

CASE REPORT

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# Successful emergency evacuation from a catastrophic loess landslide reactivated by the torrential rain in October 2021 in Tianshui, Gansu, NW China

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## Abstract

**Background:** At the beginning of October 2021, the northwest China suffered torrential rainfall and several loess landslides were induced in Northwest China. This work presents a typical case (the Zhongzhai landslide) reactivated during this period in Niangniangba town, Tianshui, Gansu, China. The retrogressive failure was triggered again in the early morning of 5 October 2021 after a succession of torrential rain, and buried 2 houses and damaged another 2 houses. In this work, the geometric feature, soil composition, evolution history and failure process were preliminary described based on field investigation, history satellite images, and unmanned aerial vehicle photogrammetry.

**Results:** The Zhongzhai landslide is mainly composed of Malan loess and the underlain silty slate, and the sliding surface is localized at their interface. The tensile cracks near the main scarp provide favorable channels for rainfall precipitation and the permeability difference between loess and silty slate enhances the liquefaction occurrence. The counter-tilt silty slate benefits water impoundment and exacerbates the flow-like slope failure. The lag effect is obvious in the Zhongzhai landslide due to the rainfall infiltration process and pore pressure generation.

**Conclusions:** Although the Zhongzhai landslide is characterized with small scar and shallow sliding surface, it provides a classic case both for evolution history investigation of loess landslide and successful emergency evacuation. Based on our preliminary study, the unstable mass at the source of the Zhongzhai landslide with an area of approximately 3600 m<sup>2</sup> that was slightly displaced in this event and has a high possibility to slide in future. Meanwhile, the Zhongzhai landslide is a retrogressive landslide and progressive failure occurred in the 2021 case, further analysis concerning the relationship among rainfall intensity, infiltration rate and pore water generation, as well as motion feature and runout prediction will be conducted.

**Keywords:** Loess landslide, Rainfall trigger, Geometric feature, Failure process, Northwest China

## Introduction

Climate warming and humidification exacerbates the occurrence of rainfall-induced loess landslides and the frequently and intensely occurrence of rainfall-induced

loess landslides has been an urgent challenge encountered in yellow river basin. The northwest China suffered torrential rainfall and clustered loess landslides were induced in Northwest China in 2021. After the extraordinary rainstorm in July in Henan Province, China, heavy rainfall struck Shanxi, Shannxi, and Gansu, China at the beginning of October 2021 and clustered loess-landslides were triggered. The Zhongzhai landslide, firstly occurred in 2013 with an area of approximately 16,900 m<sup>2</sup>, is a typical retrogressive

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failure in this even. The Zhongzhai landslide that occurred again in the early morning of 5 October 2021 after a succession of torrential rain, initiated from an elevation of 1713 m asl, rushed downslope with a total volume of approximately 15,360 m<sup>3</sup>, spread and rested in front of gully head, burying 2 houses and damaging another 2 houses. The total affected area of the 2021 Zhongzhai landslide is approximately 15,200 m<sup>2</sup>, and the length and the width are 275 m and 102 m, respectively. Fortunately, no causality is reported as the local residents were evacuated timely. It should be noted that an area of approximately 3600 m<sup>2</sup> at the source was slightly displaced in this event and it has a high possibility to slide when suffering intense precipitation and strong seismic ground motion. The Zhongzhai landslide provides a classical case for investigating the evolution history of retrogressive loess landslide.

### Geomorphic feature and geological setting

Niangniangba town lies in the dividing crest of the Yellow River and Yangtze River, and rainstorm frequently strikes this area and its vicinity in summer season (Li et al. 2021; Wang et al. 2020). Meanwhile, Niangniangba town is situated in southeast of Gansu province, the transition zone of the Longxi loess plateau, Qinling mountainous area, and Longshan mountainous area (Zhang et al. 2017), and characterized by rugged terrain and complex geological setting (Fig. 1). The elevation ranges from 1374 to 2250 m. Niangniangba is well-forested and mainly mantled by thin Pleistocene Malan loess with thickness less than 10 m (Li et al. 2021). As illustrated in Fig. 1b, the main strata of Niangniangba town comprise Middle Devonian slate (D<sub>2</sub>), upper Devonian slate and quartz sandstone (D<sub>3</sub>), Yanshanian granite (γ<sub>5</sub>), and Neogene mudstone and sandstone (N<sub>1</sub> and N<sub>2</sub>), accounting for 78.1% of the total area. Preliminary field reconnaissance discovered that the Zhongzhai landslide is a typical loess–bedrock interface landslide and the sliding surface is located in the interface between the underlain silty slate and overlying Malan loess. The Neogene red mudstone can only be sparsely observed at the source area. The Zhongzhai landslide is located on the left bank of the Liujia river, with a relative relief of approximately 120 m and a slope gradient of 20–35°. Due to the soil displacement of the landslide occurrence in 2013, a small funnel-shaped catchment area was formed at the upper slope, which enhances further slope failure occurrence during rainstorm. In addition, the slope is sparsely forested and free face was formed at the lower footslope due to road and farm construction.

