Failure mechanism and characteristics of Nantang village basalt landslide induced by excavation and rainfall in Leibo County, Sichuan, China

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Abstract. Emeishan basalts are widely distributed in Southwest China, where several largescale sliding disasters occurred in recent years. At about 5:00 am on July 2, 2017, a highelevation basalt landslide occurred on the slope of Dongbiangou in Nantang Village. Nantian Township, Leibo County, Sichuan Province, forming a deposit with a volume of about 563.0 × 10⁶m³ and burying houses, roads, and farmland. On the basis of a large number of geological surveys and engineering geological investigations on the disaster site, the formation mechanism and process were revealed by means of remote sensing satellite, unmanned aerial vehicle (UAV) aerial shot, and synthetic aperture radar on the ground, among other technical means. The results show that the weathered and broken basaltic rock mass and argillicitization zone are the internal landslide causes, while the saturated water loading and infiltration softening caused by continuous rainfall and the disturbance of highway cutting slope are the external causes. The in-depth study of the formation mechanism and formation process of the Nantang landslide shows that the weathered and fragmented basalt slope should pay attention to interception and drainage measures and support measures during the construction and prevention process, to reduce the influence of water and human excavation on slope stability.

1. Introduction
The instability of rock and soil slope is not an instantaneous overall failure but a gradual process that gradually expands from partial failure to overall failure. The influence of factors such as weak layers and structural planes in the slope results in the uneven stress distribution of the slope rock and soil, showing local stress concentration. The slope excavation, rainfall, and other factors can change the structural plane and strength parameters of rock and soil materials, resulting in changes in the location of the regional stress concentration in the slope. When the stress exceeds the strength value of the material, it will inevitably lead to intensified deformation of the rock and soil, which in turn leads to instability and failure of the slope. At present, the failure mechanism of slope under the factors of slope excavation and rainfall has been studied extensively. On August 27, 2014, a large-scale landslide in Fuquan City, Guizhou Province, China, killed 23 people, injured 22 others, and damaged 77 houses. Studies have shown that poor geological structure is the decisive factor in inducing landslides, and the combined effect of excavation and continuous rainfall is the triggering factor in inducing landslides [1].
Emeishan basalt is widely distributed in Southwest China, covering an area of $30 \times 10^4 \text{ km}^2$ in Yunnan, Guizhou, and Sichuan provinces, often forming high and steep slope landform. Once such high-level basalt slopes lose stability, they can often develop into a large-scale high-speed remote landslide disaster, causing huge casualties and property losses. On July 19, 2018, the ancient basalt landslide in Boli Village, Yanyuan County, Sichuan Province, was resurrected, destroying 186 houses in two villages on the ancient landslide body. The landslide accumulation body blocked Taozigou and formed a dammed lake [2].

At 5:00 (UTC+8) on July 2, 2017, affected by excavation and rainfall, a landslide debris flow disaster (hereinafter referred to as Nantang landslide) occurred on the basalt slope in Dongbiangou, Nantang Village, Nantian Township, Leibo County, Sichuan Province, burying about 2.5 km of under construction highways and about $1.5 \times 10^4 \text{ m}^2$ of farmland and damaging one house. Thanks to effective manual monitoring and disaster warning, the local government evacuated 153 people from 49 households around the landslide in time. No one was injured in the landslide disaster. After the disaster, the second, third, and four authors arrived at the site to conduct extensive geological surveys and personnel interviews, aiming to understand the instability mechanism and disaster risk. These authors also used unmanned aerial vehicle (UAV) data to generate digital ortho Photo map of the Nantang landslide and digital evaluation model (DEM). In subsequent studies, the team further collected regional geological data, multi-temporal optical satellite remote sensing images, ESA Sentinel-1 radar satellite images, rainfall data, seismic network observation data, and landslide investigation report. Finally, through comprehensive analysis, the instability failure mechanism and spatiotemporal evolution process of Nantang landslide under the combined effect of excavation and continuous rainfall are discussed. The research results can provide a reference for the study of the disaster mechanism of basalt slope under the condition of excavation and rainfall and can also provide a useful reference for the design and construction of cutting slope engineering under complex conditions.

