



Presenting Some Successful Cases of Regional Landslides Early Warning Systems in China

Qiang Xu, Dalei Peng, Xuanmei Fan, Xing Zhu, and Chaoyang He

Abstract

The early warning of landslides is crucial for risk management and reduction. However, it is challenging due to the complex nature of landslide behaviours and failure mechanisms. Generally, landslides undergo a certain period of evolution from deformation to failure, and own obvious three-stage deformation phases of creep slope failure. Most of landslides own obvious sudden characteristics, such as rockslide, avalanche, and loess flowslide, which are object of this study. In this paper, an early warning systems for regional landslides and a comprehensive warning model are established, taking into account deformation rate threshold and the improved tangent angle as the early warning parameters. A four-level early warning criterion is proposed. Once the early warning parameters exceeded default thresholds, relevant local authorities and scientists could immediately receive the warning information released by the 3D WebGIS-based platform. It is the 11 times our early warning system successfully forecasted landslides in four different regions since its implementation in 2017. Here, we present three typical cases of successful early warning from these three different regions and timely evacuation

in advance. It could take a reference and applicable for other cases globally.

Keywords

Slope monitoring • Early warning system • Real-time • Successful early warning

Introduction

In many countries and areas, landslide is considered as one of the most severe natural hazard, which causes huge socioeconomic losses, especially in mountainous areas (Zaki et al. 2014; Fan et al. 2019a). The monitoring and early warning of landslides are crucial for risk management and the mitigation of their effects and the reduction of loss of human lives and assets (Fan et al. 2019b). The monitoring of landslides is a powerful tool for understanding kinematic aspects of mass movements and disruptive processes. Early warning should be implemented before a catastrophic event arrive, to allow individuals to take early action and to avoid a hazard turning into a human disaster (Sassa et al. 2009).

Prediction of slopes failure is a global challenge for geoscientists due to the complex nature of landslide failure mechanisms (Intrieri et al. 2019). To overcome this challenge, we have monitored the displacement of more than hundreds of multiple types of landslides in Western China. Based on these monitoring data from a large number of landslides, we found that landslides undergo a certain period of evolution from deformation to failure, and own obvious three-stage deformation phases of creep slope failure, such as initial deformation, constant deformation and accelerated deformation (Saito and Uezawa 1961; Xu et al. 2011). Displacement deformation of landslides will be obviously arisen when the depromation phase enters the accelerated deformation (Fig. 1a). (Fan et al. 2019b) (Fig. 1a). A deformation-time curve could describe the whole process of slope

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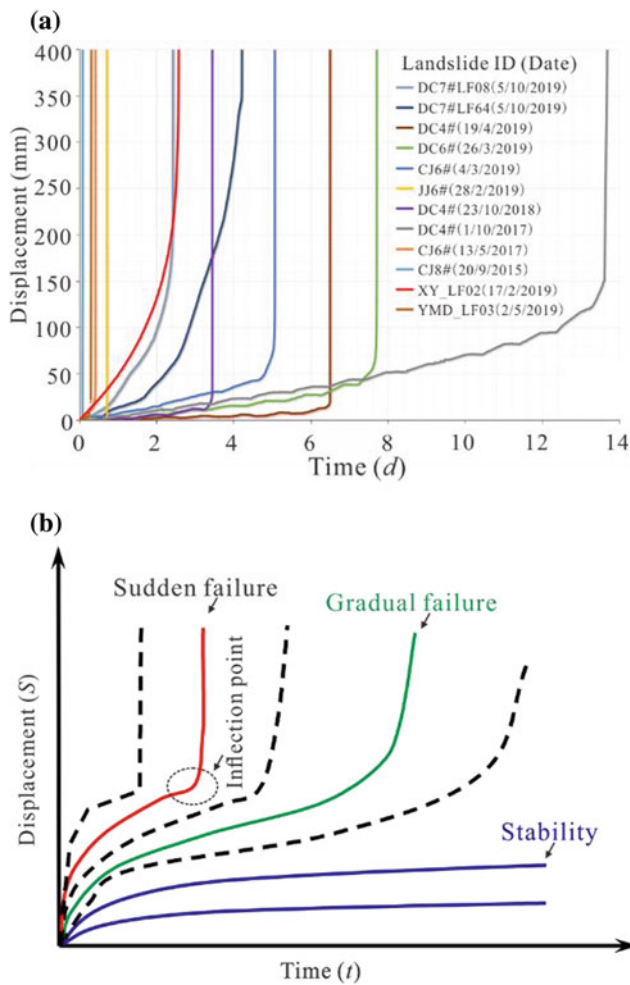


