



Highway Slope Displacement Monitoring and Stability Analysis Based on D-InSAR and GNSS

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ABSTRACT

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highway slope, Differential Interferometric Synthetic Aperture Radar, Global Navigation Satellite System, line-of-sight displacement, deformation monitoring, overall deformation

Point-based monitoring of multistage highway slopes has limited spatial coverage and cannot fully characterize overall slope deformation. To address this limitation, 22 Sentinel-1A images covering the study area from December 2021 to August 2022 were collected. Eleven images were selected to construct 10 interferometric pairs for Differential Interferometric Synthetic Aperture Radar (D-InSAR) processing. Line-of-sight (LOS) displacement was extracted from individual grid cells corresponding to four Global Navigation Satellite System (GNSS) stations, and GNSS vertical displacement was used to validate the D-InSAR results. Both methods detected pronounced changes around April 24 and August 1, 2022. The GNSS vertical displacement amplitudes at the four stations ranged from 25.10 to 27.40 mm, whereas the D-InSAR LOS displacement amplitudes ranged from 23.76 to 29.84 mm. The amplitude differences at corresponding stations ranged from 0.62 to 3.64 mm. The two datasets showed similar overall trends, indicating that D-InSAR effectively captured the main displacement variations of the slope. During the monitoring period, displacement at each station fluctuated in stages, with no sustained acceleration or continuously increasing unidirectional movement. The slope therefore remained in a relatively stable deformation state during the observation period. Analysis of profiles A-A and B-B revealed systematic displacement differences among representative points at different elevations. Displacement changes were greater at the slope toe during uplift, but greater at the slope crest during settlement. Along profile B-B, an uplift tendency at the slope toe coincided with a settlement tendency at the upper slope during some periods. These observations were used to develop an approach for identifying profile-scale overall deformation tendencies from the relative displacement responses of representative points at the slope toe, midslope, and slope crest. The results provide a basis for safety monitoring, targeted field inspections, and maintenance of highway slopes during operation.

1. INTRODUCTION

Highway slopes are important components of highway infrastructure in mountainous areas, and their deformation directly affects operational safety and traffic function. Engineering excavation, geological heterogeneity, rainfall infiltration, groundwater variations, and long-term environmental effects may cause slow, progressive, and spatially variable deformation. Subtle early changes are often difficult to identify through manual inspection. Their accumulation may eventually lead to slope cracking, damage to protective structures, or local sliding, thereby disrupting traffic. Operational highway slopes are numerous and widely distributed, and their responses may vary among slope stages and elevations. A small number of monitoring stations or periodic inspections therefore cannot fully characterize slope conditions. Deformation monitoring that combines temporal continuity with broad spatial coverage can help identify

anomalous areas, characterize overall deformation, and define priorities for field verification.

Researchers have investigated highway-slope deformation monitoring, hazard mitigation, and operational safety using field observations, numerical simulation, remote sensing, and transportation resilience assessment. Li et al. [1] combined displacement, rainfall, and anti-slide pile observations from a slope along the Yunmao Expressway with finite-element modeling to evaluate the effects of rainfall and pile arrangement on slope deformation. Zhang et al. [2] used the finite-element and material-point methods, surrogate models, and Monte Carlo simulation to assess road functionality and recovery under rainfall-induced slope failure. They found that uncertainty in slope strength strongly affected highway resilience. Liu et al. [3] developed an automated monitoring and emergency-response system for a high, steep sandstone slope along a highway under construction. Deep-borehole displacement data were used to identify deformation stages

and slip surfaces, and the effectiveness of warning and mitigation measures was demonstrated. Wu et al. [4] converted MEMS acceleration measurements into subsurface displacement and compared the results with particle image velocimetry. Their method identified displacement within the sliding zone of a gravelly-soil slope. Liu et al. [5] monitored a small highway slope using Sentinel-1A and ALOS-2 data. C-band observations were constrained by slope dimensions and coherence, whereas L-band TCP-InSAR identified local active areas. Zhang et al. [6] deployed a general-purpose BeiDou monitoring system on an expansive-soil slope protected by soilbags and analyzed its deformation using soilbag, rainfall, and crack observations. However, many existing studies rely on a limited number of stations or focus on individual rainfall events, construction periods, and local deformation processes. Long-term, continuous, and spatially distributed deformation of operational highway slopes therefore requires further investigation.

The Global Navigation Satellite System (GNSS) continuously records coordinate changes at monitoring stations. Berru Garcia et al. [7] tested a low-cost differential GNSS system at the Chin Coulee landslide. Six-month displacement trends agreed closely with those from a commercial system and previous results, although the power supply and thermal insulation required improvement. Zhang et al. [8] integrated an adaptive receiver, communications, a deployment unmanned aerial vehicle, and a cloud platform. Tests at the Dangchuan landslide demonstrated unmanned deployment and real-time monitoring in high-risk areas. Li et al. [9] compared the data quality, positioning performance, and deformation-detection capability of miniaturized GNSS antennas and conducted six months of monitoring at the Baige landslide. Although signal-to-noise ratio and multipath affected the compact antennas, they still yielded useful displacement observations. Wu et al. [10] incorporated multipath correction and stochastic-model optimization into carrier-phase receiver autonomous integrity monitoring, reducing gross errors and improving RTK reliability. Lu et al.

[11] classified mountainous-area GNSS signals using K-means++ and developed adaptive elevation-angle and class-specific stochastic models, which improved ambiguity resolution and positioning under obstruction and multipath conditions. These studies expanded GNSS applications through low-cost devices, unmanned aerial vehicle deployment, and error control. Nevertheless, GNSS measurements remain limited to discrete stations, and their spatial coverage depends on the number and placement of instruments, making it difficult to describe continuous deformation across an entire slope.

Interferometric Synthetic Aperture Radar (InSAR) can identify spatially distributed slope deformation. Cheng et al. [12] reviewed spaceborne InSAR applications in landslide monitoring and susceptibility assessment. They summarized advances in three-dimensional monitoring, failure prediction, and multisource integration, while noting the limited use of dynamic information. Novellino et al. [13] reviewed satellite-based landslide mapping and concluded that Sentinel data and artificial intelligence have accelerated inventory updating, although operational applications remain constrained by data availability and quality. Zheng et al. [14] fused asynchronous observations using a spatiotemporally constrained Kalman filter, improving the characterization of three-dimensional movement and block interactions. Xu et al. [15] linked satellite-observed precursory creep with granular-flow simulations and demonstrated the feasibility of estimating the inundation extent of the Chunchi landslide. Sreejith et al. [16] combined InSAR, GPS, rainfall data, and singular spectrum analysis to identify seasonal movement and cascading acceleration at the Joshimath landslide. Wang et al. [17] integrated SBAS-InSAR, field monitoring, machine learning, and a limit-equilibrium model to establish a data-physics framework for landslide prediction and warning. Wen et al. [18] used ascending- and descending-track InSAR together with optical imagery to investigate the Wudongde reservoir area. They found that reservoir-bank landslides were more likely to change their deformation state after impoundment.