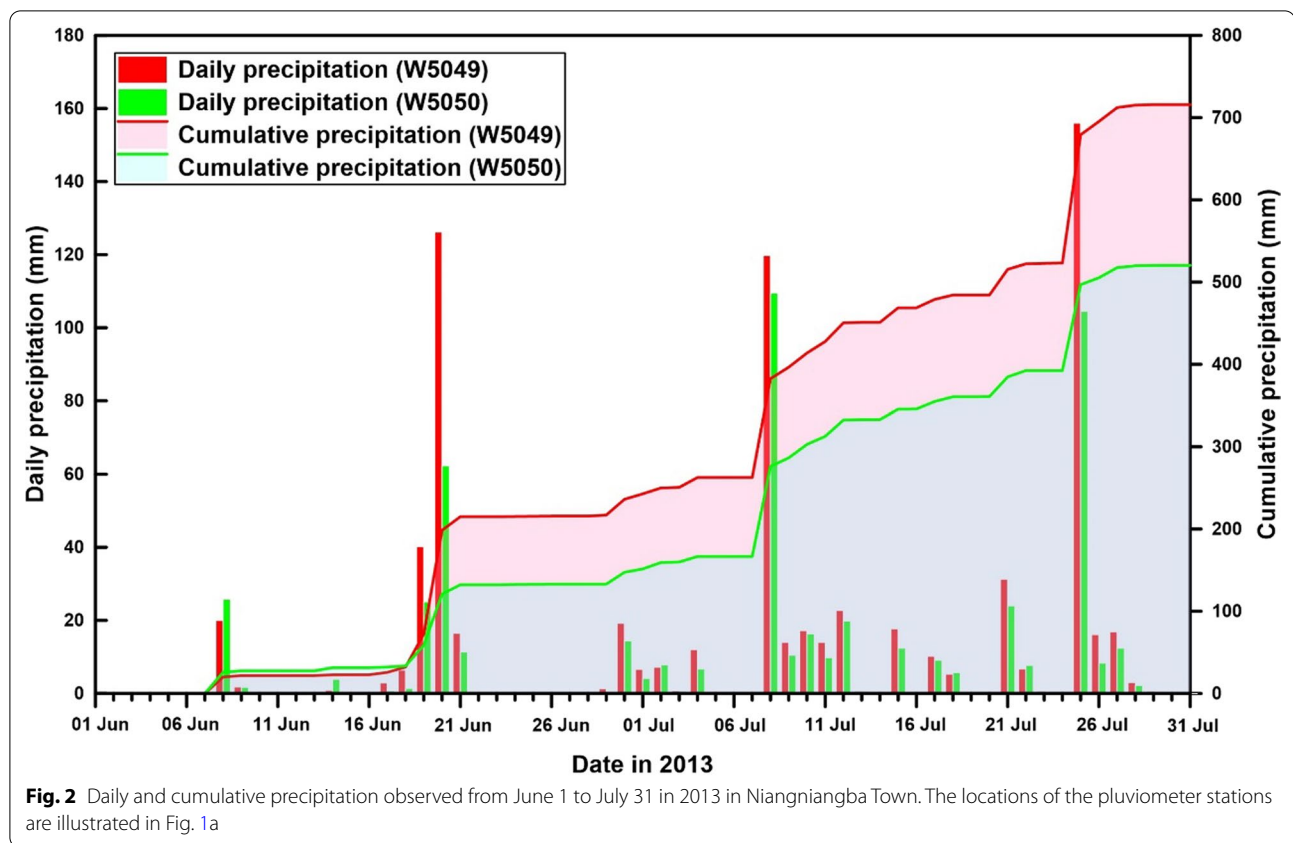
### Rainfall trigger and geometric feature

