Research on the deformation and failure mode of rock slope with multiple locking segment failure characteristics

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Abstract. Landslides are the most critical types of geological disasters in China, seriously threatening the safety of life and property of the inhabitants in the surrounding areas. Most landslides in China are large and giant rock landslide slope failures of large and giant rocks. Brittle failure of multiple locking sections usually accompanies rock slope failure. The locked section is significant for the early identification of rock slopes, slope deformation control, and slope failure prevention. This study uses the ground-based synthetic aperture radar technology to obtain the surface deformation data of the entire process of slope failure. By analyzing the development law of slope surface deformation before landslide failure, the dynamic process and evolution model of the time–space evolution of slope deformation and failure are proposed. The finding of the research shows that the deformation time-series curve of slope failure with multiple locking sections completely differs from the typical three-stage theory of slope failure deformation with creep characteristics. The failure process of each locking segment before the failure of the critical locking segment is accompanied by the transverse expansion of the shear failure of the sliding surface and the pulling failure of the trailing edge. After the failure of the last key-locking section, the final landslide failure will be formed. The entire process is a process of energy accumulation and downward movement, manifested by the stage displacement of the sliding mass, the mixed deformation characteristics of oscillation, and rising trend of the monitoring curve. Based on the characteristics of the entire surface deformation data in the landslide failure process, the research results prove the typical failure mode of rock slope with three sliding-tension cracking-shearing sections. The research results are critical in identifying the failure mode, analyzing slope stability, predicting landslide failure, and judging the scale of the landslide.

1. Introduction
Landslides and earthquakes are two major geological disasters causing huge casualties and economic losses each year across the world [1]. In China, landslides are the most critical types of geological disasters, seriously threatening the safety of life and property of the inhabitants in the surrounding areas. Most landslides in China are large and giant rock landslides [2]. In the southwest and northwest China, geological and topographical conditions are complicated, increasing the number of landslide disasters with significant casualties and property damage [3]. Since the 1980s, frequent landslide disasters have occurred in China, making China a serious landslide disaster area in Asia and even the world. Brittle failure of multiple locking sections accompanies rock slope failure, and the type of locking section failure slide is the main type of large rock slide [4]. Based on the three-stage theory of slope deformation, rock slope deformation is divided into initial, uniform,
and accelerated deformation stages \[5, 6\]. However, the deformation characteristics of actual slope failure are often not ideal three-stage deformations, indicating that the slope failure process is not necessarily a single failure mode of the locking section. Most slope failures occur in the shallow rock mass. The deformation and failure are gradual processes, showing obvious deformation symptoms and laws \[7\]. This study monitored and analyzed rock landslide deformation using a ground-based synthetic aperture radar (SAR) system to reveal the deformation and failure mode of rock slope with multiple locking segment failure characteristics. First, the ground-based SAR system and layout requirements of monitoring stations are introduced. Second, the deformation behavior and failure mode of the landslide are presented. Third, the progress of locking section failure landslide is reproduced. Finally, conclusions are presented.

2. Background

2.1. Ground-based slope stability radar

With the advancement in the field of science and technology, some conventional instruments of surface displacement monitoring methods, including total station, theodolite, level, GPS monitoring, and 3S technology, have been gradually employed \[8–12\]. The ground-based SAR system is optimal for landslide monitoring. The SAR system adopts microwave imaging technology for deformation monitoring. The system runs on a stable platform, allowing long-term repeated imaging at the same observation position. The deformation information is extracted via repeat-track differential interferometry technology. Therefore, a ground-based SAR was used herein for landslide deformation monitoring. The SAR system provides a line-of-site deformation point cloud with measurements updated every few minutes \[13\], allowing researchers to study the distribution law of slope surface deformation and its entire development progress. Figure 1 presents the observation geometry and slope deformation captured by a ground-based SAR.

![Figure 1. The observation geometry and slope deformation captured by a ground-based SAR](image)

2.2. Layout requirements of monitoring stations

To obtain accurate, reliable, and comprehensive monitoring data, certain principles must be followed in the setting of monitoring stations. First, because the radar is a precision instrument, the monitoring accuracy is 0.1 mm. Therefore, the radar station foundation must be stable to ensure that there is no vibration when the radar works; otherwise, it will seriously affect the monitoring data. Second, the radar is intervisibility monitoring, so there should be no occlusion between the radar-monitoring direction and the monitoring target; otherwise, the data at the occlusion is not the target data. Third, the distance between the radar installation site and target slope must not exceed the radar-monitoring range. Last, the deformation monitored by the radar is toward the line of sight; thus, the irradiation direction of the radar installation site and target slope cannot be vertical, and it is the best in the downward direction.