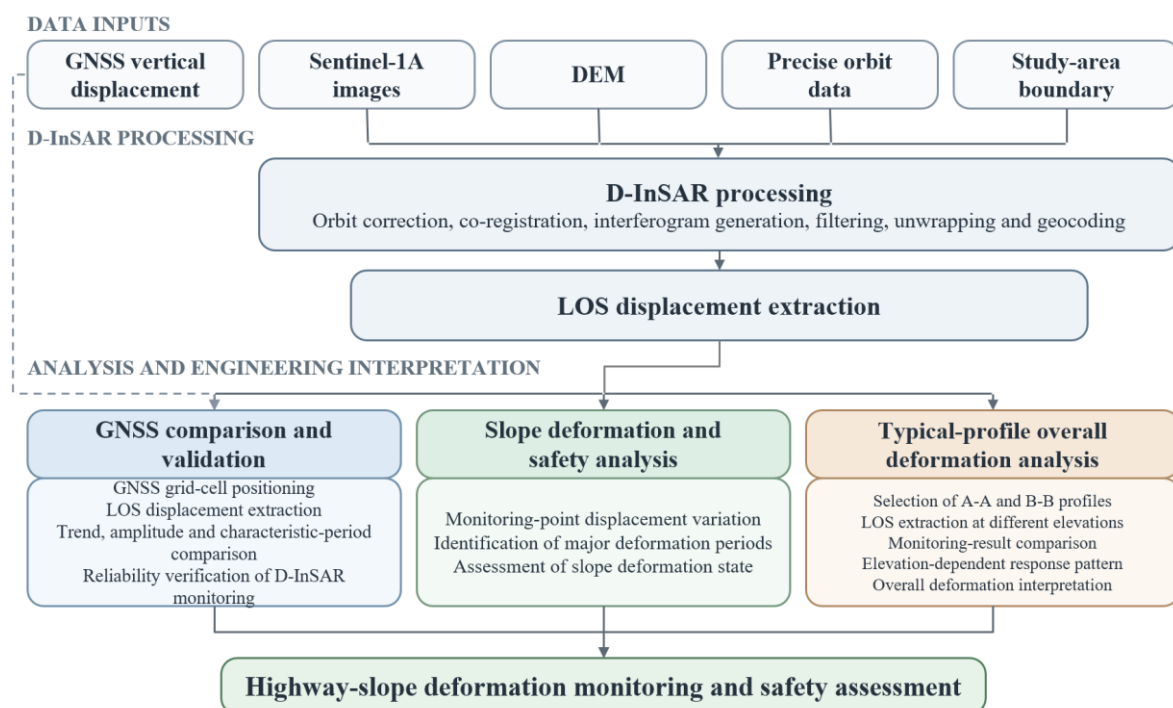


Figure 1. Research workflow

Fan et al. [19] combined ascending- and descending-track InSAR, unmanned aerial vehicle surveys, LiDAR, and wavelet analysis to update an inventory of active slopes and identify annual deformation cycles and delayed rainfall responses. Piter et al. [20] compared pixel-selection methods and showed that infrastructure monitoring is constrained by spatial resolution, vegetation-induced decorrelation, and pixel density. Li et al. [21] used downslope displacement derived from time-series InSAR as input to an LSTM-TCN model, improving the representation of long-term trends and local fluctuations. Huang et al. [22] analyzed an engineered slope using SBAS-InSAR and 44 Sentinel-1 images, identifying differences between the slope toe and crest during construction. Tai et al. [23] trained a U-Net model using StaMPS results, increasing the number of persistent-scatterer candidates in vegetated areas and supplementing seasonal deformation information. Most existing studies use PSInSAR or SBAS-InSAR to estimate deformation rates, or focus on regional detection and prediction. Few studies of operational highway slopes directly compare D-InSAR with GNSS observations and then combine station displacement with elevation-dependent responses along typical profiles to assess deformation conditions.

GNSS provides high temporal resolution and precise point observations but cannot produce a continuous deformation field over a slope. InSAR offers broad spatial coverage, but its line-of-sight (LOS) displacement is affected by imaging geometry, decorrelation, and atmospheric delay and therefore benefits from validation and interpretation using ground observations. To address the limited spatial coverage of point-based monitoring and its difficulty in characterizing continuous and overall deformation of operational multistage

highway slopes, this study used Differential Interferometric Synthetic Aperture Radar (D-InSAR) to derive LOS displacement across the study area. Concurrent GNSS vertical displacement was used to evaluate the reliability of the D-InSAR monitoring results. Displacement changes at individual stations were then analyzed to assess slope deformation during the monitoring period. In addition, two typical profiles, A-A and B-B, were selected to identify overall profile-scale deformation by comparing uplift and settlement responses at representative points located at the slope toe, midslope, and slope crest. The research workflow is shown in Figure 1.

2. STUDY AREA AND DATA

2.1 Study area

The study area is located in a mountainous and hilly region of Anhui Province. It comprises a multistage slope on the right side of chainage K36+720 to K37+100 along the south-bank highway approach of the Tongling Yangtze River Road-Rail Bridge, with a total length of approximately 380 m. The total slope height varies from approximately 8 to 30 m among chainage sections, and the highest section contains four stages. The overall slope ratio is approximately 1:1. Along the highway alignment, the number of slope stages gradually increases from one to four and then decreases to one. The main protection measures include vegetated soil spraying over mesh, anchor-frame beams, and revegetation. The study-area location, GNSS station distribution, and typical-profile locations are shown in Figure 2.

