

Long-term evolution and reactivation mechanisms of a typical loess–mudstone landslide in eastern Qinghai: Insights from remote sensing and in situ monitoring

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Case Report

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Abstract

Background

Loess–mudstone landslides are common geological hazards on the Loess Plateau, where natural processes and engineering activities influence slope reactivation. This study examines the long-term evolution, recent deformation, and reactivation mechanism of the Dazhuang landslide in Datong County, Qinghai Province. Historical records, multi-temporal orthophotos from 2003 to 2024, field geological investigations, Global Navigation Satellite System (GNSS) monitoring from 2021–2022 and 2024–2026, and concurrent rainfall data were integrated.

Results

Long-term excavation for brick production altered the slope geometry and reduced toe support. Sliding events occurred in 2007, 2010, and 2016, with the 2016 event producing the largest mapped expansion. In 2022, the rear margin expanded locally and internal deformation increased during heavy rainfall. Over the 2021–2022 monitoring period, total cumulative displacements at the upper, middle, and lower monitoring points reached 72.6, 66.5, and 51.6 mm, respectively. The monitoring records show spatially variable deformation, with pronounced late-period acceleration at the middle monitoring point. From autumn 2024 to July 2026, the three monitoring points exhibited millimeter-scale fluctuations without sustained acceleration, indicating reduced activity within the monitored area.

Conclusions

The landslide history suggests that toe excavation and repeated sliding created persistent structural damage that favored subsequent rainfall-driven reactivation. The loess–mudstone stratigraphy, pre-existing cracks, and local runoff concentration provide a geological and hydrological basis for this behavior. Combining geomorphic reconstruction with monitoring across distinct periods helps characterize changing landslide activity and guide monitoring of previously disturbed slopes.

1 Introduction

The transitional zone between the Chinese Loess Plateau and the Tibetan Plateau in northwestern China is highly susceptible to geological hazards. Slopes with a typical two-layer stratigraphy, consisting of overlying aeolian loess and underlying Neogene mudstone (red beds), are widely distributed in this region (Juang et al. 2019). Loess is characterized by well-developed vertical joints, pronounced water sensitivity, and collapsibility (Yao et al. 2020), whereas the underlying mudstone generally has relatively low permeability and is susceptible to weathering and softening. Consequently, groundwater can accumulate near the loess–mudstone contact, where weak zones susceptible to sliding may develop, contributing to the occurrence of loess–mudstone interface landslides (Li et al. 2016; Ma et al. 2025;

Xue et al. 2026a). Under natural conditions, such landslides are commonly triggered by heavy rainfall and earthquakes (Peng et al. 2015; Peng et al. 2024). With increasing urban development and engineering construction, toe excavation associated with road construction, factory development, and soil extraction has also become an important anthropogenic trigger (Meng et al. 2021; Huang et al. 2022; Peng et al. 2019; Xue et al. 2026b).

Toe excavation not only modifies the original slope geometry and creates a free face but also alters the stress boundary conditions of the slope, leading to unloading rebound, stress redistribution, and local stress concentration (Wang et al. 2014; Zhuang and Peng 2014; Zhang et al. 2020). Such engineering disturbance does not necessarily result in immediate slope failure. Instead, excavated slopes may undergo prolonged slow deformation and progressive damage accumulation, followed by delayed instability and episodic reactivation under subsequent hydraulic forcing (Peng et al. 2019; Wu et al. 2026). Rainfall infiltration can increase the water content of the slip-zone soil and reduce its peak and residual shear strengths (Wang et al. 2021), while also promoting softening and strength degradation of the underlying mudstone (Zhang et al. 2016). Pre-existing cracks formed during earlier deformation stages may further act as preferential infiltration pathways, accelerating the downward migration of rainwater into the slope interior (Zhang et al. 2021). Therefore, the long-term mechanical disturbance induced by toe excavation and the short-term hydraulic effects of rainfall may interact to produce a progressive hydro-mechanical failure process characterized by delayed response and episodic reactivation (Wu et al. 2026; Yu et al. 2023; Xue and Azmi 2026), complicating early landslide identification and hazard assessment.

Previous studies have investigated the failure mechanisms of loess and loess–mudstone slopes subjected to excavation or rainfall through field investigations, laboratory tests, physical modeling, and numerical simulations (Li et al. 2016; Huang et al. 2022; Zhang et al. 2020; Wang et al. 2021). These studies have largely examined single failure events, short-term deformation responses, or failure mechanisms under specific triggering conditions. The evolution of previously disturbed slopes and their subsequent reactivation during rainfall remain important questions. Field monitoring across different deformation stages can help connect long-term geomorphic changes with recent landslide activity. Therefore, reconstructing the long-term evolution of slopes subjected to toe excavation and analyzing the rainfall response of slope deformation at different evolutionary stages can improve understanding of delayed reactivation in loess–mudstone landslides and inform monitoring and early warning.

The Dazhuang landslide in Chengguan Town, Datong County, Qinghai Province, is a typical large loess–mudstone composite landslide. From the mid-1970s onward, long-term soil excavation at the slope toe created a high, steep free face and progressively disturbed the slope. The slope subsequently underwent long-term deformation and experienced sliding events in April 2007 and September 2010. On 25 September 2016, a large-scale reactivation occurred under rainfall conditions, involving a sliding volume of approximately $5.4 \times 10^6 \text{ m}^3$. Although the brickworks at the slope toe ceased operation in 2013, pronounced deformation recurred during heavy rainfall in August–September 2022, accompanied by through-going cracks, tilted and bent trees, and other deformation features.

Based on historical disaster records, remote sensing imagery, and field investigation data for the Dazhuang landslide, together with two periods of Global Navigation Satellite System (GNSS) surface-displacement monitoring and concurrent rainfall data from 2021–2022 and 2024–2026, this study focuses on three objectives: (1) to reconstruct the multi-stage evolution of the Dazhuang landslide under long-term toe excavation and subsequent rainfall using historical imagery, disaster records, and field geological characteristics; (2) to analyze the displacement characteristics and rainfall response during the pronounced deformation stage in 2022, and to evaluate the subsequent deformation state using the 2024–2026 monitoring results; and (3) to investigate the landslide reactivation mechanism by integrating long-term geomorphic evolution, surface deformation, rainfall response, and field geological evidence, with emphasis on toe excavation, rainfall infiltration, and local runoff concentration near the water-diversion pipeline. The results inform the assessment and monitoring of previously disturbed landslides on the Loess Plateau.