Niangniangba town is characterized with a semi-humid climate and an average annual precipitation of approximately 491.6 mm (Li et al. 2021). However, the precipitation is concentrated on the summer season. In July 2013, three successions of rainstorm with daily precipitation higher than 100 mm struck the Tianshui area (Fig. 2) and induced thousands of shallow loess landslides (He et al. 2021; Yang et al. 2013). The group-occurring shallow landslides in 2013 claim 24 fatalities and 1 missing person, and the economic loss reaches up to 8.275 billion RMB (Yu et al. 2014; Guo et al. 2015). In fact, a cumulative precipitation as high as 715.8 mm from 1 June 2013 to 31 July 2013 was observed and a high daily precipitation of 156 mm was recorded in the Qianjiaba station (W5049 rain gauge) (Fig. 2). This means that Niangniangba suffered approximately 1.45 times of the average annual precipitation within 2 months. Again, in October 2021, a torrential precipitation struck Niangniangba town. Based on the rain gauge (HHZ001, installed on June 2021 by our team) approximately 28.5 km away from the Zhongzhai landslide, a maximum daily precipitation of 93.93 mm was recorded on 3 October 2021 and the maximum hourly precipitation was 22.54 mm. Although the torrential precipitation at the beginning of October 2021 suffers an eclipse compared with the 2021 event, it resulted in several shallow landslides in Niangniangba town. Thereinto, the Zhongzhai landslide is a prototypical exemplar.

The 2021 Zhongzhai landslide initiated in the early morning of 5 October 2021, following two days of continuous precipitation (Fig. 3). Based on the satellite image and digital elevation model (DEM) (Worldview data) after the 2013 even, as well as the high-resolution terrain and ortho-image generated by unmanned aerial vehicle (UAV) photogrammetry after the 2021 even, the geometric feature of the 2021 Zhongzhai landslide was characterized. The 2021 Zhongzhai landslide is a typical reactivation of the 2013 rainfall-induced landslide case and the main sliding area nearly overlaps the 2013 case. The length and width of the 2021 Zhongzhai landslides are 275 m and 102 m, respectively (Fig. 4a). The pre-failure and post-failure DEMs enable the area, volume and thickness estimation. The area and volume of the landslide source are 8048 m<sup>2</sup> and 15,360 m<sup>3</sup> meaning the average depth of the source is 1.9 m; the area and volume of the landslide deposition are 7153 m<sup>2</sup> and 15,200 m<sup>3</sup> meaning the average depth of the deposition is 2.1 m. The total affected area of the 2021 Zhongzhai landslide is approximately 15,200 m<sup>2</sup>, slightly less than the affected area of the 2013 case (16,900 m<sup>3</sup>). Meanwhile, an area of approximately 3600 m<sup>2</sup> at the upper slope (pink shadow in Fig. 4a) was slightly displace and remained at







