. 1 Watchtower exhibits conspicuous subsidence, with a maximum subsidence rate approaching 10 mm/month. This suggests that erosion induced by intense, short-duration rainfall serves as the primary factor driving the subsidence and deformation of the Great Wall in Segment D1.

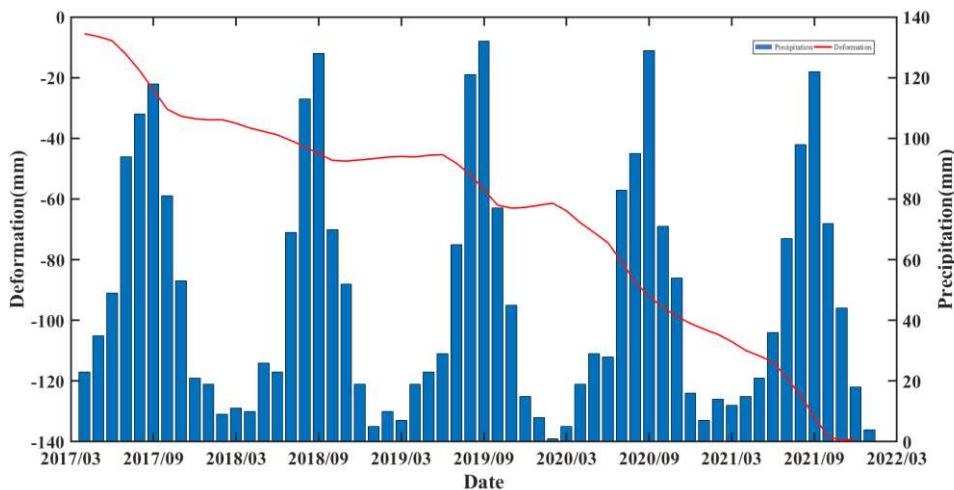


Figure 7. Time Series Ground Deformation and Precipitation at Luoquebao Beacon tower.

Segment D2 is located in Shuocheng District, Shuozhou City, where the wall is predominantly constructed with sturdy brick and stone materials. The topography of the Great Wall's location is characterized by mountains and hills, with significant undulations and intense geological activities. The deformation rates of the D2 wall are illustrated in Figure 8. During the construction of the D2 segment of the Great Wall, advantageous topography was utilized along the western side of Shuocheng District, particularly the Daliang Mountains and other ranges, where the wall extended along the ridge lines. Consequently, factors such as unstable slope landslides and earthquakes have emerged as significant causes of deformation in the D2 segment. This study investigates areas with significant subsidence rates in the D2 segment, based on the distribution of subsidence rates. Figure 9 displays photographs of four locations in the D2 segment with severe deformation, captured by the Shanxi Provincial Cultural Heritage Bureau in 2018. It is evident that all four locations exhibit unstable slope bodies, indicating that deformation and subsidence in the D2 segment are primarily induced by unstable slope landslides and seismic events resulting from crustal movement.