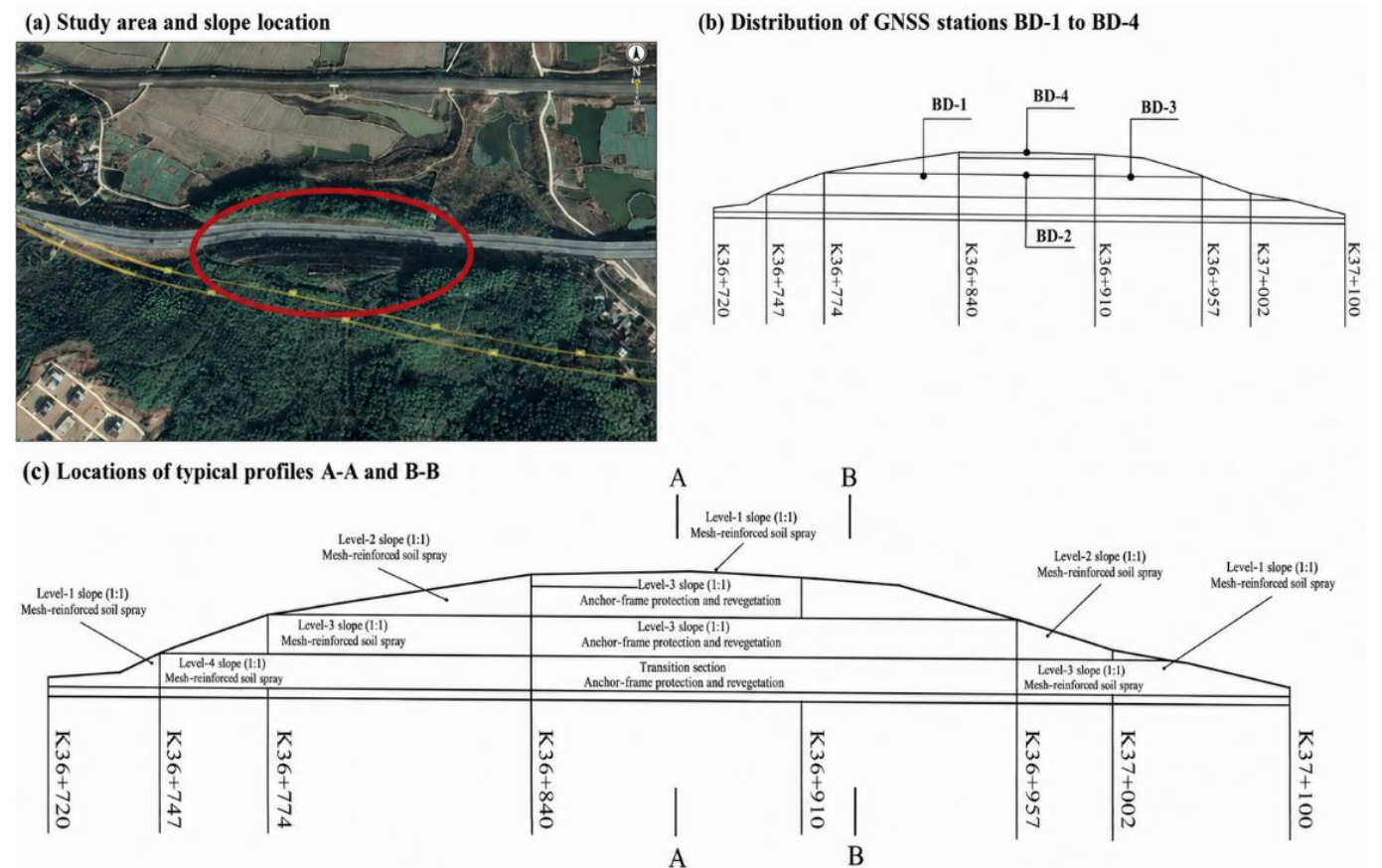


Figure 2. Study area and monitoring layout

Four GNSS monitoring stations, BD-1 to BD-4, were installed on site. BD-1 is located at the crest of the second slope stage at chainage K36+820. BD-2 and BD-4 are located at the crests of the second and fourth slope stages, respectively, at chainage K36+865. BD-3 is located at the crest of the second slope stage near chainage K36+930. Profiles A-A and B-B are located near chainages K36+880 and K36+920, respectively. Representative points along these profiles were extracted from the D-InSAR results to describe LOS responses at different elevations and served a different analytical purpose from the field GNSS stations.

2.2 Data sources

Same-track Sentinel-1A Level-1 single-look complex (SLC) images acquired in Interferometric Wide-swath (IW) mode with VV polarization were selected for the study area. The revisit interval was approximately 12 d. A digital elevation model (DEM) with a spatial resolution of approximately 30 m was obtained using the data-download tool integrated into ENVI. It was used mainly for topographic-phase simulation, orbit refinement, and geocoding. Auxiliary data included precise orbit files, the vector boundary of the study area, and basemap data for overlay visualization.

Table 1. Acquisition dates of the Sentinel-1A images

No.	Acquisition Date	No.	Acquisition Date
1	20211201	12	20220424
2	20211213	13	20220506
3	20220106	14	20220518
4	20220118	15	20220530
5	20220130	16	20220611
6	20220211	17	20220623
7	20220223	18	20220705
8	20220307	19	20220717
9	20220319	20	20220729
10	20220331	21	20220810
11	20220412	22	20220822

Table 2. Interferometric pairs used for the D-InSAR and GNSS comparison

Pair ID	Interferometric Pair	Spatial Baseline (m)	Temporal Baseline (d)
a	20211201-20220106	58.74	36
b	20211201-20220130	23.97	60
c	20211201-20220223	139.76	84
d	20211201-20220319	88.83	108
e	20211201-20220412	23.00	132
f	20211201-20220506	21.39	156
g	20211201-20220530	110.04	180
h	20211201-20220623	124.99	204
i	20211201-20220717	107.59	228
j	20211201-20220810	85.32	252

A total of 22 Sentinel-1A images covering the study area were collected from December 2021 to August 2022, and their

acquisition dates are listed in Table 1. Based on temporal matching and D-InSAR processing requirements, 11 images were selected. The image acquired on December 1, 2021 was used as the common master image and paired with the other 10 images to construct 10 interferometric pairs. The resulting interferometric pairs and their baseline parameters are presented in Table 2. These pairs were used to derive LOS displacement across the study area and to compare it with concurrent GNSS vertical displacement.

In total, 22 Sentinel-1A images were collected for the monitoring period. To align D-InSAR results with GNSS observation dates, 11 images were selected. The image acquired on December 1, 2021 was used as the master image and paired with the other 10 images to form 10 interferometric pairs.