Fig. 1 Deformation characteristics of landslides. **a** Successive different landslide cumulative displacement-time curves (The difference of these landslides lies that some landslides have longer deformation period before failure (years, months, and days) than some others (hours, minutes)); **b** Movement patterns of slope displacement-time curve

failure. The curve is developed based on the statistical analysis of failure characteristics of landslides and on many displacement–time monitoring data (Fig. 1b) (Gance et al. 2014).

Movement patterns in different landslide have been extensively documented (Varnes 1978; Petley and Allison 1997), which could be divided into three distinct patterns being evident: stable, gradual failure, and sudden failure (Fig. 1b). (1) Stable: some landslides may undergo long periods of creep and movement will finally keep steady stable. (2) Gradual failure: there may be long-term displacement at low strain rates, frequently termed ‘creep’. Creep may vary in rate on a seasonal basis but movement will rarely cease altogether, representing a gradual failure. And there are many successful warnings cases for gradual failure (Casagli et al. 2010). (3) Sudden failure: there are cases of short-term movement at very high rates of displacement

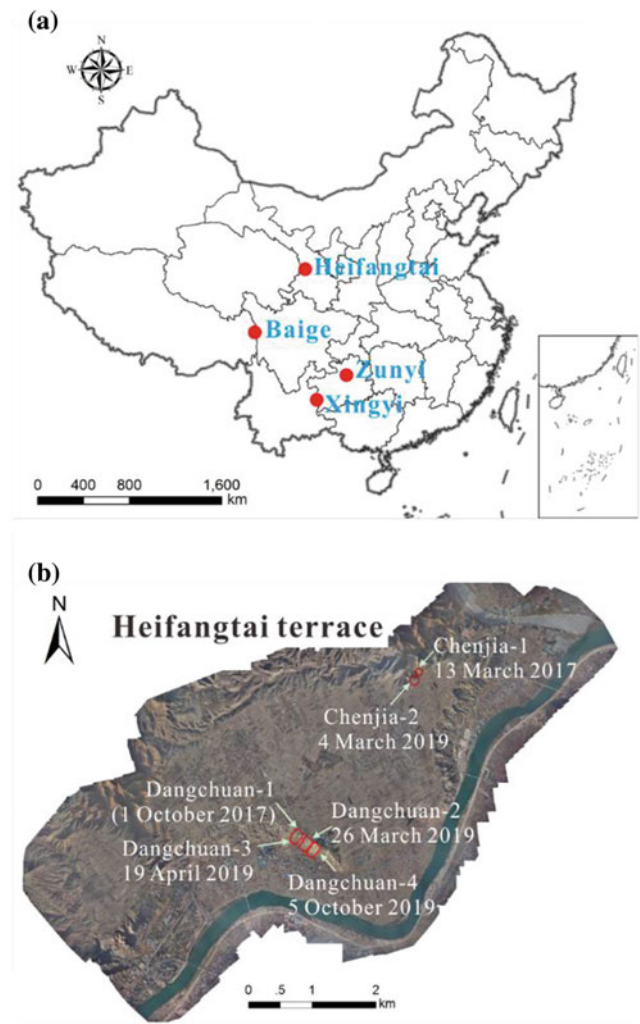


Fig. 2 Map showing locations in China where SKLGP's early warning system successfully predicted the eleven landslides in four regions (for details see Table 1)

(Carlà et al. 2017). With this know-how, a real-time early warning system based on the new artificial intelligence and data transmission technologies was developed by State Key Laboratory of Geohazard Prevention and Geoenvironment Protection (SKLGP). This system has successfully predicted 11 landslides since 2017 and saved thousands of lives in China (Fig. 2 and Table 1). In this study, the application of our self-developed landslide early warning systems (LEWS) to Baige rockslide-avalanche, Longjing rockslide in Xingyi, and loess flowslide at Heifangtai is described, covering monitoring strategies and early warning model.