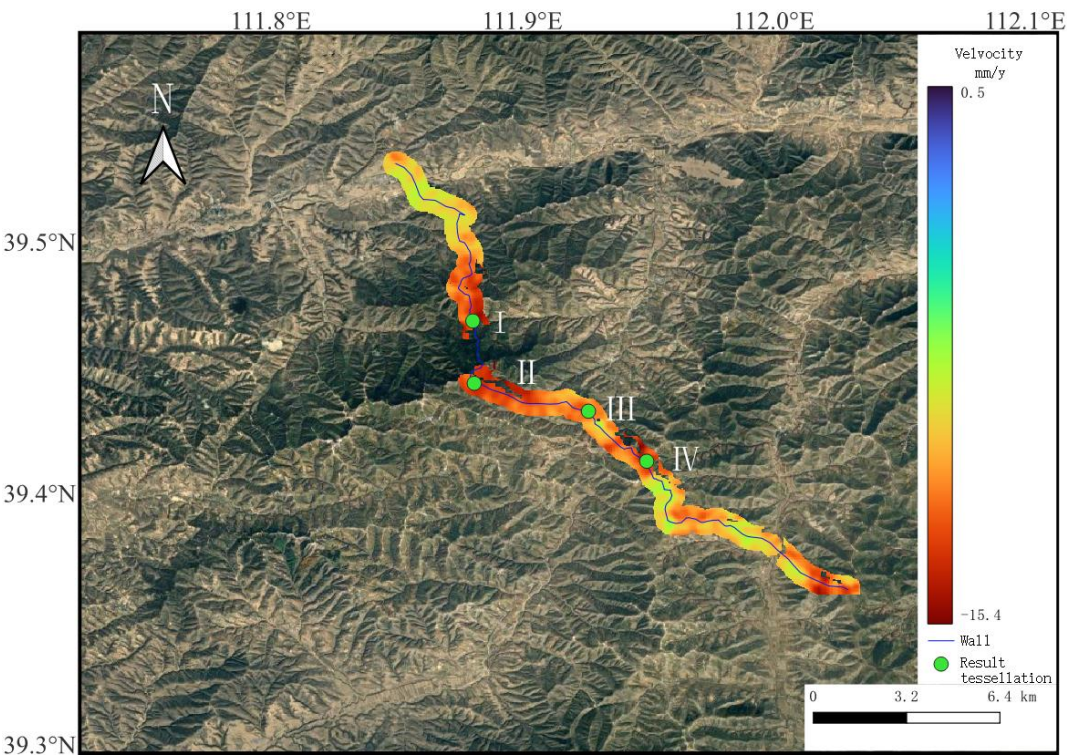


Figure 8. Deformation Rate Map of Great Wall Segment D2.

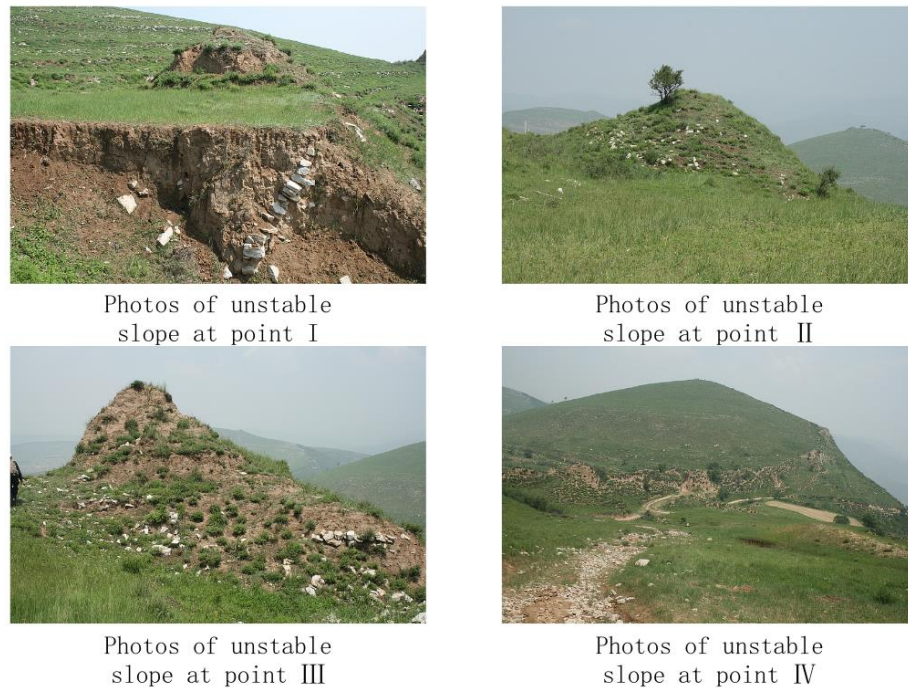


Figure 9. Photographs of Unstable Slope Sections of the D2 Segment of the Great Wall.

Segment D3 is situated in the northern part of Datong City, covering the counties of Huairan and Youyu. The wall primarily comprises yellow clay, which contains a significant amount of sand, gravel, and crushed stone. The topography of the area is characterized by plains and hills. The deformation rates of the D3 wall are depicted in Figure 10. Shanxi Province boasts abundant coal resources, with over fifty coal mines located in Datong City alone as of December 2022. A profile analysis was conducted on the D3 segment, extracting surface subsidence data from four profiles: L1, L2, L3, and L4, as shown in Figure 11. It is evident from Figure 11 that significant subsidence is observed in the southern portions of L1, L2, and L4, as well as in the northern part of L3. By comparing historical satellite images with this subsidence data, it is apparent that all four subsidence locations coincide with active coal mining areas. Based on this observation, it can be inferred that surface deformation resulting from coal mining activities is the primary cause of subsidence and deformation in the D3 segment of the Great Wall.