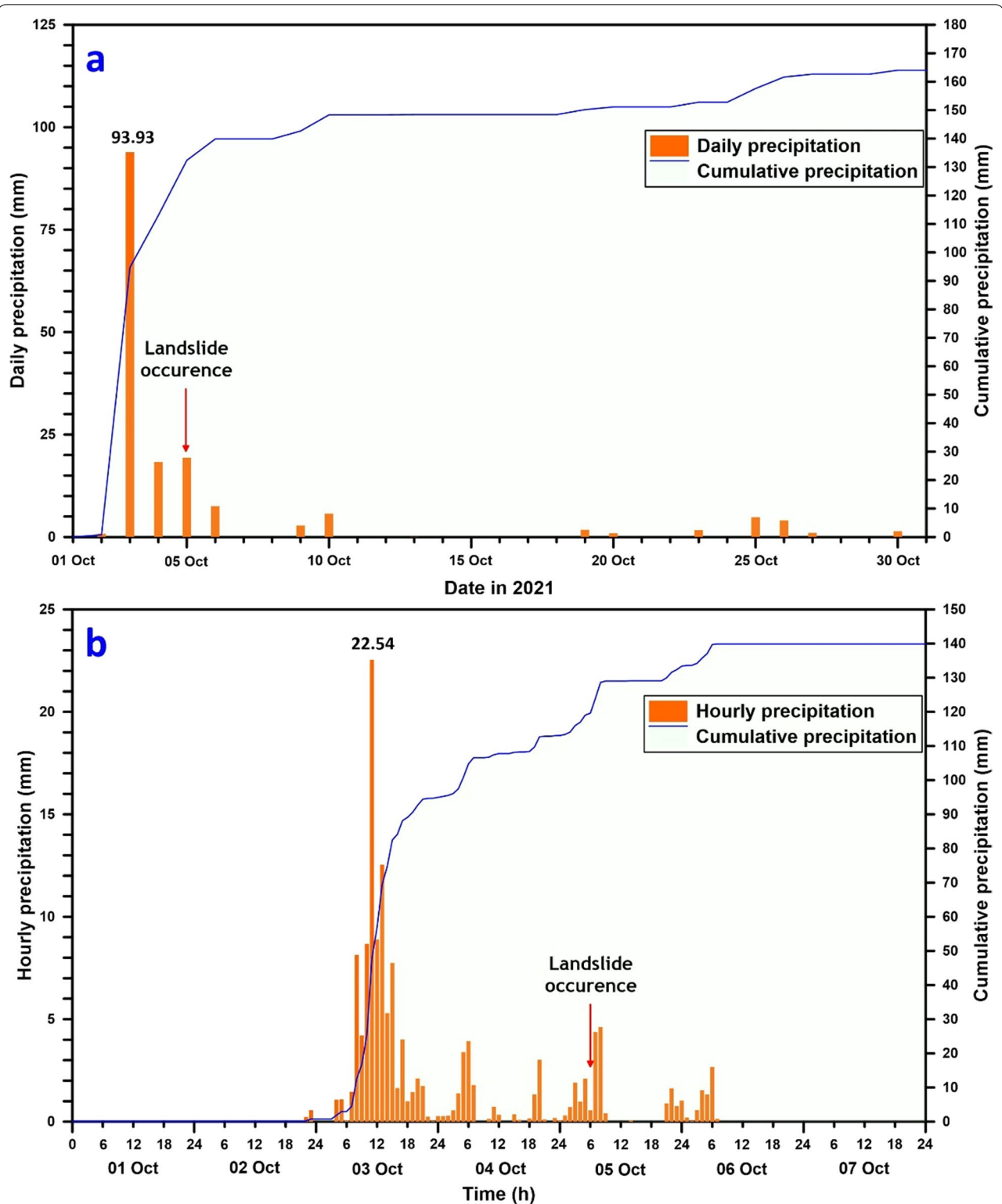
the source area. This area with a volume of more than 10,000 m<sup>3</sup> will definitely be the source of Zhongzhai landslide in future failure. The 2021 Zhongzhai landslides completely buried two houses including their courtyards and damaged another 2 houses at the right side of its deposition area (Fig. 4b). The geometric feature of the 2021 Zhongzhai landslide indicates the energy and volume are weak than the 2013 case. Controlled by the previous deposition, the sliding mass was split and blocked by the damaged houses (Fig. 4b).