3. METHODS

3.1 Basic principles and processing of D-InSAR

Interferometric Synthetic Aperture Radar (InSAR) is a surface-deformation measurement technique developed from synthetic aperture radar imaging. It processes two complex SAR images acquired over the same area at different times or from different orbital positions. Differences in phase information between the images are then used to derive surface deformation or topographic information. The interferometric geometry is shown in Figure 3.

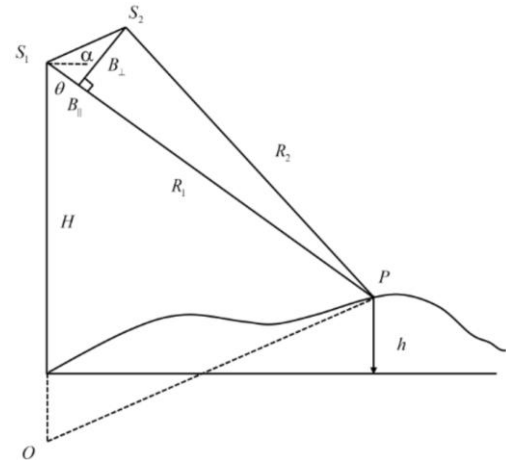


Figure 3. InSAR interferometric geometry

Two accurately co-registered complex SAR images form an interferogram. The interferometric phase can be decomposed as follows:

$$\Delta\phi_{int} = \Delta\phi_{flat} + \Delta\phi_{topo} + \Delta\phi_{def} + \Delta\phi_{atm} + \Delta\phi_{noise} \quad (1)$$

where, $\Delta\phi_{flat}$ is the flat-earth phase, $\Delta\phi_{topo}$ is the topographic phase, $\Delta\phi_{def}$ is the deformation phase, $\Delta\phi_{atm}$ is the atmospheric-delay phase, and $\Delta\phi_{noise}$ represents noise and other residual phase components. After the flat-earth and topographic phases are removed using precise orbit data and an external DEM, the differential interferometric phase can be expressed as:

$$\Delta\phi_D = \Delta\phi_{def} + \Delta\phi_{atm} + \Delta\phi_{noise} \quad (2)$$

The relationship between the deformation phase and the slant-range change between the ground target and the satellite is:

$$\Delta\varphi_{def} = -4\pi\Delta R/\lambda \tag{3}$$

where, λ is the radar wavelength and ΔR is the slant-range change between the ground target and the satellite. D-InSAR measures the projection of the true three-dimensional surface displacement onto the LOS direction rather than an independent vertical or horizontal displacement component. Accordingly, all D-InSAR results in this study are referred to as LOS displacement. GNSS vertical displacement was used to evaluate the D-InSAR results in terms of temporal trend, fluctuation magnitude, and characteristic periods. The sign of LOS displacement indicates the slant-range change of a target relative to the reference image along the radar line of sight (LOS). Its spatial meaning must be interpreted together with the satellite imaging geometry and slope aspect.

D-InSAR processing was performed with the SARscape module in ENVI. The workflow included precise orbit correction, subsetting, master and slave image selection, co-registration, interferogram generation, removal of flat-earth and topographic phases, Goldstein filtering, phase unwrapping, orbit refinement and re-flattening, phase-to-LOS displacement conversion, and geocoding. The earlier image was used as the master and the later image as the slave, and the multilook ratio was set to 1:3. A DEM with a resolution of approximately 30

m was used to simulate and remove the topographic phase. Goldstein filtering was applied to suppress phase noise, followed by phase unwrapping with the minimum-cost-flow method at a coherence threshold of 0.15. The orbit-refinement radius was set to 30 m. After re-flattening, the differential phase was converted to LOS displacement. The 10 interferometric pairs were used to derive LOS displacement in the study area from December 2021 to August 2022.

3.2 Comparison of D-InSAR LOS displacement with GNSS vertical displacement

Vertical displacement measured by the field GNSS stations was used in this study. For each GNSS station, the corresponding spatial grid cell was located in ArcGIS Pro using the station coordinates, and the multi-temporal D-InSAR LOS displacement series was extracted from that cell. No neighborhood average was calculated from surrounding grid cells. The extracted series therefore represents LOS displacement in the grid cell corresponding to the GNSS coordinates. Although GNSS vertical displacement and D-InSAR LOS displacement are measured along different directions, both record deformation changes at the monitoring location. GNSS field observations were used as a reference to evaluate the consistency of D-InSAR results in terms of temporal trend, fluctuation magnitude, and correspondence during characteristic periods. The grid cells corresponding to the GNSS coordinates are shown in Figure 4.

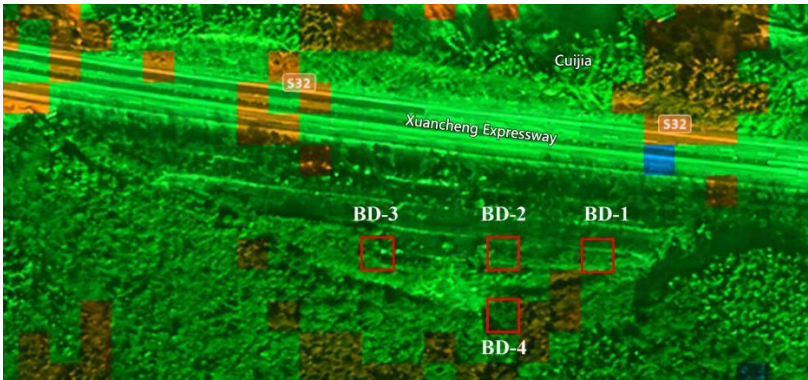
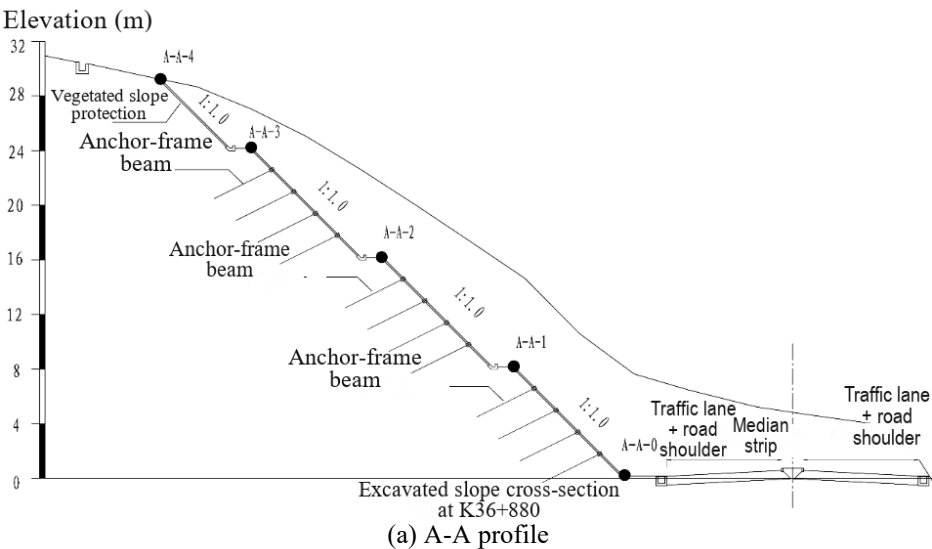