In order to solve the key problem of “when a landslide will occur”, main procedures have been undergone in this study: (1) the location and size of potential landslides were investigated based on the effective integration of Space-Sky-Ground three-dimension surveys (Xu et al. 2019). (2) a field study site was carried out and the characteristics of

Table 1 Successful and detailed landslides predictions by the LEWS (Fan et al. 2019b; Xu et al. 2020)

Landslide ID	Lead time (h)	Occurrence of landslide	Region
Chenjia-1	1.02	13/05/2017	Heifangtai
Chenjia-2	2.03	04/03/2019	Heifangtai
Dangchuan-1	11.17	01/10/2017	Heifangtai
Dangchuan-2	0.68	26/03/2019	Heifangtai
Dangchuan-3	0.30	19/04/2019	Heifangtai
Dangchuan-4	32.15	05/10/2019	Heifangtai
Baige-1	24	03/11/2018	Baige
Baige-2	0.5	11/11/2018	Baige
Baige-3	0.5	21/11/2018	Baige
XY-1	0.88	17/02/2019	Xingyi
YMD-1	0.33	02/05/2019	Zunyi

sudden-type landslides were summarized. (3) a monitoring method with self-adaptive adjusting sampling frequency is developed to monitor potential landslides. (4) a series of landslide warning thresholds with the improved tangent angle model and the deformation rate were proposed using the data processing method.

These successful experiences provide an impressive example of how a LEWS can help for preventing and mitigating landslide risks. We believe the practical implementations and the successful history of our LEWS will surely benefit other countries as well and improve global landslide resiliency.

Monitoring and Warning Methods Proposed in this Study

Monitoring Strategy

Displacement and other displacement-derived quantities are the main monitored parameters, which widely used for the early warning of landslides all over the world (Fan et al. 2019b). The cumulative displacement obtained from improved crack gauges present the most continuous and reliable data during the accelerated deformation stage (Xu et al. 2020). With the advantage of a self-adaptive data acquisition technique developed by (SKLGP) (Zhu et al. 2017), the crack gauge can automatically adjust the sampling frequency with respect to the displacement rate velocity (Fig. 3) (Fan et al. 2019b).

Multiple Criteria Warning Model

A general and quantitative criterion for LEWS was proposed by Xu et al. (2011), which described the improved tangential angle (α), referring to the deformation rate of the displacement-time curve at a given time (Eq. 1). This angle was used to specify different alert levels (Fan et al. 2019b).

$$a = \arctan \frac{v_i}{v_0} \quad (1)$$

where a is improved tangential angle; v_i is displacement rates; v_0 estimates of the creep rate at constant deformation state.

Catastrophic landslides often occur suddenly without any noticeable precursors, and are of a very short duration after entering the accelerated deformation and the speed is relatively fast in the imminent sliding stage (Qi et al. 2018). The early warning and prediction of the occurrence of landslides may be misjudged based on the traditional improved tangent angle method as the early warning criterion. Due to this reason, multiple alert thresholds are established in our LEWS. On the basis of the improved tangential angle criterion, the slope sudden failure also consider whether the deformation rate is larger than a critical rate value ($V_1 < V_2 < V_3$), the incremental rate (ΔV) at the three deformation stages of landslide (Fan et al. 2019b). The comprehensive warning criteria, taking into account three thresholds of improved tangential angle, three thresholds of deformation rate, and deformation rate increment are shown in Fig. 4.