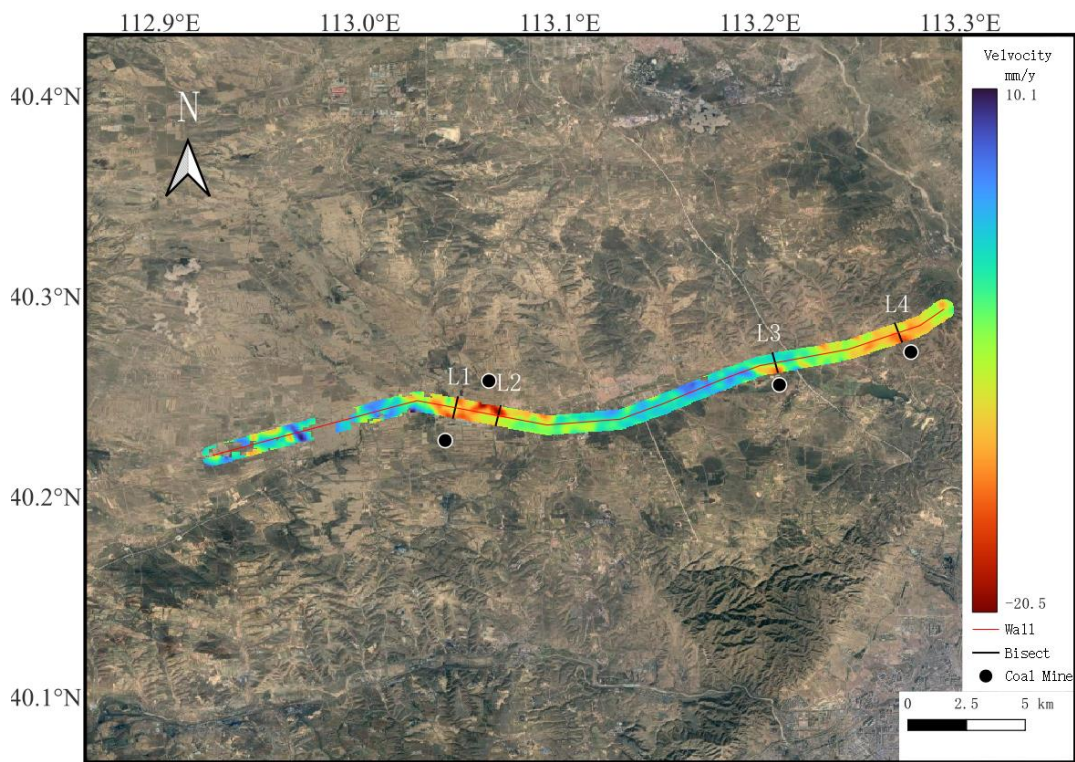


Figure 10. Deformation Rate Map of Great Wall Segment D3

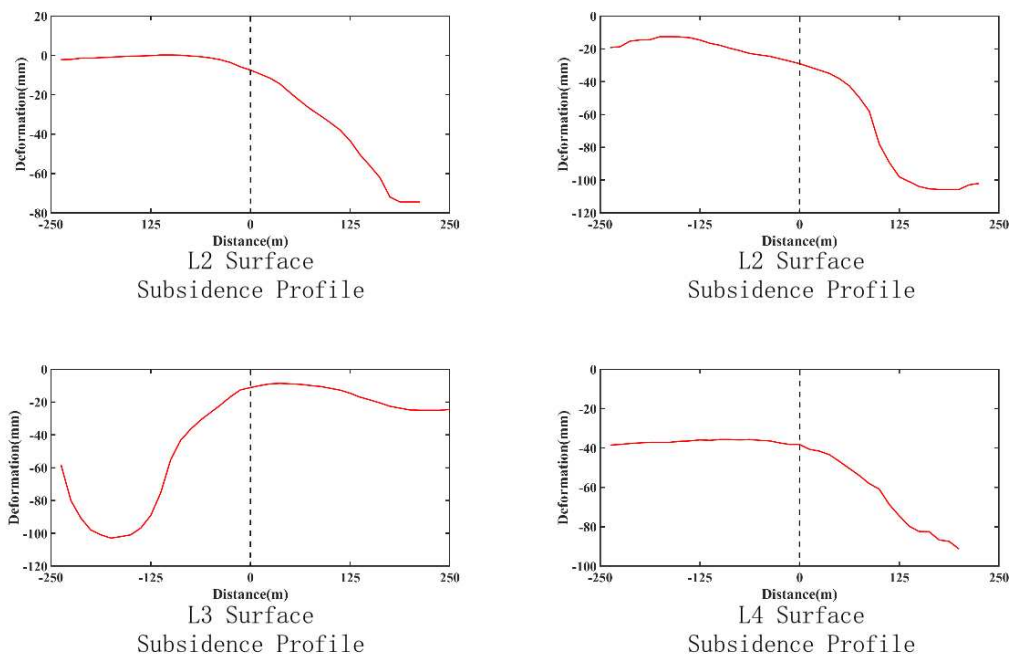


Figure 11. Cross-sectional Profile of Surface Subsidence for Segment D3 of the Great Wall.

Segment D4 is located in Yanggao County, Datong City. The wall mainly consists of highly pure yellow clay, and the terrain is characterized by alluvial plains and hills. The deformation rates of the D4 wall are shown in Figure 12. The exposed surface rocks in this area are fragmented, and adverse geological phenomena like interlocking and landslides provide ample solid material sources for debris flows [17,18]. Reports from the Yanggao County Land and Resources Survey Bureau indicate that the county frequently experiences natural disasters such as debris flows and earthquakes due to