Figure 4. D-InSAR grid cells corresponding to the GNSS monitoring stations



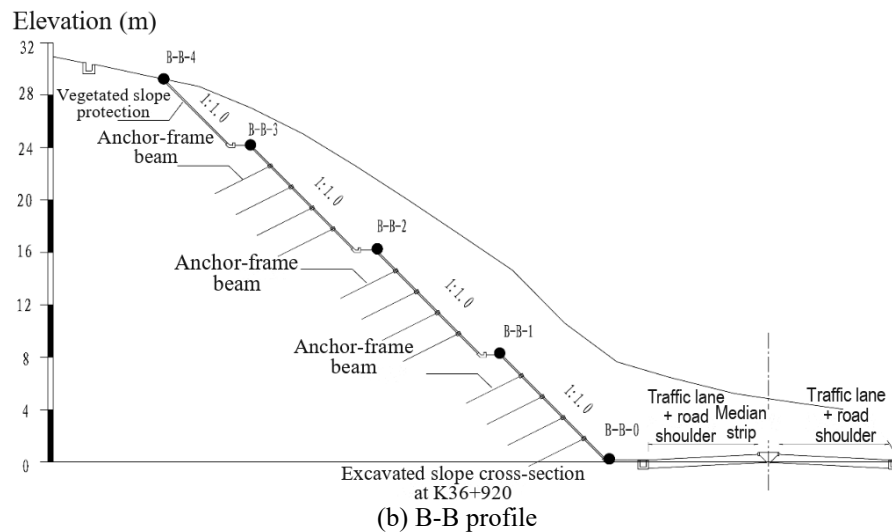


Figure 5. Typical profiles and representative points at different elevations

For each station, the maximum, minimum, and amplitude of the D-InSAR LOS displacement and GNSS vertical displacement were tabulated together with the amplitude difference between the two datasets. These statistics describe the numerical ranges and overall fluctuation magnitudes of the two observations. The amplitude difference was used to assess their similarity in overall fluctuation magnitude, whereas differences between the extrema provided supplementary information on the effect of observation direction.

3.3 Selection of typical profiles and representative points

To analyze deformation responses at different chainages and elevations along the same slope, two typical profiles, A-A and B-B, were selected near chainages K36+880 and K36+920, respectively. Five representative points were selected from the toe to the crest of each profile. A-A-0 and B-B-0 are located at the slope toe, whereas A-A-1 to A-A-4 and B-B-1 to B-B-4 are located successively at different slope stages or their corresponding crests. The profiles and representative-point locations are shown in Figure 5.

The LOS displacement at each representative point was extracted from the corresponding D-InSAR grid cell according

to its spatial location. Profiles A-A and B-B are located at different chainages along the same slope and describe LOS displacement from the slope toe to the crest at two locations.

4. MONITORING RESULTS AND ANALYSIS

4.1 D-InSAR LOS displacement and GNSS vertical displacement results

For the period from December 2021 to August 2022, the D-InSAR LOS displacement series at BD-1 to BD-4 are shown in Figure 6, the concurrent GNSS vertical displacement series are shown in Figure 7, and their trends and magnitudes are compared in Figure 8. Both datasets showed relatively small fluctuations from December 13, 2021 to April 2022. Relatively large changes occurred in both datasets around April 24 and August 1, 2022, indicating good correspondence during the main fluctuation stages and characteristic periods. The D-InSAR results were consistent with the field GNSS observations and effectively captured the main displacement changes of the slope, demonstrating the reliability of D-InSAR for monitoring this highway slope.