### Evolution history and failure process

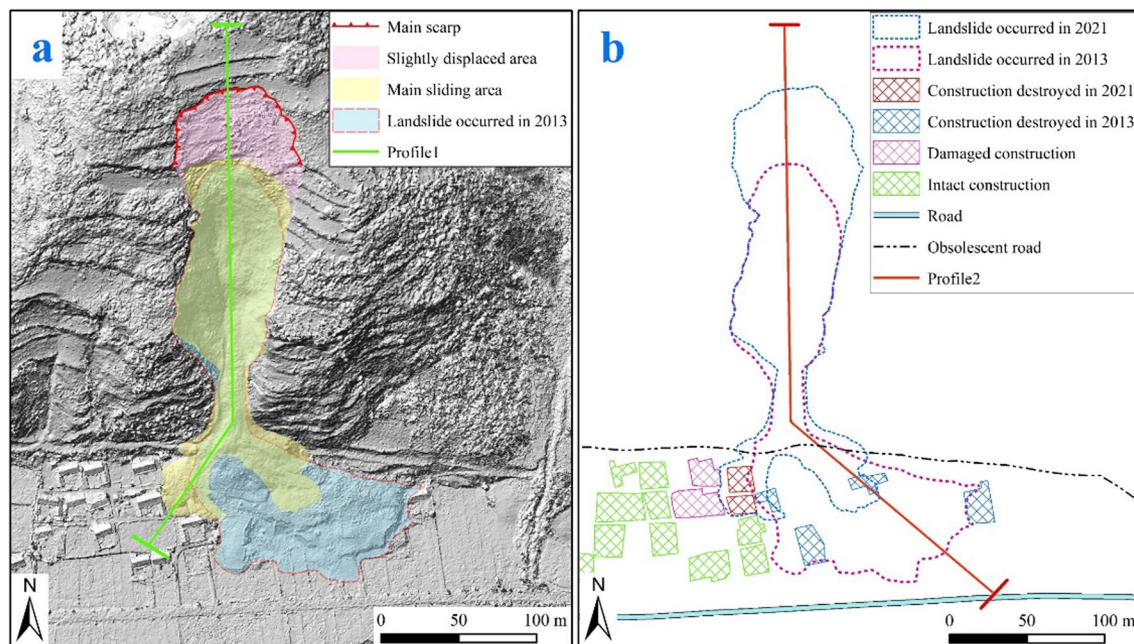
To investigate the evolution history of the Zhongzhai landslide, multi-temporal ortho-images were collected. Detail information concerning the source, date, and resolution of the ortho-images is listed in Table 1. Before the 2013 Zhongzhai landslide, a small valley can be observed at the lower slope and the upper slope was well farmed (Fig. 5a). A road that was obsoleted after the 2013 slope failure (Fig. 4b) can be observed at the footslope. Then, during the torrential precipitation in June and July 2013, slope failure occurred and four houses were buried

and destroyed (Fig. 4b). From 2013 to 2019, no obvious slope failure or localized collapse can be recognized (Fig. 5b–g). The growth of plants on the slope indicates this period is characterized with adequate precipitation but not enough to trigger further slope failure. In Fig. 5h, tensile cracks appeared at the top of the main scarp (2013 case), indicating progressive failure originated. In October 2021, slope failure occurred and the downslope movement further buried 2 houses after the torrential precipitation.

To verify the soil composition and remaining slightly displaced soil at the source area, detailed field investigation was conducted. Figure 6a presents the front panoramic view of the 2021 Zhongzhai landslide and locations of investigated area. Figures 6b, c illustrate the main scarp with a height of 4–5 m and transverse cracks of the remaining soil slightly displaced (pink shadow in Fig. 4a). Figure 6d, e show the sliding zone soil with a mix of highly weather silty slate and loess and sparsely observed mudstone near the previous main scarp of 2013 case. Figure 6f–h are the photographs of disrupted loess deposition, striations at the right flank near the toe of surface of



**Fig. 3** Daily, hourly, and cumulative precipitation of the HHZ001 pluviometer station in October 2021. **a** Daily and cumulative precipitation from 01 October 2021 to 31 October 2021. **b** Hourly and cumulative precipitation from 01 October 2021 to 07 October 2021. The location of the HHZ001 pluviometer station is illustrated in Fig. 1a