its unique geological and geomorphic conditions. Combining this information with the "Assessment Map of Landslide Risk in China" published by the China Geological Environment Monitoring Institute, it can be inferred that Yanggao County falls under the category of low-risk landslide disaster and moderate landslide hazard zone, as shown in Figure 13. This suggests that geological hazards resulting from the region's special geological conditions are the primary factors contributing to the subsidence of the D4 segment of the Great Wall. Additionally, the opening of the Yanggao section of the Great Wall for tourism has introduced human-induced effects on the subsidence and deformation of the D4 segment due to tourism activities and potential anthropogenic damage.

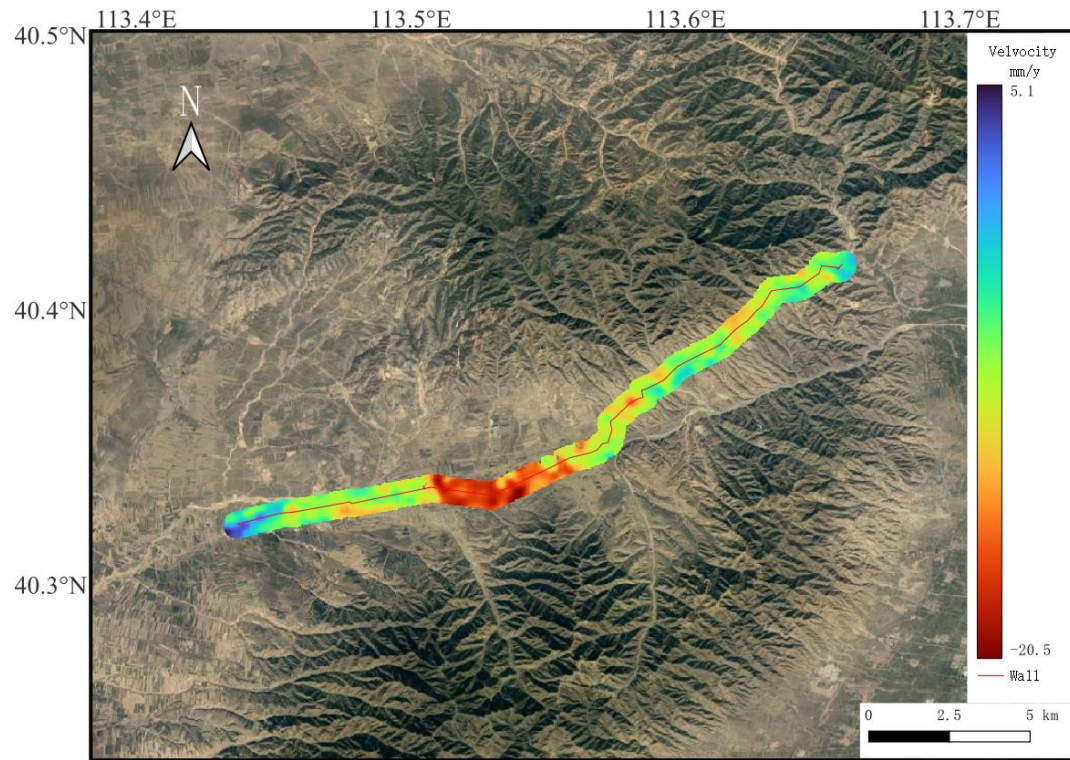


Figure 12. Deformation Rate Map of Great Wall Segment D4.