Fig. 3 Components of the improved self-adaptive crack gauge and monitoring data. **a** Intelligent crack gauge monitoring station; **b** Integrated intelligent landslide crack gauge; **c** Schematic diagram of self-adaptive acquisition frequency

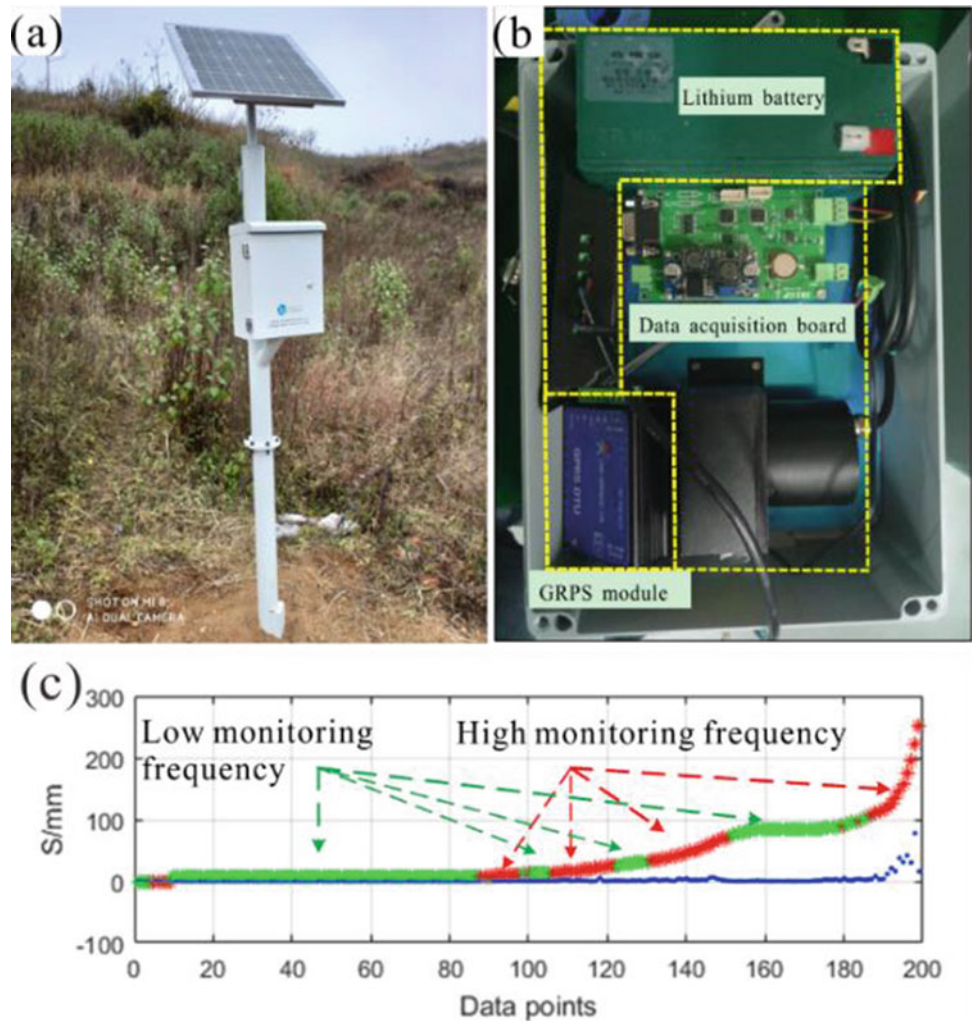
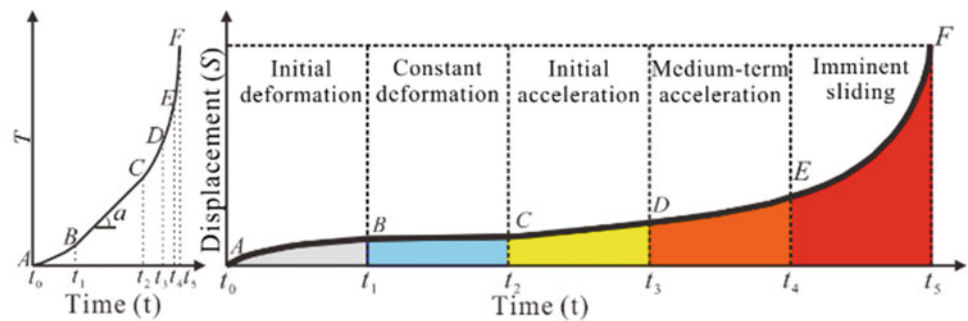