2 Geomorphology and geological setting

The Dazhuang landslide is located in the Huangshui River Basin in eastern Qinghai Province, northwest of Xining (Fig. 1a). The study area is characterized mainly by loess hills and river valleys. The main valley and tributary gullies are well developed, and fluvial incision has formed geomorphic units including ridges, gully slopes, and valley floors. The slopes generally descend from the northern mountains toward the valley lowlands and show pronounced topographic relief. Long-term gully erosion has strongly dissected the loess-covered terrain, producing exposed slope faces that favor landslide formation and evolution.

The stratigraphy of the study area comprises pre-Quaternary bedrock and Quaternary unconsolidated deposits (Fig. 1b). Middle–Upper Pleistocene loess is widely distributed on hills and slopes along both sides of the main valley, whereas Holocene alluvial–proluvial deposits occur mainly as belts along the main valley and tributary valley floors. Neogene gypsiferous mudstone is locally exposed. Lower Sinian strata (*Z1*) are extensively exposed in the northern and southern mountainous areas; Upper Triassic strata (*T3*) occur mainly as belts in the northwest, with local exposures in the east and southwest; and Middle–Lower Jurassic strata (*J1–2*), dominated by sandstone and shale, are mainly distributed in the southeast, with small exposures northwest of the landslide. The strata directly related to the Dazhuang landslide are primarily Quaternary loess and the underlying Neogene mudstone.

The Dazhuang landslide is situated on the northern side of the main valley, close to the confluence of a tributary gully and the main valley, at the transition from loess-covered slopes to valley terrain. The landslide slope has substantial relative relief. The upper slope materials consist mainly of Malan loess and loose deposits produced by multiple historical sliding events, whereas the underlying stratum is Neogene mudstone. This stratigraphic combination exhibits a marked hydrogeological contrast: pores and fractures in the overlying loess facilitate rainfall infiltration, whereas the underlying mudstone has relatively low permeability and is water-sensitive, which can promote the accumulation of infiltrated water near the loess–mudstone contact zone. The free-face topography produced by gully incision,

together with the loess–mudstone two-layer stratigraphy, provides the fundamental geomorphological and geological conditions for landslide formation, long-term deformation, and subsequent reactivation.

3 Landslide characteristics

The Dazhuang landslide occupies the slope on the northern bank of the Heilin River in Datong County, Xining, with Dazhuang Village and Yangpo Village located near the slope toe (Fig. 2). The old landslide is approximately 800 m long and 1,700 m wide, with an average thickness of about 30 m and an estimated volume of approximately $4.0 \times 10^7 \text{ m}^3$. The elevations of the rear margin and slope toe are approximately 2,740 and 2,550 m, respectively, giving a relative relief of about 190 m and an average slope angle of approximately 14° . Owing to repeated sliding and long-term surface erosion, three levels of landslide benches have developed on the slope, which is dissected by multiple gullies and exhibits a distinct stepped morphology.

The 2024 unmanned aerial vehicle (UAV) orthophoto shows that the main deformation area is located in the western part of the old landslide. In plan view, the area is irregular in shape and extends generally from north to south, with the rear margin in the upper slope and the front extending toward the valley near the slope toe. This area is approximately 700 m long in the north–south direction and 100–500 m wide in the east–west direction, covers approximately 0.2 km^2 , and has a main sliding direction of about 205° . A relatively continuous main scarp occurs along the rear margin, whereas multiple stepped benches and deeply incised gullies occur in the middle and lower parts. During the continuous rainfall in 2022, pre-existing gullies were deepened by approximately 1–2 m, and local gully banks experienced collapse and mudflow-related failure.

The river flows along the southern toe of the landslide, and several spring outlets occur in the middle and eastern parts of the slope, indicating groundwater discharge within the slope. Cracks in the upper slope, local ponded depressions, and the strip-shaped subsidence zone near the water-diversion project may all affect surface-water concentration and infiltration (Fig. 2a).

Comparison of the historical landslide boundaries (Fig. 2b) shows that the landslide area identified in 2013 was mainly concentrated in the middle–front part of the slope. Following the large-scale reactivation in 2016, the landslide expanded markedly toward the rear margin and both lateral sides. In 2024, the landslide generally retained the main outline formed in 2016, although local adjustments remained at the rear margin and along parts of the boundary. Historical investigation records indicate that the Dazhuang landslide experienced sliding events of different magnitudes in 2007, 2010, and 2016, demonstrating repeated activity within and around the pre-existing landslide. Its detailed evolutionary process is further analyzed in Section 5 using multi-temporal orthophotos.

To characterize recent landslide activity, GNSS surface-displacement monitoring points were installed within the landslide, and a rain gauge was deployed in the upper part of the slope (Fig. 2a). These

measurements provide the basis for subsequent analyses of the 2022 landslide reactivation, rainfall–deformation response, and post-reactivation deformation during 2024–2026.

4 Data and methods

The analysis combined historical landslide records, nine orthophotos acquired between 2003 and 2024 (Fig. 3), field observations from 2022 and 2024, and GNSS and rainfall records from 2021–2022 and 2024–2026 (Figs. 4 and 5). Multi-temporal imagery was compared to trace changes in excavation extent, landslide boundaries, and slope morphology. Field observations characterized scarps, cracks, seepage, ponding, and landslide materials, and were combined with topographic data to construct a longitudinal geological profile. GNSS displacement records from the upper, middle, and lower parts of the slope were examined alongside rainfall records to describe spatial differences in movement and temporal changes in landslide activity.