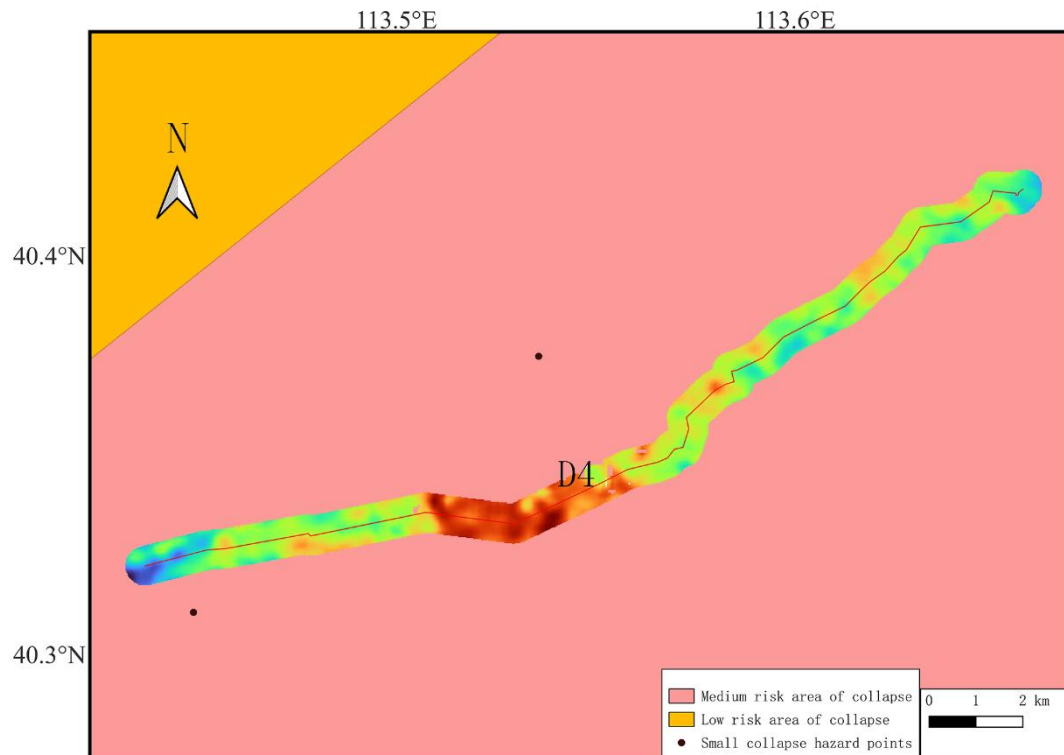


Figure 13. Geological Hazard Assessment Map of Segment Yanggao of the Great Wall.

4.3. Risk Mapping Analysis along the Great Wall Corridor

A thematic classification was performed using a threshold of 10 mm/year to differentiate between relatively stable and significantly changing surface deformations. Figure 14 presents the resulting thematic classification map of deformation stability along the Great Wall corridor in Shanxi Province. The analysis shows that approximately 210 km of deformation segments with absolute values exceeding the 10 mm/year threshold, accounting for 24.2% of the total observed segment length, are influenced by a combination of factors such as geological hazards, unstable slopes, mining activities, and soil erosion. In contrast, 75.8% of the Great Wall segments exhibit lower subsidence rates, indicating relative surface stability. The thematic classification map of deformation stability along the Great Wall corridor in Shanxi Province provides guidance and data support for identifying potential damage to the corridor landscapes and wall remnants of the Great Wall. This information is valuable for the comprehensive planning and conservation of large-scale linear heritage sites, similar to the Great Wall.