After the occurrence of Nantang landslide, the history of disaster deformation, the process of disaster, and the data after the disaster were obtained through multichannel and multi-technical means. The geological environment conditions, deformation history, typical characteristics, and failure mechanism of landslide event are comprehensively analyzed in this study. Table 1 presents the main data and sub-technical methods used in this article.

| Data                           | Resolution | Date              | Data sources                                          |
|--------------------------------|------------|-------------------|------------------------------------------------------|
| Before landslide               |            |                   |                                                      |
| Digital Elevation Model (DEM)  | 10m        | 2014              | Sichuan Bureau of Surveying & Mapping Geoinformation |
| Geological map                 | 1:5000     | 1972              | Geological Bureau of Sichuan Province                 |
| Photograph of pre-sliding      |            | 2017.02-2017.07   | Construction workers and local residents              |
| Google Earth image             |            | 20150212;20170419 | Google Earth (Landsat-7)                              |
| ArcGIS image                   |            | After landslide   |                                                      |
| Sentinel-1 SAR image           |            | 20160112-20160815 | European Space Agency (ESA)                           |
| During landslide               | Daily rain | 2017.05.01-2017.07.02 | National Meteorological Data Center               |
| Rainfall                       |            |                   |                                                      |
| After landslide                | 0.15m      | 2017.07.08        | Author by DJI Phantom 4 Pro                          |
| UAV image                      |            | 2018.03           | Chengdu Survey, Design & Research Institute Co., Ltd. of China Power Construction Group |
| Investigation & design report  |            |                   |                                                      |
| Nantang landslide stabilization engineering |            |                   |                                                      |

Table 1. Summary of the available data

2. Geological settings
As shown in Fig. 1, Nantang landslide is located on the left bank of Jinsha River at the junction of Leibo County in Sichuan Province and Yongshan County in Yunnan Province, about 1 km away from Leibo County. The landslide is geomorphologically located on the southwest slope of the residual mound on the incomplete leveling surface of the fourth level. The platform elevation of the residual mound is 1440 m, and the lowest point is located in the Dongbiangou with an elevation of 1020 m and an elevation difference of nearly 420 m. Affected by the monsoon climate in the eastern Qinghai–Tibet Plateau, Leibo County has an average annual rainfall of 586.3–851.2 mm, mainly from May to August, with a maximum daily rainfall of 125.3 mm.

![Figure 1. Geological map of the study.](image)

The landslide area is located in the middle of the Leibo–Yongshan rhomboid tectonic basin on the southwestern margin of the Yangtze Platform. The Lianfeng, Ebian–Jinyang, and Mabian–Yanjin faults are far from the landslide [3], which have little impact on the landslide. The Majiaheba fault is the main structural trace in the study area. It is a NE-trending, 17-km-long and 5-km-wide, medium- to high-angle thrust fault [4]. Nantang landslide is located on the hanging wall of Majiahe dam fault. Affected by it, the integrity of rock mass in landslide area is poor. The exposed strata in the landslide area are the Permian Emeishan basalt (P2β) and Quaternary (Q) sediments. The Permian Emei Shan Formation is dominantly comprised of dark gray dense, porphyritic, and amygdaloidal basalts. Affected by tectonic and weathering, the surface layer is clayed, and there are a large number of joints and fissures in the shallow rock mass, showing a fragmented structure. The average thickness of fully strongly weathered rock mass is more than 30 m.

In order to relieve the traffic pressure in the county seat of Leibo County and divert the transit traffic flow, Leibo County plans to build a beltway around the main urban area. In August 2016, the bypass road through slope of Dongbiangou, Nantang Village, began to be built. As of the occurrence of the landslide disaster on July 2, 2017, road construction has formed three strips of excavation surfaces at different elevations of the slope.