5 Long-term evolution and deformation (2003–2026)

From the mid-1970s onward, long-term slope cutting and soil excavation for brick production at the slope toe gradually created a steep excavation face approximately 15–20 m high. Orthophotos from 2003 and 2006 (Fig. 3a, b) show that the excavation extent above the brickworks continued to expand, progressively disturbing the original toe morphology and support conditions. Historical records indicate that cracks began to appear in the upper slope in 2005, after which the slope entered a stage of pronounced deformation. Long-term toe excavation altered the slope geometry and boundary conditions, creating an adverse engineering geological setting for subsequent sliding.

On 25 April 2007, sliding occurred in the middle–front part of the Dazhuang landslide, involving a volume of approximately $9.0 \times 10^5 \text{ m}^3$ and damaging approximately 300,000 bricks at the Dazhuang brickworks and about 1.33 ha of farmland (20 mu). On 29 September 2010, another local sliding event occurred, with a volume of approximately $1.1 \times 10^5 \text{ m}^3$, damaging approximately 100,000 unfired bricks. After 2013, engineering activities such as soil extraction continued near the slope toe. Multi-temporal imagery from 2013 to 2015 shows that soil extraction progressively cut into and modified the landslide front, removing part of the pre-existing sliding mass. As a result, the recognizable landslide boundary exhibited an apparent contraction (Fig. 3c, d), accompanied by further modification of the toe geometry and support conditions.

On 25 September 2016, the Dazhuang landslide underwent another large-scale reactivation, involving a sliding volume of approximately $5.4 \times 10^6 \text{ m}^3$. Imagery acquired in October 2016 (Fig. 3e) shows pronounced upslope expansion of the rear margin, widespread destruction of the original terraces, strong internal topographic disruption, and a distinct tongue-shaped accumulation at the front. This event produced the largest mapped spatial expansion in the 2003–2024 imagery and largely established its present overall morphology.

From 2018 to 2020, changes in the overall landslide boundary were limited, and the rear scarp and frontal morphology formed in 2016 were largely preserved. By 2022, the overall outline largely retained the earlier morphology, but the upper rear margin locally expanded further upslope, indicating episodic reactivation of the pre-existing landslide. The 2024 imagery shows only limited changes in the overall outline relative to 2022, while the newly expanded rear-margin area remained preserved.

During the heavy rainfall period from August to September 2022, the slope exhibited pronounced hydrological and deformation responses. Field investigations identified subsidence pits, cracks, and local sliding on the landslide benches. At the crown, a crack approximately 250 m long, 0.1–0.4 m wide, and up to about 1.6 m in visible depth was observed, together with ponded depressions and tilted and bent trees. Near the water-diversion pipeline on the eastern bench, a strip-shaped subsidence zone approximately 0.2 m wide had developed. This depression may concentrate surface runoff and promote local infiltration.

Concurrent GNSS monitoring recorded sustained deformation (Fig. 4). Over the 2021–2022 monitoring period, total cumulative displacements at DB01, DB02, and DB03, located in the upper, middle, and lower parts of the landslide north of the Dazhuang brickworks, reached 72.6, 66.5, and 51.6 mm, respectively. Following the heavy rainfall on 17 August 2022, deformation accelerated, most clearly at DB02. An additional displacement of approximately 29.5 mm was recorded between 17 August and 3 September. The monitoring records show that the magnitude and timing of deformation varied across the slope.

GNSS records from 2024 to 2026 were used to assess activity after the 2022 reactivation (Fig. 5). The three monitoring points initially showed fluctuations of varying amplitudes in horizontal, vertical, and total displacement. From autumn 2024 to July 2026, the recorded displacements generally fluctuated within a millimeter-scale range without sustained acceleration. This pattern indicates lower activity at the monitored locations than in 2022.

Several substantial rainfall events occurred during 2024–2026, but the three monitoring points showed no sustained acceleration associated with these events. Together, the two monitoring periods document pronounced deformation in 2022 followed by low-amplitude displacement fluctuations in 2024–2026. Pre-existing cracks, weak zones, and local runoff concentration remain relevant to future activity and warrant continued monitoring.

6 Field investigation and landslide structure

To further characterize the surface deformation, sliding-mass composition, and hydrogeological features of the Dazhuang landslide, a field investigation was conducted in 2024. The investigation focused on the landslide boundary, main scarp, rear-margin cracks, local ponding and seepage, sliding-mass materials, and depositional characteristics at the landslide front. Figure 6a shows the overall landslide morphology and the locations of representative investigation sites. The red dashed line indicates the landslide boundary, whereas the red stars and corresponding letters mark the locations of the geological features shown in Fig. 6b–i.

A prominent main scarp occurs along the rear margin of the landslide (Fig. 6b), where a relatively continuous tensile zone and tensile cracks are visible (Fig. 6c), indicating pronounced tensile deformation in the rear part of the slope. Strip-shaped subsidence and a seepage zone occur locally in the middle–upper part of the landslide (Fig. 6d), while a distinct ponded depression and adjacent tensile cracks are present in the upper part of the landslide (Fig. 6e). A strip-shaped subsidence zone approximately 0.2 m wide near the pipeline of the Yinda–Jihuang Water Diversion Project may concentrate surface runoff and promote infiltration. Owing to repeated sliding and long-term deformation, the landslide mass is strongly fragmented and contains mixed materials. Locally, loess is mixed with highly weathered mudstone debris (Fig. 6f), and loose, irregular deposits occur in the middle–lower accumulation zone (Fig. 6h). Trees are locally tilted and bent (Fig. 6g), indicating that the slope has undergone sustained or repeated slow deformation. The landslide front is close to the residential area (Fig. 6i), indicating that renewed landslide activity could directly affect residents and infrastructure near the slope toe.

Based on topographic data and field investigation results, a longitudinal geological profile of the Dazhuang landslide was constructed along the main sliding direction of approximately 205° (Fig. 7). The profile is approximately 750 m long, and the ground-surface elevation decreases from about 2,660 m at the rear margin to approximately 2,500 m at the front, giving a relative relief of about 160 m. The slope shows an overall stepped morphology descending from rear to front, consistent with the multiple landslide benches identified during the field investigation. A prominent main scarp occurs at the rear margin. The interpreted sliding surface extends from the rear margin into the slope, dips gently toward the front, and gradually approaches the ground surface near the landslide toe. The frontal terrain is relatively gentle, with local alluvial deposits.