3. Basic characteristics of surface deformation preceding slope failure

The landslide failure process of rock slope is a long-term evolution process involving incubation, development, maturity, and occurrence \[14–16\]. In the process, the deformation and change matching
with each stage will appear. Numerous cases of rock slope-locking section landslide show that in the middle and front edge of the landslide, there are often multistage locking sections. In the landslide development process, the stress in different stages and positions will change and then produce corresponding deformation characteristics. Therefore, by analyzing the development and change in the entire surface and time series of the slope landslide process, this section reveals the evolution planning and characteristics of the rock slope failure in the multiple locked section of the rock slope. The landslide dynamic development process of the sliding body is analyzed by evaluating the behavior at horizontal and longitudinal measuring point lines (Figure 2).

![Figure 2. Deformation-observed position for each state](image)

3.1. The formation of the trailing edge crack
For the sliding landslide, Figure 3 shows that the failure first occurs at the back edge of the sliding mass. The fracture is approximately 23 m in length, 5–12 cm in width, and trend nearly north–south. The echelon feather crack is performed at both ends of the fracture, approximately 8–18-cm long and 2–5-cm wide; on both ends of the tension, the fracture gradually disappears. The main reason is that shear failure occurs inside the slope, resulting in the accumulation of deformation. When the deformation exceeds the cooperative deformation capacity of the rock mass, one or more tension cracks will be formed at the trailing edge of the sliding mass. These cracks develop and extend to the surface of the slope. Because the rock mass of the upper part of the slope inclines outward to the free surface formed by the tension cracks, the rock mass on the upper part of the landslide body gradually deforms downward and outward, forming obvious arc-shaped tension cracks on the upper part of the original slope.

![Figure 3. The tension crack at the top of the slope](image)

3.2. Longitudinal multiple locking segments failure with domino thrust
Figure 4 shows the cumulative deformation curve of five longitudinal measuring points. The curve shows that the five measuring points from top to bottom all experienced the deformation stage from uplift to subsidence. For top No. 1 measuring point, the duration from the beginning of uplift deformation to the reverse of the deformation direction is approximately 18 days and the maximum
deformation is approximately 185 mm. For No. 2 measuring point, the maximum deformation is approximately 243 mm, lasting approximately 42 days from the beginning of the uplift deformation to the reverse of the deformation direction. At this stage, the deformation of No. 1 measuring point is invagination deformation. For No. 3 measuring point, the duration from the beginning of uplift deformation to the reverse of the deformation direction is approximately 65 days and the maximum deformation is approximately 241 mm. At this stage, the deformation of No. 1 and No. 2 measuring points is invagination deformation. For No. 4 measuring point, from the beginning of uplift deformation to the reverse of the deformation direction, the total duration is approximately 78 days and the maximum deformation is approximately 245 mm. At this stage, the deformation of No. 1–3 measuring points is subsidence deformation. Compared with No. 1–4 measuring points, the deformation curve of No. 5 measuring point at the bottom shows obvious distinct characteristics. There is no inversion on the deformation curve of the curve, and uplift deformation begins to appear on the 80th day until failure occurs.

According to monitoring data analysis (Figure 4), the deformation of the sliding mass in each stage is often caused by the pushing action of the upper sliding mass. Before being driven by the upper sliding mass, the deformation is in a stage of uniform deformation. Normal creep mainly causes deformation. However, once the upper sliding mass is pushed to the next locking section, nonlinear deformation will occur because of the influence of the upper sliding mass. When the抗滑动 capacity of the locking section is insufficient to support the rock mass separated from the parent rock, the local locking section is sheared, the fracture surface develops and moves downward, the sliding force increases, and the energy is transferred to the next locking section. The locking section then develops and transfers energy from top to bottom in the longitudinal direction, and the locking section is gradually destroyed until the final landslide failure.

The failure process of the entire rock slope with multiple locking segments is mainly characterized by two features. One is the failure process, which is a gradual increase in sliding force and the gradual destruction of the locking section, similar to a domino effect. Once the failure of the locking section is formed, the final landslide failure will be formed. Then, with the formation of the sliding surface, the unstable body will rotate in the upper part and uplift in the lower part along the arc-shaped sliding surface in space. The deformation is characterized by uplift and then internal rotation. In other words, before the local locking section is damaged, the deformation corresponds to a protrusion caused by extrusion. As the locking section moves downward, the upper deformation rotates along the sliding surface.

Figure 4. Cumulative deformation curve of longitudinal measuring points

3.3. The formation and development of the rotating axis

Figure 5 illustrates the entire process of landslide formation. In the first stage, the deformation is mainly manifested as the local outward inclination of the upper part of the slope, with deformation of approximately 84 mm. In the second stage, the deformation is mainly manifested by the subsidence of the upper part of the slope and local uplift, with the deformation of the uplift and upper part of
approximately 84 and 116 mm, respectively. From the third to the fifth stage, the deformation curve shows the same characteristics as the second stage and their local uplift deformation is 84, 88, and 93 mm and the maximum deformation of the upper part is 291, 430, and 794 mm, respectively.