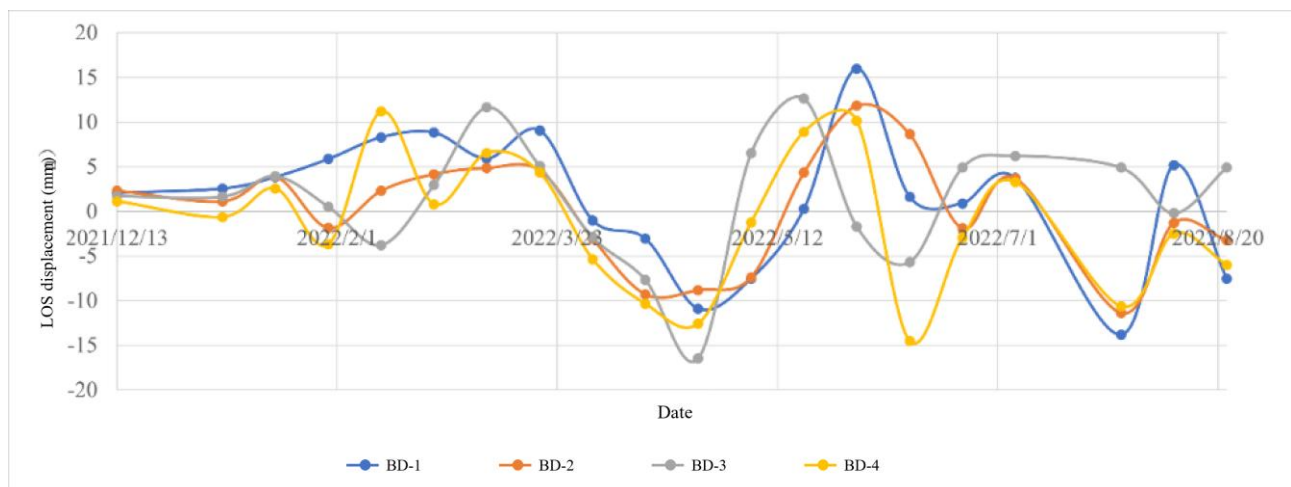


Figure 6. D-InSAR LOS displacement time series at the monitoring stations

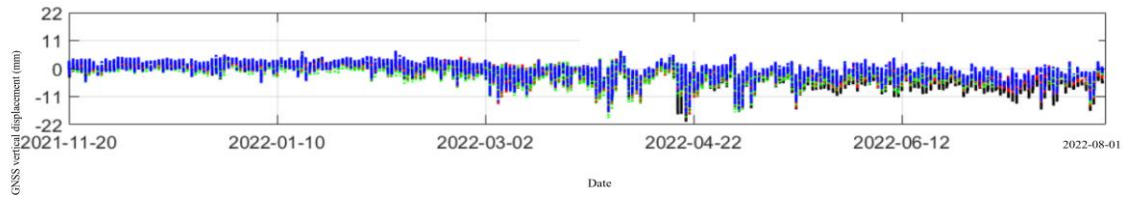


Figure 7. GNSS vertical displacement time series

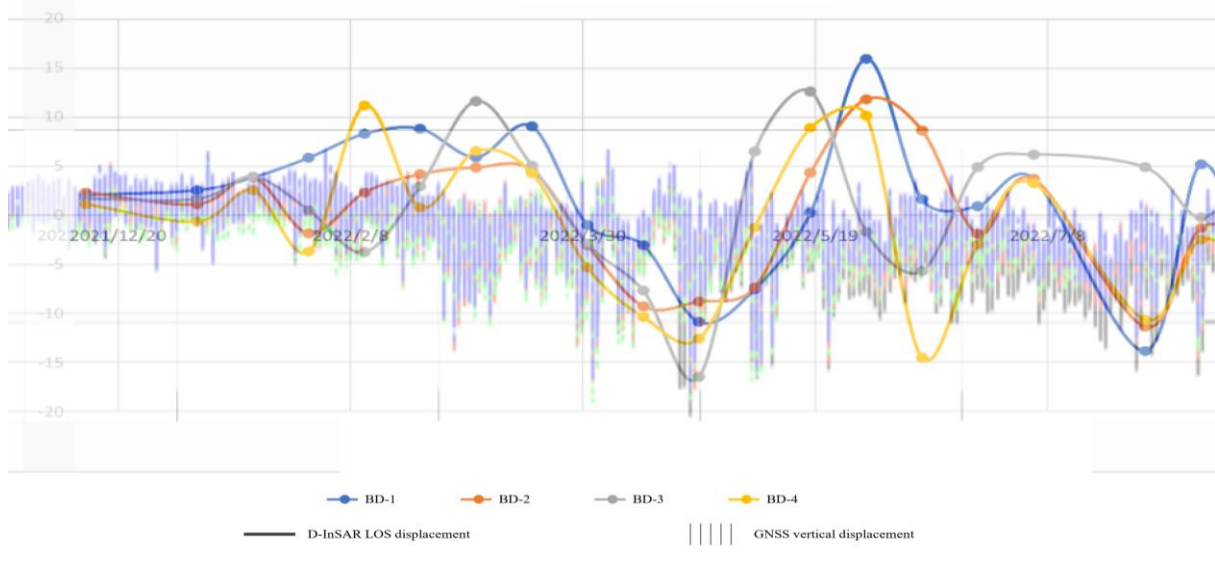


Figure 8. Comparison of D-InSAR LOS displacement and GNSS vertical displacement trends

Table 3. Statistical comparison of D-InSAR LOS displacement and GNSS vertical displacement (mm)

Station	Maximum GNSS Vertical Displacement	Minimum GNSS Vertical Displacement	GNSS Vertical Displacement Amplitude	Maximum D-InSAR LOS Displacement	Minimum D-InSAR LOS Displacement	D-InSAR LOS Displacement Amplitude	Amplitude Difference at Corresponding Station
BD-1	6.20	-20.80	27.00	16.00	-13.84	29.84	2.84
BD-2	7.40	-20.00	27.40	11.82	-11.94	23.76	3.64
BD-3	6.70	-19.50	26.10	12.63	-16.48	29.11	3.01
BD-4	7.30	-17.80	25.10	11.18	-14.54	25.72	0.62

The amplitude in Table 3 is the difference between the maximum and minimum values during the monitoring period. The GNSS vertical displacement amplitudes at the four stations ranged from 25.10 to 27.40 mm, whereas the D-InSAR LOS displacement amplitudes ranged from 23.76 to 29.84 mm. The amplitude differences at corresponding stations ranged from 0.62 to 3.64 mm. BD-4 had the smallest amplitude difference, at 0.62 mm, whereas BD-2 had the largest, at 3.64 mm. As shown in Figure 8, the D-InSAR and GNSS series followed similar trends during the main fluctuation stages, and both showed large changes around April 24 and August 1, 2022. Their close correspondence during characteristic periods and similar displacement amplitudes indicate that D-InSAR was consistent with the field GNSS observations and effectively captured the main deformation changes in the study area.

4.2 Slope deformation and safety status during the monitoring period

As shown in Figure 6, the D-InSAR LOS displacement at BD-1 to BD-4 generally fluctuated around zero, with values ranging from -16.48 to 16.00 mm. Fluctuations were small

from December 2021 to February 2022. Some stations showed negative changes from March to April 2022. A pronounced change occurred around April 24, 2022, followed by a reversal. Relatively large changes occurred again around August 1, 2022.

Although displacement at the monitoring stations fluctuated in stages, no sustained acceleration or continuously increasing unidirectional deformation was observed. The slope therefore remained in a relatively stable deformation state during the monitoring period. The pronounced changes around April and August 2022 should be prioritized for field verification.

4.3 Elevation-dependent responses and overall deformation patterns along typical profiles

4.3.1 Monitoring results along profile A-A

Profile A-A contains five representative points at different elevations, designated A-A-0 to A-A-4. A-A-0 is located at the slope toe, and A-A-1 to A-A-4 are located successively on the first through fourth slope stages. Their LOS displacement series showed similar stage-dependent trends, but the response amplitudes differed markedly among elevations.

Under the displacement sign convention adopted in this

study, positive values indicate an uplift tendency and negative values indicate a settlement tendency. During positive changes, representative points near the slope toe generally showed larger positive displacement, and the displacement tended to increase toward the toe. During negative changes on March 31, April 12, April 24, and July 29, 2022, settlement generally increased toward the slope crest, as shown in Figure

9.