Fig. 4 Outline of the four-level comprehensive early warning criterion based on velocity threshold and tangential angle



Deformation stage		Initial deformation	Constant deformation	Acceleration deformation		
				Initial acceleration	Medium-term acceleration	Imminent sliding
Early warning parameters	Deformation rate V (mm/d)	$V < V_1$	$V_1 \leq V < V_2$	$V_2 \leq V < V_3$	$V \geq V_3$	
	Rate increment ΔV (mm/d)	$\Delta V < 0$	$\Delta V \approx 0$	$\Delta V > 0$		
	Tangential angle a ($^\circ$)	$a < 45^\circ$	$a \approx 45^\circ$	$45^\circ < a < 80^\circ$	$80^\circ \leq a < 85^\circ$	$a \geq 85^\circ$
Early warning level		—	Attention	Caution	Vigilance	Alarm

Application of the Method

Since the proposed the comprehensive early warning model has been established, we were able to successfully warn 11 landslides spread across China (Fig. 2 and Table 1). In this document, we present the experiences acquired in the monitoring and warning of three landslide cases named Baige landslide, loess flowslide and Xingyi rockslide. The early warning of these landslides prevented casualties and property losses, and guaranteed the safety of more than 1000 people’s lives and property, and achieved very good economic and social benefits.

Case 1: Baige Rockslide-Avalanche

In the early morning of October 11, 2018, a large rockslide-avalanche occurred at the border between Sichuan Province and Tibet. The landslide was located on the west bank of the Jinsha River near Baige Village, Jiangda County, Tibet. The landslide formed a dam with a water storage capacity of about 290 million m³. It was fully drained by October 13 with the completion of partial discharge, and the danger was relieved. Then, on 3 November 2018, the landslide reactivated again in the form of a large rockslide that dammed the river for a second time and formed a new barrier lake with a volume of 5.24×10^8 m³. These two landslides

and river blocking events have aroused widespread social concern. After the October 11, 2018 event, 16 global navigation satellite system (GNSS) receivers, 16 crack gauges, and 1 rainfall gauge were placed on tensile cracks behind the source area. Sudden increases were observed three times, and they are consistent with the increase in recorded displacement time histories. First increase occurred at 18:00 local time on November 3, 2018, during the slope failure. The other two were observed at 8:00 on 11 November 2018 and at 11:00 on 21 November 2018. The early warning system performed remarkably well as predictor of the slope failure on November 3 is presented in this paper. At 21:00 on 3 November 2018, the deformation rate was 60 mm/d and the maximum tangent angle was 85°. The early warning system was able to predict the second large-scale slope failure 24 h in advance, along with minor rock falls during the spillway construction (Fan et al. 2019a). (Fig. 5).

Case 2: Heifangtai Loess Flowslide

Heifangtai is located on the fourth terrace of the Yellow River, in the semi-arid area of the Loess Plateau and at the confluence of Huangshui River and the Yellow River. A total of 77 landslides were identified on the Heifangtai terrace according to image taken on 18 January 2015 (Fig. 2). One of loess landslide named Dangchuan-1 loess flowslide is

Fig. 5 Monitoring network, observed displacements and successful implementations of early warning for Baige rockslide-avalanche. **a** Orthographic image of post-sliding (taken on 5 November 2018); **b** Location map of installed monitoring instruments (GNSS gauge (GP) refers to the GNSS displacement sensors and CG refers to crack gauges); **c** Displacement curve before the landslide event on 3 November 2018 (using crack gauge CG02)