**Fig. 4** High-resolution terrain (a) and planar view (b) of the Zhongzhai landslide occurred in 2013 and 2021

**Table 1** Detail information of multi-temporal images of the Zhongzhai landslide

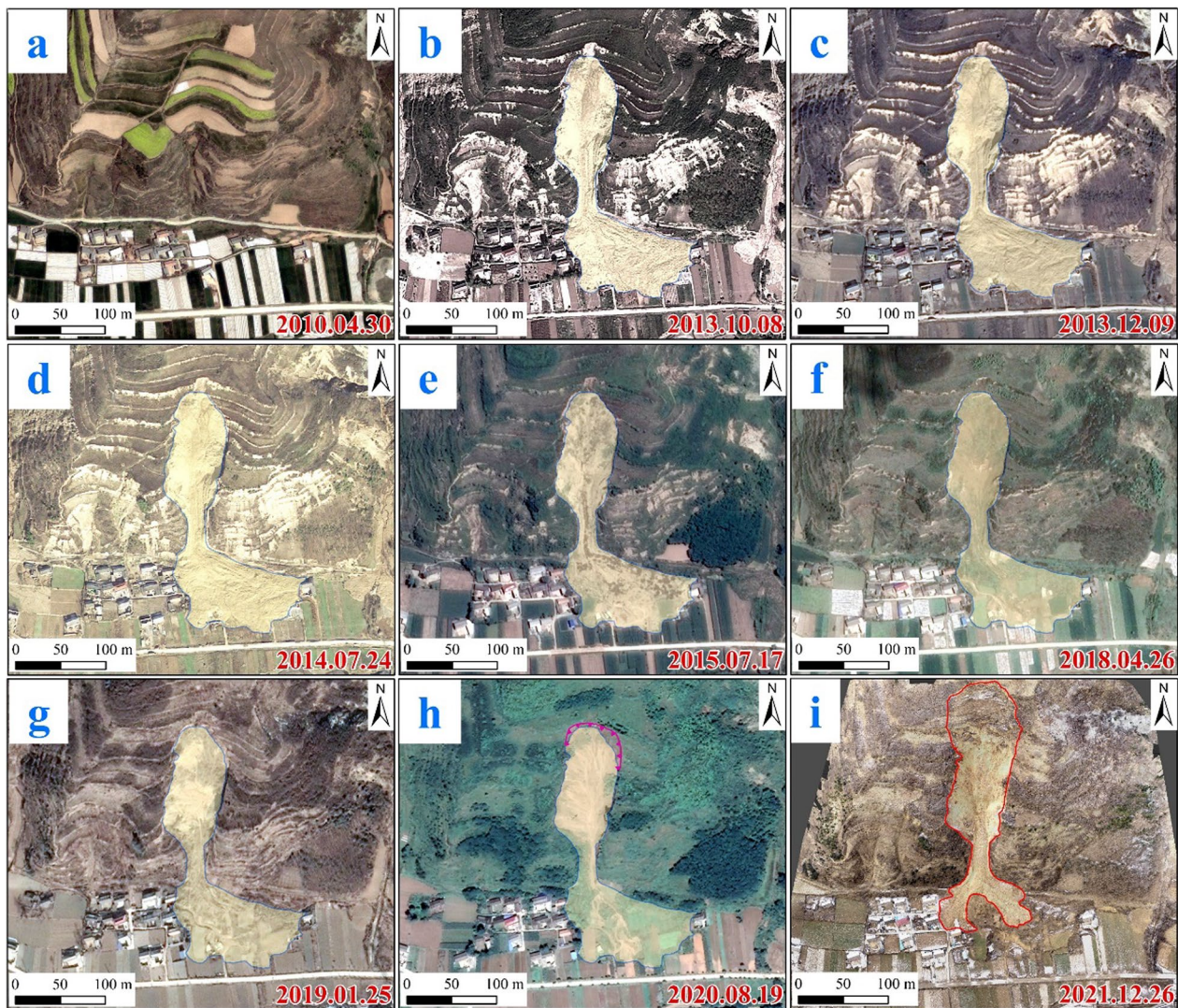
NO	Date	Source	Resolution (m)
1	2010.04.30	Google earth	0.14
2	2013.10.08	Google earth	0.14
3	2013.12.09	Google earth	0.14
4	2014.07.24	World view	0.46
5	2015.07.17	Google earth	0.14
6	2018.04.26	Google earth	0.14
7	2019.01.25	Google earth	0.14
8	2020.08.19	Google earth	0.14
9	2021.12.26	UAV	0.04

rupture, and buried house at the landslide toe. Figure 6i is the silty slate with a dip angle of approximately  $59^\circ$  out-cropped 29 m right to the landslide.

On the basis of the pre-failure and post-failure terrain, the pre-failure and post-failure ground surfaces are obtained. In combination of the field investigation, the longitudinal profiles are depicted (Fig. 7). The Zhongzhai landslide is mainly composed of Malan loess and the underlain silty slate. Considering the Neogene mudstone can only be sparsely observed, the mudstone was not