To examine the relative responses at the slope toe and crest more clearly, the displacement series at A-A-0 and A-A-4 are compared in Figure 10. The A-A-0 curve generally lies above the A-A-4 curve. This relationship indicates that the toe response was greater during uplift, whereas the crest response was greater during overall settlement.

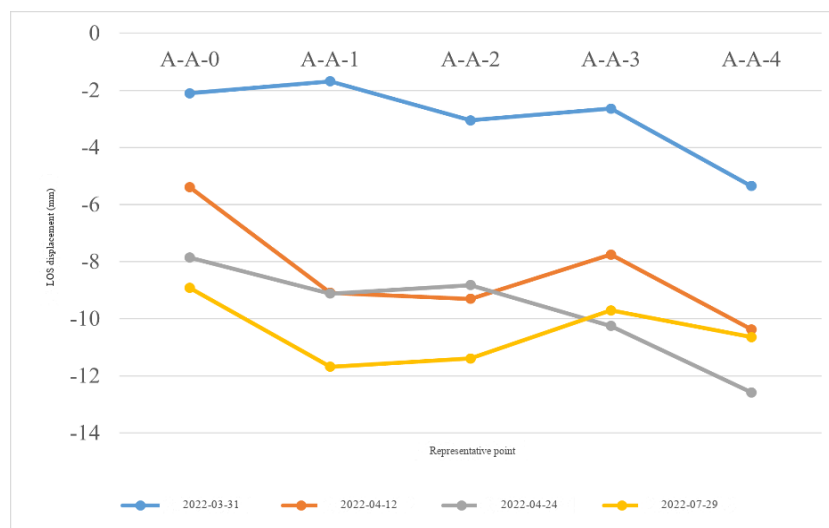


Figure 9. LOS displacement variations along profile A-A on typical dates

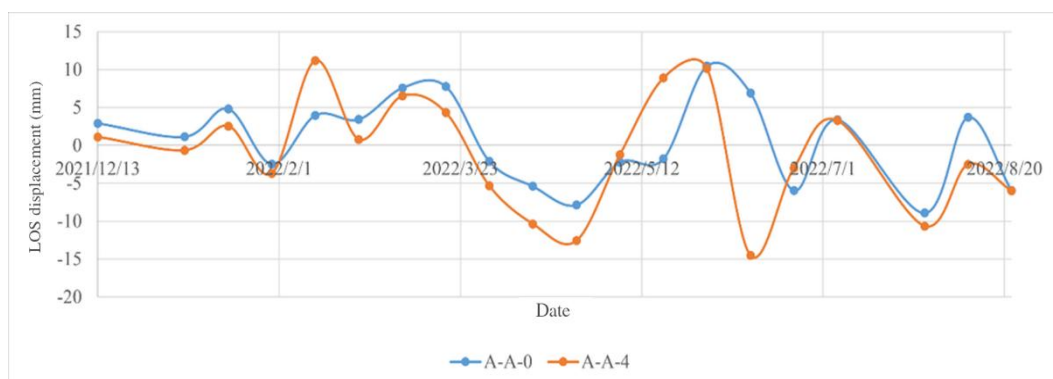


Figure 10. LOS displacement time series at A-A-0 and A-A-4

4.3.2 Monitoring results along profile B-B

Profile B-B contains five representative points at different elevations, designated B-B-0 to B-B-4. B-B-0 is located at the slope toe, and B-B-1 to B-B-4 are located successively at different slope stages or their corresponding crests. Their LOS displacement series showed stage correspondence, while response amplitudes varied among elevations.

Figure 11 shows that displacement responses differed among the monitoring locations. When the slope exhibited an uplift tendency, displacement at the toe point B-B-0 was generally greater than that at the upper points, indicating a stronger uplift response at the toe. When the slope exhibited a settlement tendency, settlement generally increased toward the crest. Figure 12 compares the displacement series at the toe point B-B-0 and crest point B-B-4. Their responses were not identical, but the overall elevation-dependent pattern was similar to that observed along profile A-A.

4.3.3 Elevation-dependent response patterns and overall deformation analysis

Results from profiles A-A and B-B show that LOS

displacement at different elevations along the same profile followed broadly corresponding stages, while the response amplitude varied systematically with elevation. During overall uplift, displacement at the slope toe was generally greater than that at upper positions, indicating a stronger toe response as the profile moved upward. During overall settlement, negative displacement was generally greater at upper positions, indicating a stronger settlement response as the profile moved downward. During some characteristic periods along profile B-B, an uplift tendency at the slope toe coincided with a settlement tendency at the upper slope, reflecting profile-scale overall downward deformation.

A single point records only local displacement and cannot fully represent the deformation state of an entire slope. Comparing displacement direction and relative amplitude among representative points at the slope toe, midslope, and crest, together with their variation with elevation, makes it possible to identify the overall deformation tendency of a profile.

Based on the monitoring results at different elevations along profiles A-A and B-B, their common elevation-dependent

responses are summarized as the profile-scale overall deformation patterns shown in Figure 13. These patterns support the interpretation of the overall deformation tendency.