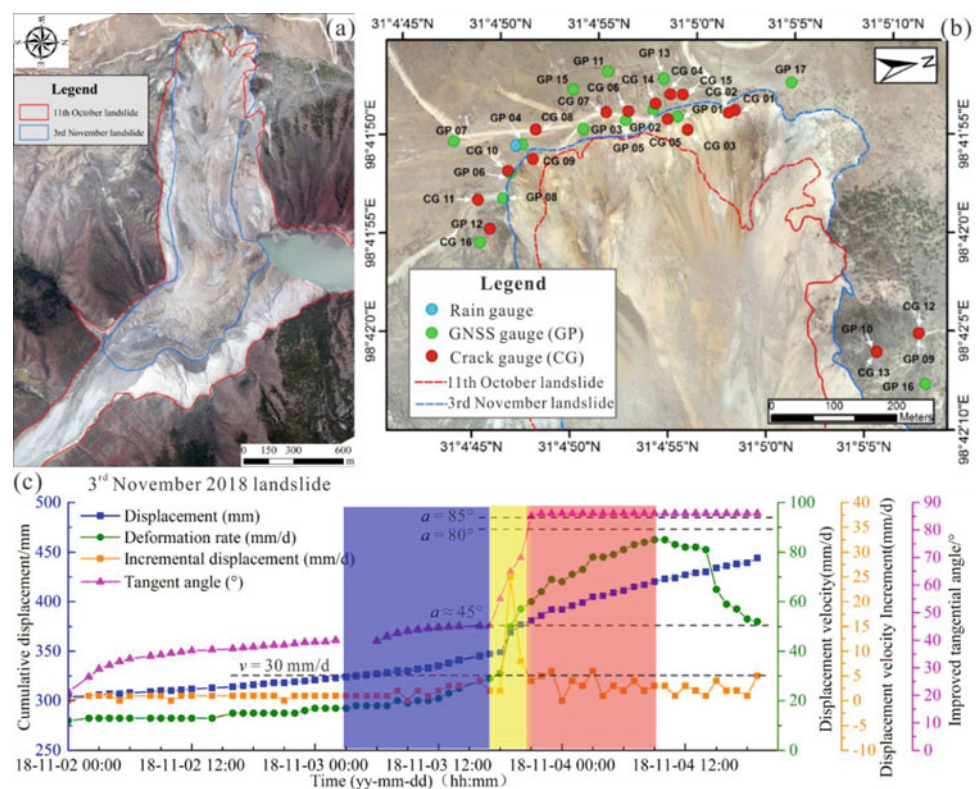
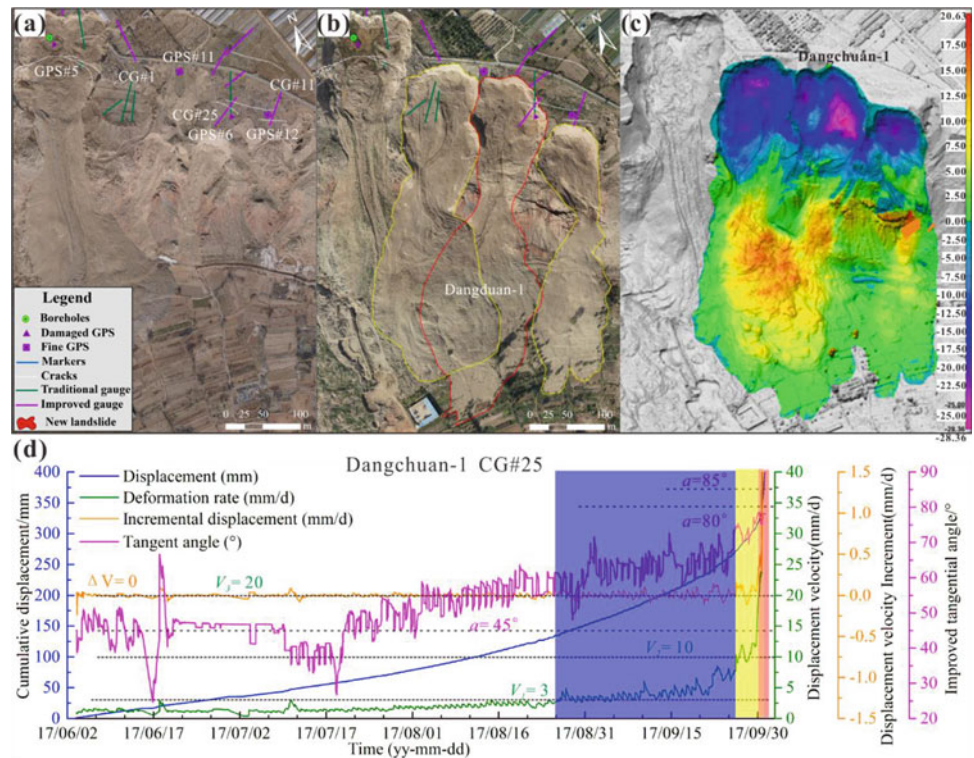