The longitudinal profile shows Quaternary Malan loess overlying Neogene mudstone. The interpreted sliding surface lies within the loess in the rear segment and approaches the loess–mudstone contact zone farther downslope. This geometry links deformation in the rear loess to the stratigraphic and hydrological conditions in the middle and lower parts of the slope.

7 Discussion: reactivation mechanism

The landslide history and recent observations suggest that reactivation reflects the combined effects of the loess–mudstone stratigraphy, structural damage associated with toe excavation and repeated sliding, and rainfall infiltration.

7.1 Geological controls

The Dazhuang landslide is a typical loess–mudstone composite landslide. The landslide mass consists mainly of Quaternary aeolian loess overlying Neogene mudstone. The overlying loess contains abundant pores and fractures that facilitate rainfall infiltration, whereas the underlying mudstone has low permeability and pronounced water-sensitive softening behavior. This permeability contrast can favor

water accumulation near the loess–mudstone contact zone, where increased water content can reduce shear strength.

Repeated sliding disrupted the slope and produced cracks and loosened zones. The subsidence pits, crown cracks, local sliding, and tilted trees observed in 2022 document this accumulated deformation. These cracks provide potential infiltration pathways through which subsequent rainfall can affect deeper slope materials.

7.2 Legacy effects of toe excavation

The long-term evolution of the Dazhuang landslide is closely associated with soil excavation at the slope toe. Early deformation events were concentrated mainly north of the Dazhuang brickworks, spatially coinciding with long-term slope cutting and soil excavation at the toe. Toe excavation altered the slope geometry and reduced support at the front, changing the stress conditions within the slope. Repeated excavation maintained a steep frontal face, while successive sliding events expanded the disturbed area and the network of cracks and weak zones. The altered geometry and accumulated structural damage provided a persistent legacy of excavation.

The brickworks closed in 2013, although soil extraction continued near the toe afterward. Reactivation in 2016 and renewed deformation during the heavy rainfall of 2022 show that the disturbed slope remained susceptible to later movement. This sequence suggests that excavation history, inherited slope damage, and subsequent hydrological conditions jointly influenced reactivation.

7.3 Heavy rainfall and local runoff concentration

Pronounced reactivation occurred in 2022. The increase in GNSS displacement during the August rainfall supports rainfall as a trigger for the renewed movement. Rainfall infiltration can increase the water content and unit weight of slope materials and soften weak zones and mudstone, promoting renewed movement.

The strip-shaped subsidence zone near the Yinda–Jihuang pipeline on the eastern landslide bench may also affect the local rainfall response. The depression can collect surface runoff and promote infiltration into the fractured landslide mass. Together with ponded depressions and cracks at the crown, it provides a potential route for localized water input during heavy rainfall.

7.4 Changes in deformation pattern

During 2007–2016, toe excavation and the subsequent upslope expansion of the landslide suggest a retrogressive failure pattern. In 2022, renewed movement involved both local expansion of the rear margin and deformation within the pre-existing landslide. Although total cumulative displacement was greatest at the upper monitoring point, the middle point showed the clearest acceleration late in the monitoring period. Rainfall infiltration into fractured material in the middle–rear part may have promoted renewed movement and increased loading on the downslope mass, contributing to push-type reactivation.

Taken together, the observations support an evolutionary sequence involving geological preconditioning, excavation-related damage, repeated sliding, and rainfall-driven reactivation. The loess–mudstone stratigraphy provides the geological setting, while toe excavation and earlier sliding altered slope geometry and created persistent structural damage. Rainfall infiltration through this disturbed slope offers a mechanism linking the history of engineering disturbance to subsequent reactivation.

8 Conclusions

Based on historical records, multi-temporal orthophotos, field geological investigations, and GNSS monitoring data from 2021–2022 and 2024–2026, this study examined the long-term evolution, recent deformation characteristics, and reactivation mechanism of the Dazhuang landslide. The main conclusions are as follows:

- (1) The Dazhuang landslide has evolved through repeated disturbance and reactivation. Long-term toe excavation at the brickworks progressively altered the slope geometry and support conditions, and subsequent soil extraction further cut and reshaped the landslide front. Sliding events of different magnitudes occurred in 2007, 2010, and 2016. The overall landslide boundary changed little between 2018 and 2020, followed by local upslope expansion of the rear margin in 2022. This sequence shows episodic reactivation within a broadly persistent landslide outline.
- (2) Renewed deformation in 2022 was associated with heavy rainfall. Over the 2021–2022 monitoring period, total cumulative displacements at the upper, middle, and lower monitoring points reached 72.6, 66.5, and 51.6 mm, respectively, while the middle monitoring point showed the clearest late-period acceleration. GNSS records and remote sensing imagery document both internal deformation and local expansion of the rear margin.
- (3) The reactivation mechanism reflects the interaction of geological conditions, excavation-related damage, and rainfall infiltration. The loess–mudstone stratigraphy, altered toe geometry, and fractures produced by earlier deformation created conditions favorable for renewed movement. Rainfall infiltration can soften weak zones, while crown cracks, ponded depressions, and the subsidence zone near the water-diversion pipeline may concentrate local water input. These processes connect the legacy of toe excavation with subsequent rainfall-driven reactivation.
- (4) From autumn 2024 to July 2026, the three GNSS monitoring points showed millimeter-scale displacement fluctuations without sustained acceleration, indicating reduced activity within the monitored area. Continued monitoring of displacement, rainfall, and local runoff pathways is warranted to track future changes in activity.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

R.L., Y.S., Q.J., P.S., and X.Z. drafted the manuscript. R.L. and Q.J. conducted the field investigation and analyzed the evolutionary history. Y.S. and X.Z. interpreted the reactivation mechanism. All authors reviewed the manuscript.

Data availability

All data employed in this work are available from the authors upon request.