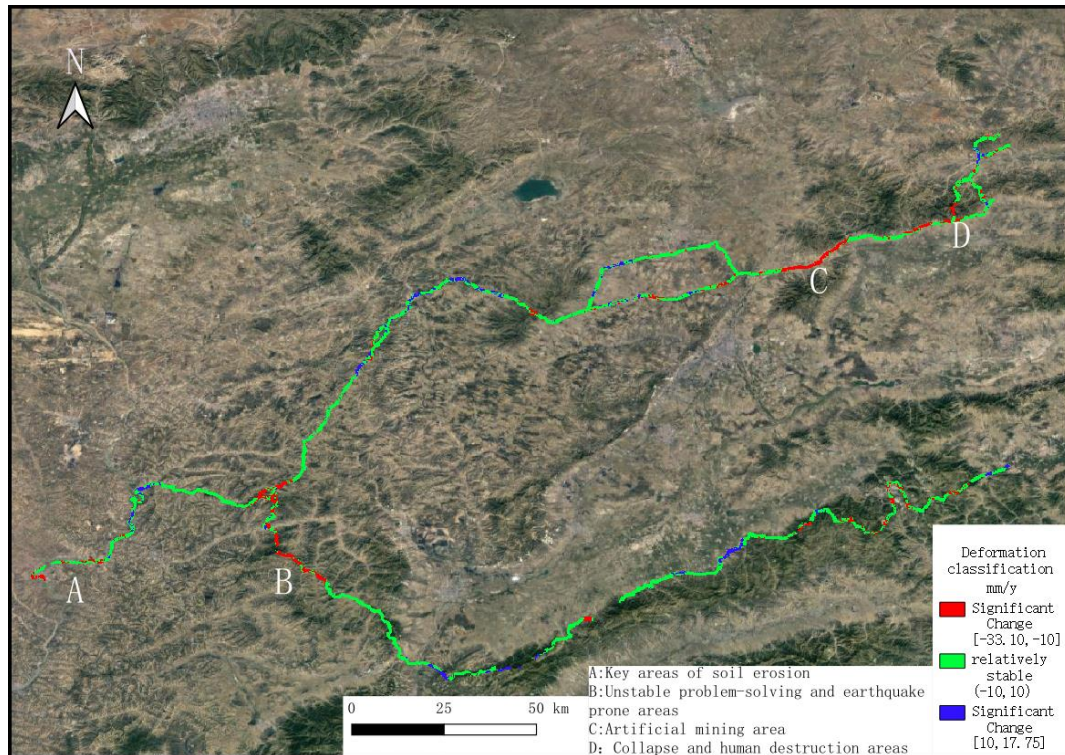


Figure 14. Thematic Classification Map of Deformation Stability along the Great Wall Corridor in Shanxi Province.

5. Conclusion

This study utilizes Sentinel-1A ascending orbit images and employs the SBAS-InSAR technique to conduct an exploratory research on surface deformation monitoring along the Ming Great Wall landscape corridor in Shanxi Province. The study period spans from March 2017 to January 2022. By implementing GACOS atmospheric phase correction and Goldstein filtering in the SBAS-InSAR method, the researchers were able to obtain statistically significant millimeter-level annual deformation velocity fields for the 896.53 km-long Ming Great Wall landscape corridor in Shanxi Province. The study findings indicate that, over the five-year period from 2017 to 2022, various sections of the Ming Great Wall in Shanxi Province exhibited considerable deformation caused by both natural and anthropogenic factors.

An analysis of the thematic classification map of deformation stability along the Great Wall corridor in Shanxi Province shows that 75.8% of the Ming Great Wall landscape corridor remains relatively stable, while 24.2% experiences more significant deformations (with annual deformation rates exceeding 10 mm/year in absolute value). This provides quantitative monitoring data and introduces a novel approach for identifying deformation hazards, localizing target areas, and improving and maintaining the architectural heritage of the Ming Great Wall in Shanxi Province.

The research demonstrates that the SBAS-InSAR technique, based on coherent points, proves to be highly applicable in natural landscape regions. Moreover, it can be extended to macroscopic monitoring and dynamic assessment of other large-scale linear cultural heritage sites such as other sections of the Great Wall and canals.

6. Patents

Author Contributions: Conceptualization, Q.L. and K.C.; methodology, Q.L. and X.W.; software, Q.L., X.W. and K.C.; validation, Q.L., X.W., K.C. and J.Z., Z.Y.; formal analysis, Q.L., X.W. and K.C.; investigation, Q.L., X.W. and K.C.; resources, Q.L.; data curation, Q.L.; writing—original draft preparation, Q.L., X.W. and K.C.; writing—review and editing, Q.L., X.W. and K.C.; visualization, X.X.; supervision, Q.L., X.W. and K.C.; project

administration, Q.L.; funding acquisition, K.C.; All authors have read and agreed to the published version of the manuscript.

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