included in the profile. The mobilized apparent friction angle (Sassa et al. 1996, 2005) of the Zhongzhai landslide is about  $17.9^\circ$  (Fig. 7b). Based on the high-resolution terrain, multi-temporal ortho-images, and insight from field survey, it is inferred that the 2021 Zhongzhai landslide initiated from the retrogressive failure near the previous main scarp due to rainfall infiltration along the cracks. Then, free face appeared and the upper slope was slightly displaced, forming the potential source for further failure in future. The tensile cracks in Fig. 5h provides a favorable channel for rainfall precipitation and the permeability difference between loess and silty slate enhances the liquefaction occurrence. In addition, the counter-tilt silty slate (especially in the upper slope) benefits water impoundment, which exacerbates the flow-like slope failure. It should be noted that the 2021 Zhongzhai landslide occurred two days after the strongest rainfall on 3 October and the lag effect is obvious. It is inferred that the lag effect is resulted from the dynamic rainfall infiltration to the loess and the lag effect is significantly affected by the depth of the sliding surface and the development of the tensile cracks near the main scarp. Further investigation concerning the infiltration velocity, pore pressure generation and potential soil liquefaction will be conducted in the following work.





**Fig. 5** Ortho-images illustrating the evolution history of the Zhongzhai landslide. **a** Ortho-image on 30 April 2010. **b** Ortho-image on 8 October 2013. **c** Ortho-image on 9 December 2013. **d** Ortho-image on 27 July 2014. **e** Ortho-image on 17 July 2015. **f** Ortho-image on 26 April 2018. **g** Ortho-image on 25 April 2019. **h** Ortho-image on 19 August 2020. **i** Ortho-image on 26 December 2021. The pink line in (**h**) indicates the crack due to progressive failure. The blue line and red line indicate the landslide boundaries occurred in 2013 and 2021, respectively.

### Emergency evacuation and control proposal

At 5:36 pm (CST) on 6 October 2021 (9:36 am UTC of October 6), the orange alert was released by the local government for both weather and potentially ensuing geological disaster in Niangniangba town, Tianshui. Then, the director (also the monitor) of Zhongzhai village immediately organized the evacuation of the local residents after receiving the early-warning notification. 14 families comprising 63 persons were urgently evacuated. Then, three successions of slope failure occurred

with a maximum lasting approximately 1 min within 3 days. The first failure initiated at around 6:10 am on 6 October 2021, and another two occurred at around 8:30 am and 11:30 am, respectively. The 2021 Zhongzhai landslide completely destroyed two houses (2 families) with a direct economic loss of 0.5 million. The successful evacuation and emergency evacuation should be attributed to the effective and extensive application of the “mass observation and mass prevention” policy advocated by the geological expert in China. The “mass observation and mass





**Fig. 6** Photographs showing details of the Zhongzhai landslide. **a** Front panoramic view. **b** Main scarp. **c** Cracks due to retrogressive failure at the source area. **d** Slide zone soil with a mix of highly weathered silty slate and loess near the minor scarp. **e** Sparsely scattered Neogene mudstone near the minor scarp. **f** Loess deposition at the accumulation area. **g** Striation remaining at the right flank. **h** Buried houses at the toe area. **i** Exposed silty slate right to the Zhongzhai landslide