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Figures

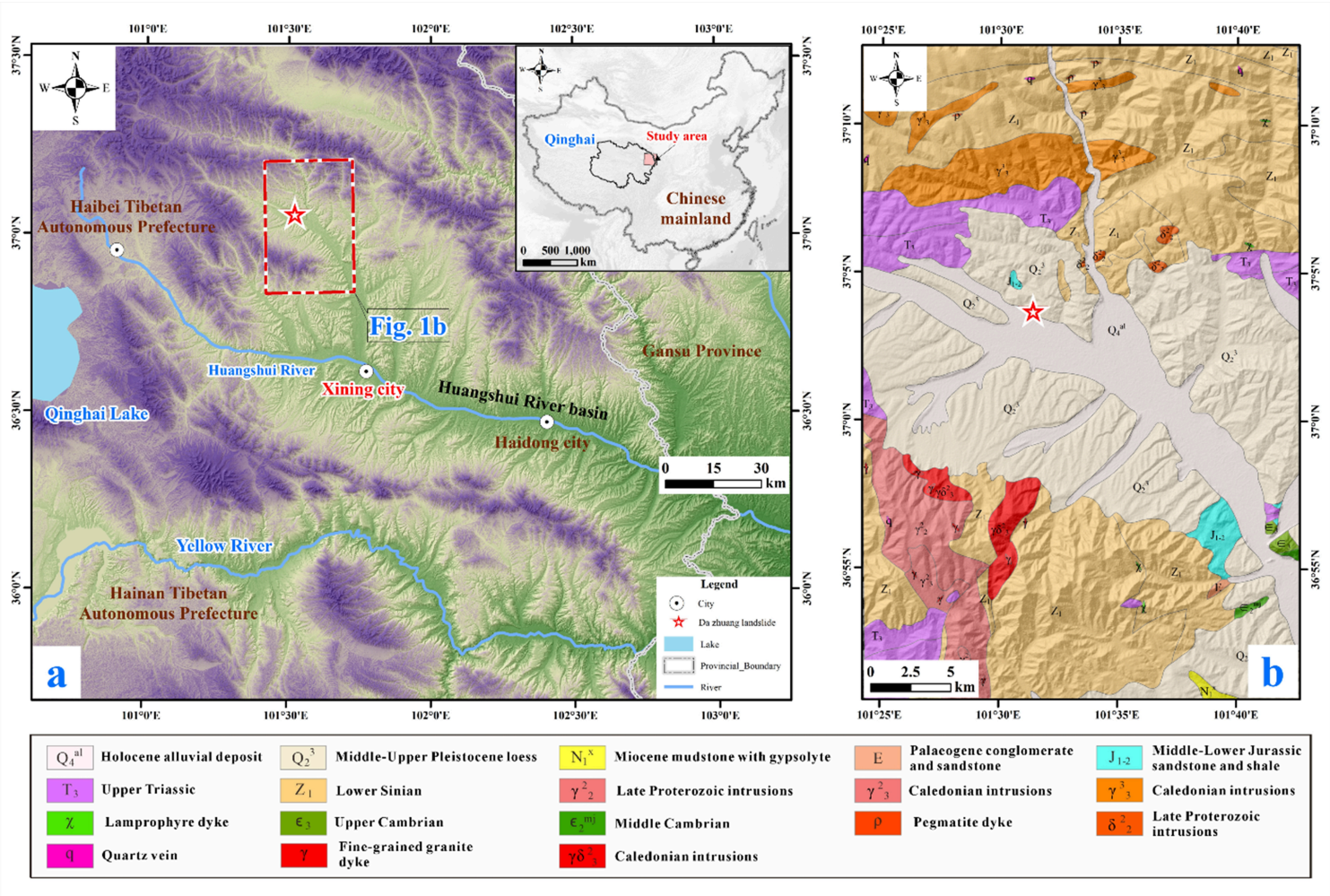


Figure 1

Location and geological setting of the Dazhuang landslide and its vicinity. (a) Location; (b) geological setting.