Fig. 6 Monitoring network, observed displacements and successful implementations of the loess flowslide Dangchuan-1 at Heifangtai. **a** Orthophoto image and monitoring system layout before landslide; **b** Orthophoto image and monitoring system layout after landslide; **c** Elevation change from the pre-slide to the post-slide; **d** Complete monitoring curve of cumulative displacement-time, deformation rate, increment of deformation rate and tangent angle curve



located on the southwest of the Heifangtai terrace. The source area of the landslide is 300 m in length and 20 m in width. Volume of the runout materials is about $3.4 \times 10^5 \text{ m}^3$. The landslide has begun to deform and the rate of deformation has gradually increased since the end of August 2017. At 23:41 on 30 September 2017, the deformation rate was 99.45 mm/day and the maximum tangent angle was 88.27° . A successful prediction of the flowslide was achieved 8 h before the occurrence (Xu et al. 2020) (Fig. 6).

Case 3: Xingyi Rockslide

On 17 February 2019, a large rockslide occurred in Longjing village, Xingyi city, Guizhou Province. The rockslide was initially triggered in 2014 due to the removal of rock mass near the slope toe for road construction. Since then, the rockslide had become a potential threat to the local residents, pedestrians, and traffic. The deployment of the crack sensors and its distribution on the site are illustrated in Fig. 7a. To avert human and economic losses, emergency mitigation measures were implemented and a self-developed real-time LEWS. At 5 a.m. on 17 February 2019, the deformation rate was of about 251 mm/day, the cumulative displacement was of 829.2 mm, and the tangent angle was more than 85° . The real-time geological disaster monitoring and early warning system automatically send out the red early warning level to scientists, local government and

residents, and then evacuate the relevant personnel by local government and residents in the site. A successful prediction of the rockslide was achieved 53 min before the occurrence on 17 February 2019. Prompt action taken by scientists and local authorities averted human and economic losses completely (Fig. 7).

Conclusions

Early warning systems are valuable tools for risk reduction, and they empower the community by providing timely alerts spanning hours, thus saving invaluable lives. Our self-developed LEWS helped to predict and mitigate eleven landslides, including two new landslides and nine reactivation landslide, eventually achieving zero casualties or injuries and almost no property losses. These cases of successful monitoring, early warning, and prediction and mitigation of landslides are very exceptional worldwide due to their complex nature. In this study, we presented three successful cases of early warning for disastrous landslides in China. The improved data monitoring and processing method were introduced. A comprehensive early warning model was established to realize the comprehensive dynamic and real-time early warning of landslide, taking into account the deformation rate threshold and improved tangent angle as the early warning parameters. Four alert levels were proposed on the basis of analysing the characteristics of displacement time