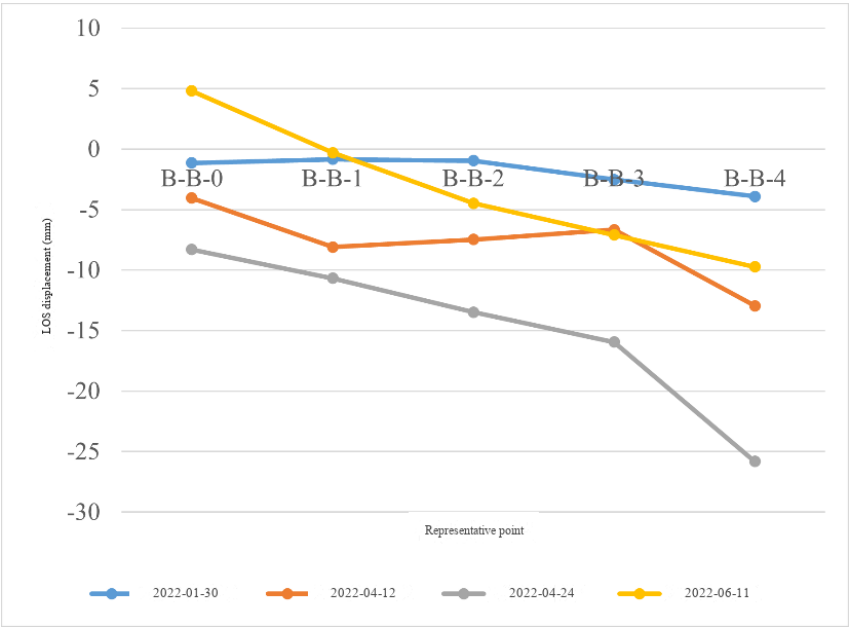


Figure 11. LOS displacement variations along profile B-B at typical times

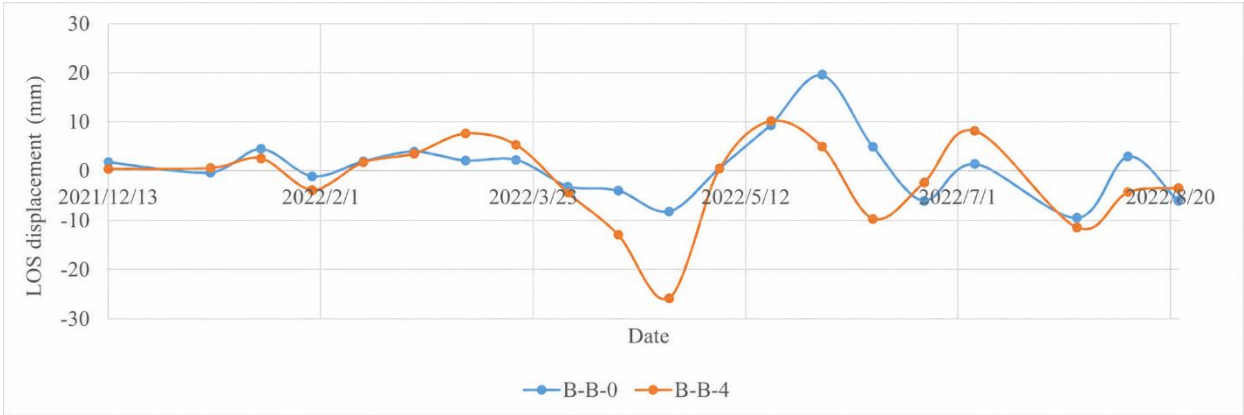


Figure 12. LOS displacement time series at B-B-0 and B-B-4

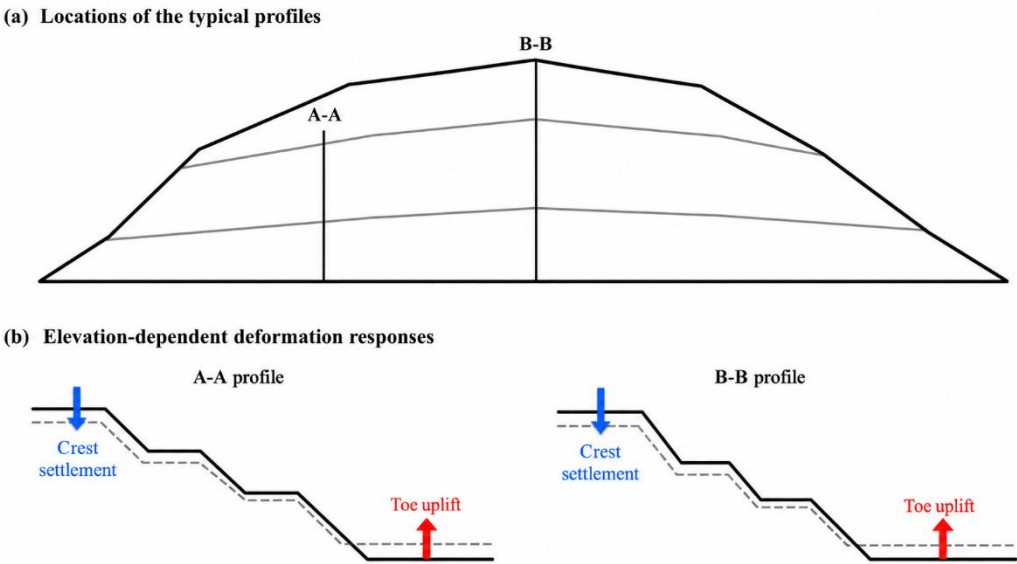


Figure 13. Schematic summary of elevation-dependent responses and overall deformation patterns

5. CONCLUSIONS

D-InSAR was used to monitor LOS displacement of an operational multistage highway slope in Anhui Province. Field GNSS observations and displacement responses at different elevations along typical profiles were then used to analyze the slope deformation state and overall deformation characteristics. The main conclusions are as follows:

(1) From December 2021 to August 2022, D-InSAR LOS displacement and GNSS vertical displacement were consistent in their main trends, characteristic periods, and overall fluctuation magnitudes. Both datasets showed large changes around April 24 and August 1, 2022. The GNSS vertical displacement amplitudes at the four stations ranged from 25.10 to 27.40 mm, whereas the D-InSAR LOS displacement amplitudes ranged from 23.76 to 29.84 mm. The amplitude differences at corresponding stations ranged from 0.62 to 3.64 mm. These results show that D-InSAR reliably captured the main slope displacement changes.

(2) Displacement at the monitoring stations fluctuated in stages, but no sustained acceleration or continuously increasing unidirectional movement was observed. The slope therefore remained in a relatively stable deformation state during the monitoring period. The pronounced changes around April and August 2022 warrant attention during subsequent field inspections and targeted verification.

(3) LOS displacement responses at different elevations along profiles A-A and B-B showed systematic differences. The slope-toe response was generally greater during uplift, whereas settlement was generally greater at upper positions during settlement stages. Along profile B-B, slope-toe uplift and upper-slope settlement also coexisted during some periods. Comparing the displacement directions and relative amplitudes at the slope toe, midslope, and crest can identify the overall deformation tendency of a typical profile.

Overall, integrating D-InSAR with GNSS effectively characterized the main deformation processes of the operational highway slope, and displacement differences among representative points at different elevations supported profile-scale overall deformation analysis. The monitoring duration and number of typical profiles were limited, and long-term displacement prediction and quantitative safety classification were not conducted. Future work may use longer InSAR monitoring series, deep-learning methods for future displacement prediction, and safety-assessment indicators to support slope-risk warning and maintenance management.

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