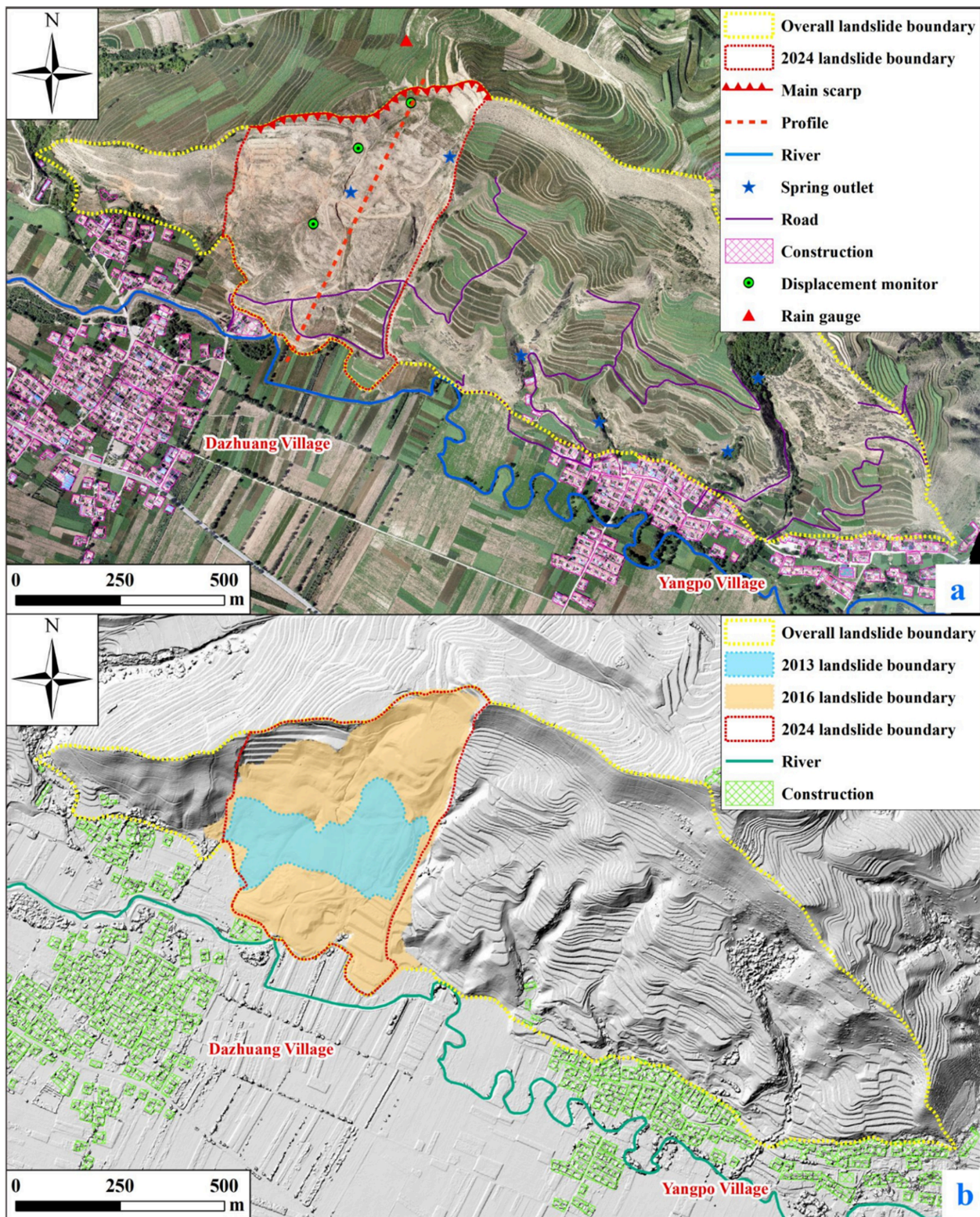


Figure 2

Geomorphology, historical landslide boundaries, and monitoring layout of the Dazhuang landslide. (a) Landslide morphology and monitoring locations; (b) comparison of the landslide boundaries mapped in 2013, 2016, and 2024.



Figure 3

Multi-temporal orthophotos showing the evolution of the Dazhuang landslide from 2003 to 2024: (a) 9 July 2003; (b) 2 February 2006; (c) 8 October 2013; (d) 11 August 2015; (e) 8 October 2016; (f) 13 May 2018; (g) 7 February 2020; (h) 31 October 2022; and (i) 31 July 2024. The green shaded areas in panels (a) and (b) indicate the excavation extent of the brickworks. The pink dashed lines in panels (c) and (d) delineate the mapped landslide or deformation area affected by soil extraction activities. The blue

dashed lines in panels (e)–(g) and the red dashed lines in panels (h)–(i) indicate the interpreted landslide boundaries at the corresponding stages.

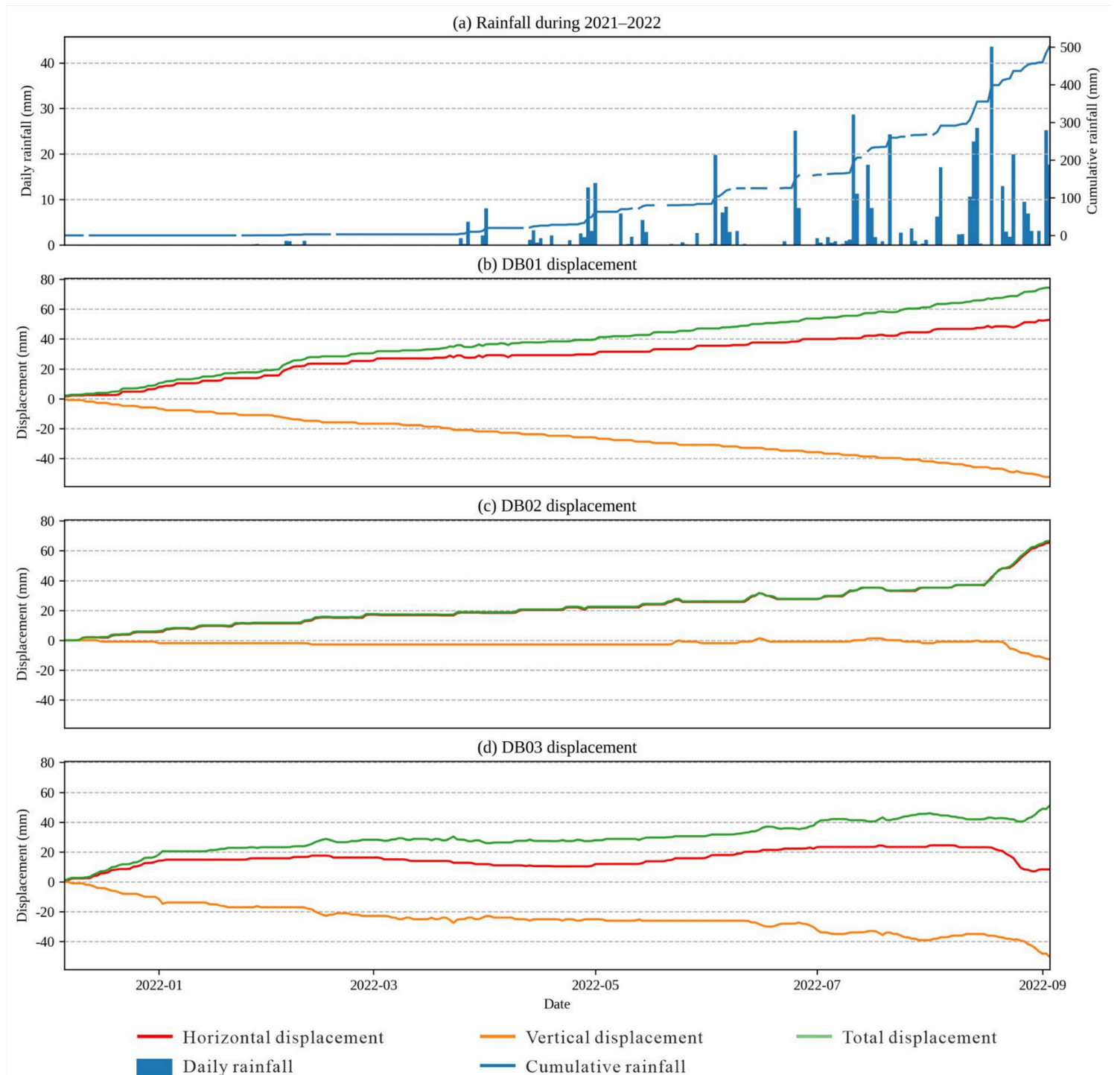


Figure 4

Rainfall and GNSS displacement monitoring results of the Dazhuang landslide from 2021 to 2022. (a) Daily and cumulative rainfall; (b–d) horizontal, vertical, and total displacement at DB01 (upper slope), DB02 (middle slope), and DB03 (lower slope), respectively.