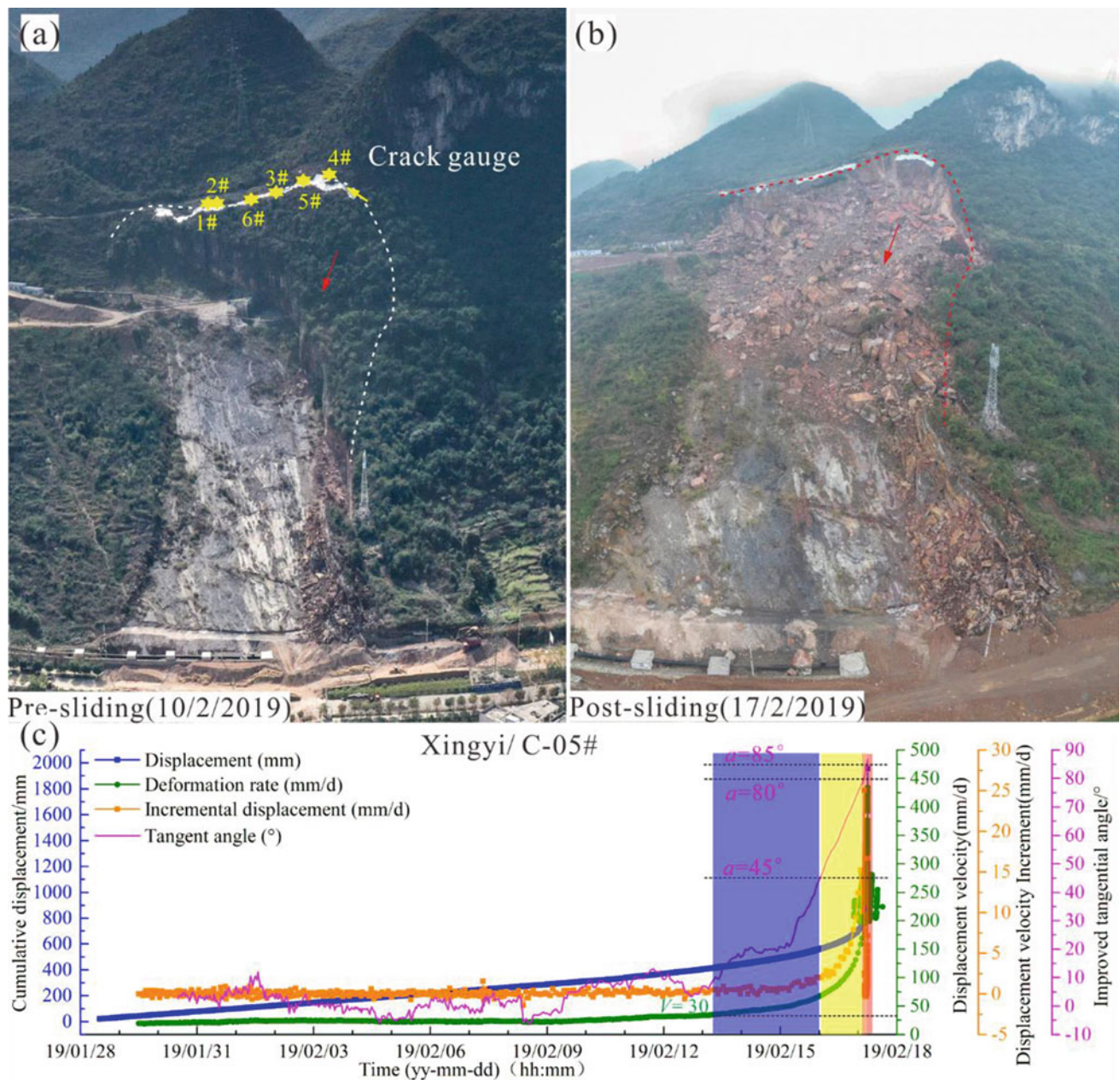


Fig. 7 Monitoring network, observed displacements and successful implementations of the Xingyi rockslide. **a** Location and distribution of installed monitoring instruments and pre-sliding image; **b** Image of

post-sliding; **c** Cumulative displacement obtained by crack gauge C-05 and the derived curves of α , v , and Δv with corresponding alert levels of data from 27 January 2019 to 17 February 2019

series. The warning time in advance was from 0.3 h to 32 h. Our study also contributed to the compilation of a comprehensive database of displacement time histories of landslides that will be helpful for predicting similar landslides in the future.

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