Figure 5 illustrates that there is a middle rotation axis at each link of the domino in the longitudinal movement but not in the partial camber caused by tension cracks in the initial stage. In addition to the local extroversion caused by tension cracks in the initial stage, a central axis of rotation exists thereafter. The upper part of the rotating shaft rotates inward to form an invagination, and the lower part of the rotating shaft rotates outward to form an external convex. The proportion of the internal rotation part is larger than that of external rotation part. Figure 5 shows that the development of the rotation axis in the five stages of landslide development is divided. Except for no rotation axis in the first stage of rock and soil mass extroversion, there is a deformation middle rotation axis in each stage thereafter. With the development of the failure surface, the axial downward movement of the central rotation is faster and closer to the critical sliding stage and the proportion of the internal rotation part is larger. Therefore, with the formation of the landslide mass, the increase in the sliding force is greater than that of the locking section. Therefore, with the maturity of the sliding mass, the stability decreases more severely until final failure occurs.

Figure 5. Deformation curves of slope in various stages along longitudinal direction

3.4. Lateral diagonal pull

The initial shear cracks gradually form and develop the landslide mass. In this process, the shear cracks on the lateral flank are generated and developed corresponding to the formation and development stages of the landslide mass. By analyzing the deformation information of landslide trailing edge (110-m long, taking one point every 5 m), according to the deformation characteristics of the slope, the deformation curve is drawn (Figure 6). The maximum deformation at each stage is toward the main sliding line. The maximum deformation in the first stage is extroversion deformation with a deformation amount of 48 mm. The deformation in the second to the fifth stage is uplift deformation of 89, 281, 469, and 534 mm, respectively.

Lateral deformation develops because the main sliding line is the traction axis, the middle deformation is the largest, and the deformation on both sides gradually reduces. During the sliding mass development, the deformation range of both sides gradually extends. In the process of slow deformation of the front locking section driven by the rear sliding mass, the deformation and development of the main sliding line of the sliding mass are the fastest, pulling the rock mass on both sides to deform cooperatively. When the deformation of both sides of the rock mass exceeds its deformation limit, a shear dislocation zone is formed and tensile cracks appear on both sides of the wing. The external performance is that the shape of the sliding surface after the occurrence of the landslide takes the main slip line in the middle as the symmetry axis, and the shear cracks on both sides of the lateral wing are symmetrically generated.
3.5. The process of sally port break
At every stage of landslide development, the sliding force was at the back of the slipping mass because of shear failure. Antislide patches locked the sections producing compressive stress mainly focused on the main slip line. Figure 6 shows large lateral deformation in the middle and smaller deformation on the two sides, explaining the compressive stress concentration area at the main slide line. Furthermore, because each level of the slide mass was wide at the top and narrow at the bottom, there was a lower pressure stress concentration. The range of the upper slide mass increased faster than that of the locked patches in the lower part in every stage. This divergence phenomenon explains the formation of the landslide. When the shear capacity breakthrough of the locked patches was less than the upper slide force, the locked patches were broken, releasing the upper slide mass.

Figure 7 shows the process of the sally port break. The starting point of landslide destruction is the deterioration of landslide rock and soil because of rainfall at the back of the slide mass, decreasing the antisliding ability and the start of destruction with tension fracture in the upper slope. As the stress expanded, deformation and destruction continuously developed. There was a transverse pull on both sides of the soil to the main sliding direction, exerting a greater proportion of the force downward and then domino-type traction destruction occurred longitudinally. The front of the soil-rock mass was finally pushed out, resulting in instability and slope failure. This form of expression fully conforms to the typical failure mode of rock slope with three sliding-tension cracking-shearing sections.
4. Conclusions
This paper presents a ground-based SAR study of rock slope deformation. Through field monitoring and theoretical analysis, the spatial evolution law of landslide formation and deformation characteristics in the rock slope failure process were examined. The following general rules are suggested:

(1) Based on the dynamic evolution characteristics of rock slope deformation and failure, this study summarizes aspects such as the formation of tension cracks at the back edge of a landslide, domino-type failure of multiple locking segments, downward movement of the central rotation axis, lateral expansion, and the failure of the key-lock section.

(2) The multistage locking section is linear toward the main sliding line of the landslide. With the gradual failure of the locking section, the surface deformation of the main sliding line of the landslide shows characteristics of the mixed deformation of oscillation and rising trend.

(3) The rock slope failure with multiple locking sections is an energy accumulation and transfer process. With each locking section failure, the upper deformation range gradually expands and the sliding force nonlinearly increases until the sliding force exceeds the antisliding force. Finally, the shear failure of the locking section results in the formation of a landslide.

(4) Although the deformation analysis is effective to analyze the rock slope failure mechanism, the internal stress for the study of the rock slope failure mechanism must be monitored and analyzed[17]. The failure mechanism of rock slope landslides can be revealed in depth only through a comprehensive analysis of deformation and force.

These results can be used to identify prewarning signs of rock slope landslides to facilitate the prevention and treatment of landslides and improve the general understanding of landslide phenomena occurring in rock slopes.

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