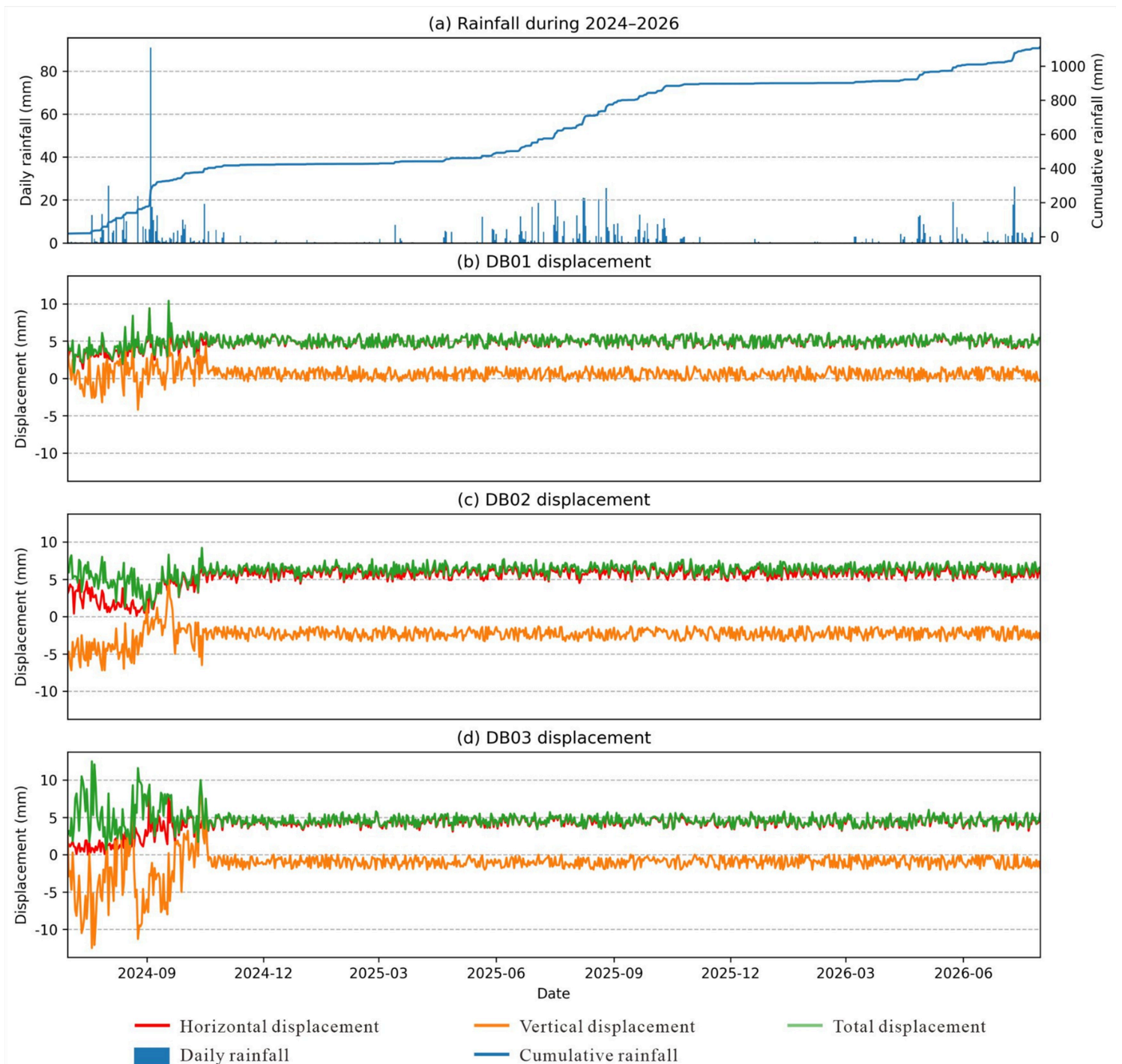


Figure 5

Rainfall and GNSS displacement monitoring results of the Dazhuang landslide from 2024 to 2026. (a) Daily and cumulative rainfall; (b–d) horizontal, vertical, and total displacement at DB01 (upper slope), DB02 (middle slope), and DB03 (lower slope), respectively.