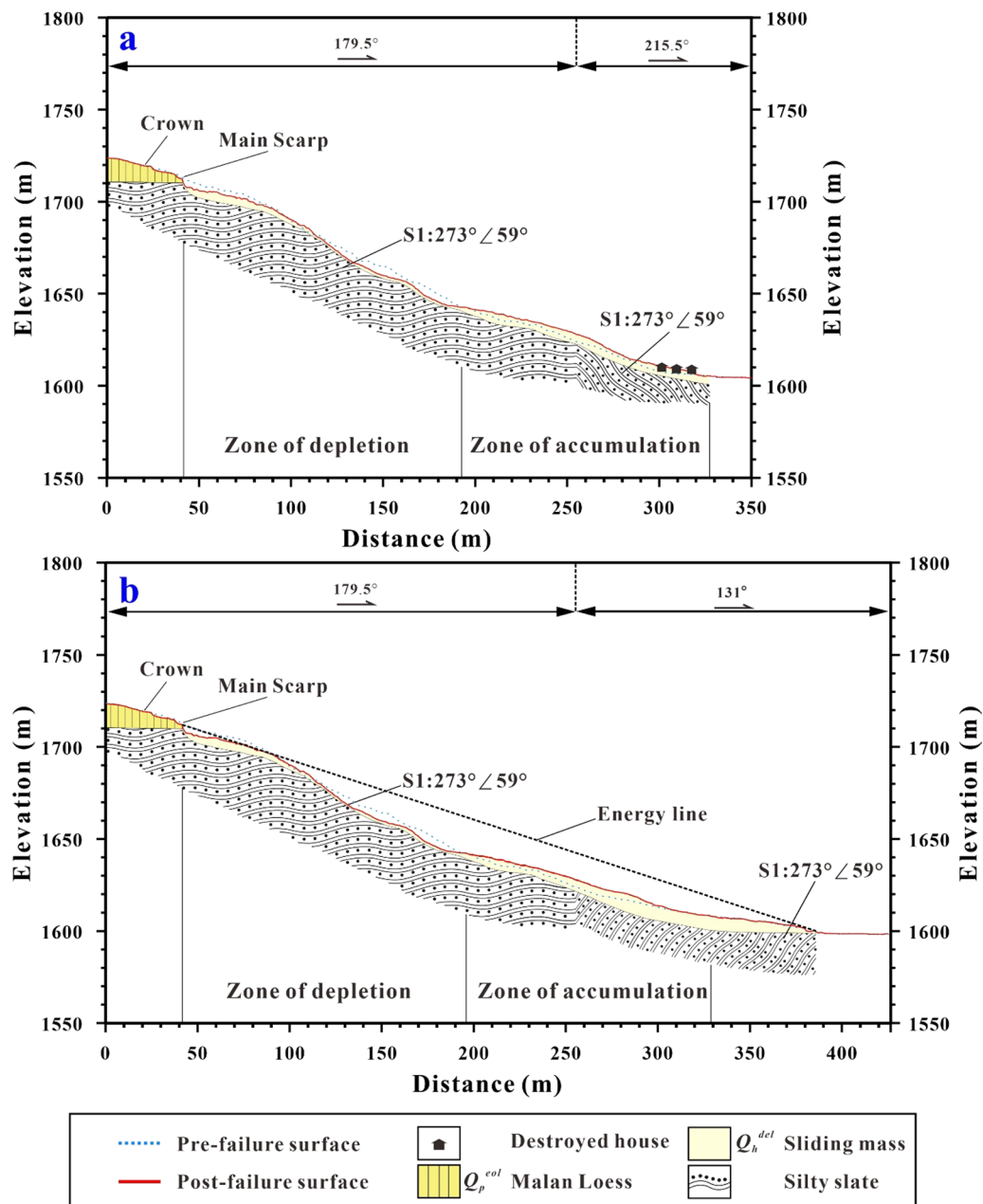
prevention” policy proves to be an effective measure in coping with geodisasters for mountainous area where monitoring facilities cannot be entirely covered.

As was mentioned before, an area with a volume of more than 10,000 m<sup>3</sup> will be the main threat of the village at the footslope. The transverse cracks serve as preferential seepage channels for rainfall infiltration. In light of this fact, drainage channel at the source area is recommended and real-time monitoring system including crackmeter, Global Navigation Satellite System (GNSS), and pore-pressure monitoring system should be installed.

## Conclusion

Although the Zhongzhai landslide (both in 2013 and 2021) is characterized with small scar and shallow sliding surface, it provides a classic case both for evolution history investigation of loess landslide and successful emergency evacuation. The availability of pre-failure high-resolution terrain and ortho-images enables the evolution history study of the loess-bedrock interface landslide. The “mass observation and mass prevention” policy enables the early identification and emergency evacuation. Considering the torrential precipitation frequently experienced in Niangniangba town and its vicinity, regional rainfall-threshold study for shallow loess landslides should be conducted. Meanwhile, the





**Fig. 7** Longitudinal profiles of the Zhongzhai landslide. The survey lines of profile 1 (a) and profile 1 (b) are denoted in Fig. 2

Zhongzhai landslide is a retrogressive landslide and progressive failure occurred in the 2021 case, further analysis concerning the relationship among rainfall intensity, infiltration rate and pore water generation, as well as motion feature and runoff prediction will be conducted.

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#### Author contributions

SZ and PS wrote the main manuscript, JR, HW, PX, and TW prepared figures. All authors reviewed the manuscript. All authors read and approved the final manuscript.

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**Availability of data and materials**

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

**Declarations****Competing interests**

The authors declare no competing interests.

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