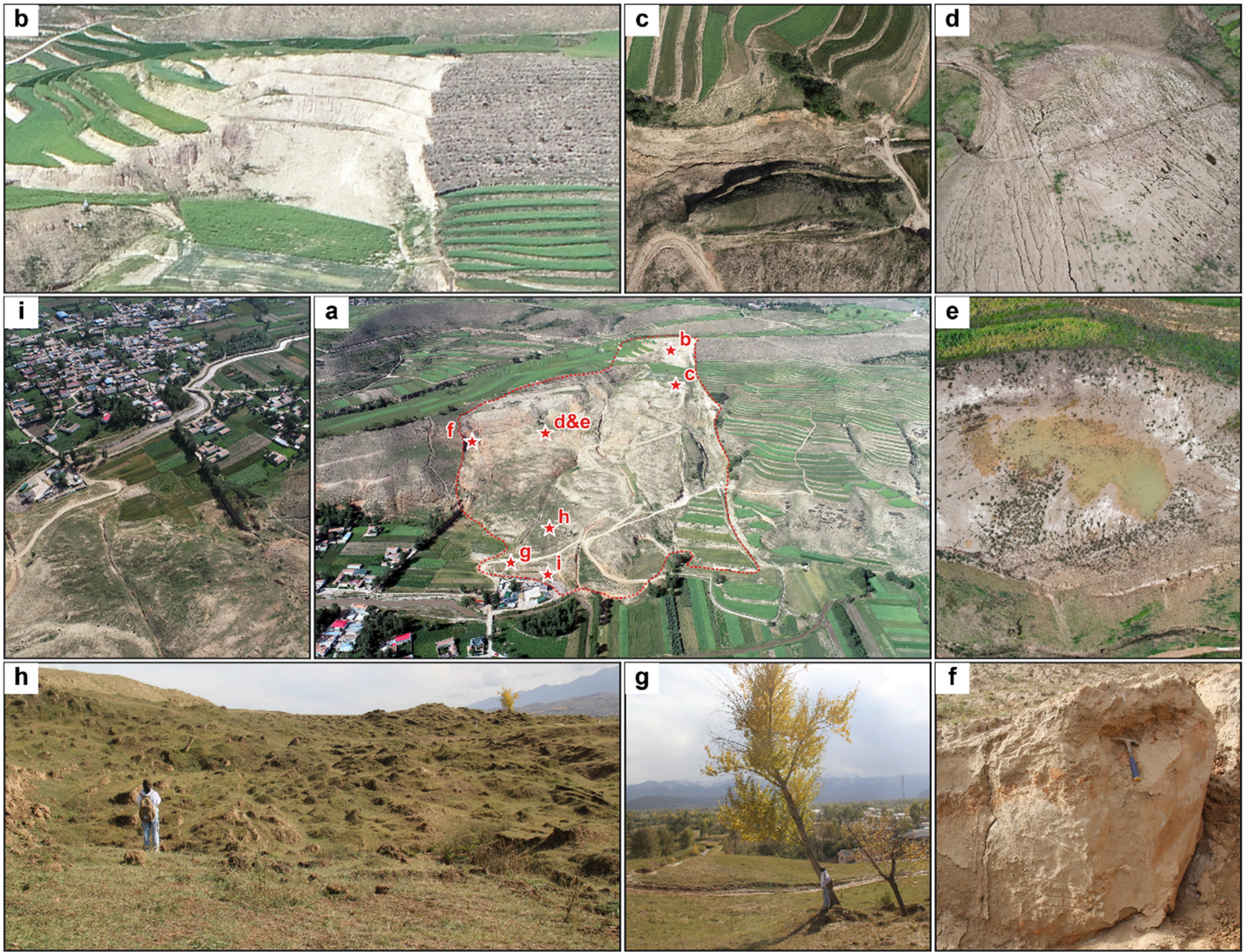


Figure 6

Typical surface deformation and depositional features of the Dazhuang landslide. (a) Panoramic view; (b) main scarp; (c) through-going tensile cracks at the rear margin; (d) seepage zone near the Yinda–Jihuang Water Diversion Project; (e) ponded depression and tensile cracks in the upper part of the landslide; (f) mixed deposits of loess and highly weathered mudstone debris; (g) tilted trees associated with slope deformation; (h) blocky deposits in the accumulation zone; and (i) landslide toe and adjacent residential area. The red dashed line denotes the landslide boundary, and the red stars and corresponding letters indicate the locations of the features shown in each panel.

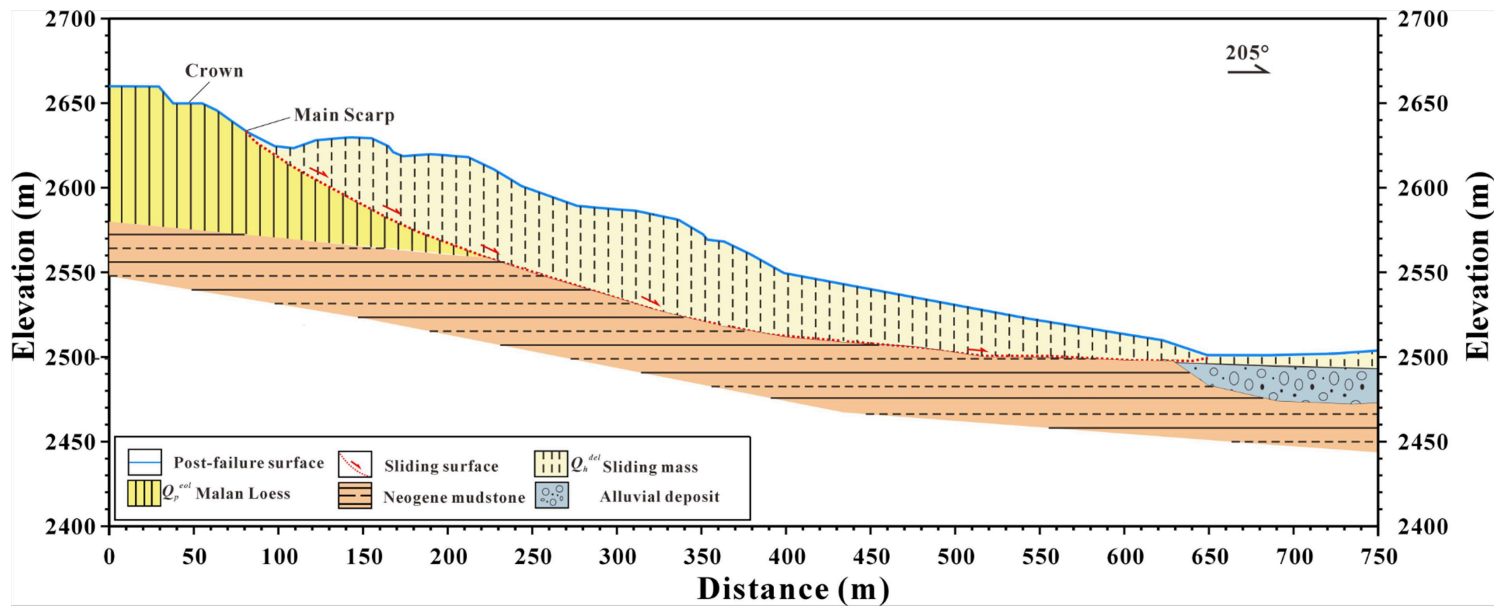


Figure 7

Interpreted longitudinal geological profile of the Dazhuang landslide. The location of the profile is shown in Fig. 2.