3. Deformation history and process of landslide
In order to understand the slope deformation before sliding, multi-period remote sensing images, historical photos, and InSAR data were used to analyze the slope deformation before sliding.

3.1. Macro-deformation based on remote sensing images and photograph
Figure 2 shows the multiphase historical image of Nantang landslide. The fourth image is from the satellite remote sensing image of Google Earth platform, while the seventh image is from the AcrGIS platform. The specific shooting time is unknown, but it is believed to be a remote sensing image shortly after the landslide. The rest of the images were taken from beltway construction workers and
local residents during the site investigation. The shooting or acquisition time of all images is shown in the lower right corner of each image.

Field investigation and remote sensing images show that there is no obvious sign of slope activity before the construction of the beltways. On August 26, 2016, after the construction enterprise was determined on beltways in Leibo County, the construction began in November 2016. On February 23, 2017, the beltway was constructed to the middle of the upper section (elevation 1225~1223 m), and there was no sign of deformation and failure of the slope after excavation (Fig. 2a). Local residents and road construction workers also unanimously confirmed that there were no signs of cracking, subsidence, or deformation in the area before February 23, 2017. With the progress of the construction of the upper section of the beltway, the photographs of March 21, 2017 (Fig. 2b), and March 27, 2017 (Fig. 2c), show that there is a small range of landslide deformation on the slope, and the unstable deformation is accumulated to the middle section of the beltway (elevation 1193~1200 m). The aforementioned small-scale collapse deformation was also confirmed by the remote sensing image (Fig. 2d) on April 19, 2017, and its deformation range was not further expanded.

**Figure 2.** Multiphase historical images of Nantang landslide. The fourth and seventh images are from remote sensing data of different periods; other images were taken by mobile phones of construction workers and local residents.
Since June, Leibo has entered the rainy season. The photograph taken on June 20, 2017 (Fig. 2e), showed that the deformation range of the upstream side of the landslide did not significantly expand, but the deformation instability area was newly added in the middle of the landslide and was still accumulated above the middle of the beltway after deformation instability. On the morning of July 1, 2017, the deformation and failure of the local landslide in the early stage intensified, causing the deformation area of the upper section of beltway to be integrated. The elevation of the trailing edge of the landslide deformation reached 1360 m, and the front accumulation reached the lower section of beltway (Fig. 2f). At 5 a.m. on July, 2 2017, the overall instability of the old landslide revived, resulting in the overall decline of the trailing edge gentle slope platform and the shear from the upper part of the beltway. A large number of landslides collapsed down and piled up to the Dongpogou (Fig. 2g).

3.2. InSAR deformation analysis of the surface

InSAR can effectively detect the creep deformation in the early stage of landslide instability [5-8]. In this study, small baseline subset. InSAR method was used to analyze a total of 18 ESA Sentinel-1 radar satellite data from December 20, 2015, to December 24, 2016, and the surface deformation map around the landslide area was obtained (Fig. 3a). The results show no obvious deformation in the landslide area. As shown in Fig. 3b, the time-dependent deformation curve extracted from point A in the slip source region fluctuates between -5 mm and +5 mm. Before the road excavation, there was no deformation in the sliding source area in the historical image (Fig. 2), indicating that there was no creep deformation of the slope before the road construction excavation.

![Differential interference results around the landslide of radar satellite images: no obvious deformation was found in the landslide area.](image)

**Figure 3.** Differential interference results around the landslide of radar satellite images: no obvious deformation was found in the landslide area. (a) Differential interference results of surface displacement and (b) deformation curve of monitoring point A.

4. Geological characteristics after the landslides

Combined with the field investigation and the analysis of multisource and multi-period image data in the landslide area, we have a clear understanding of the Nantang landslide. The Nantang landslide is a high landslide debris flow disaster chain formed by the partial resurrection of the old landslide. As shown in Fig. 4, the elevation of the highest point of the Nantang landslide source area is 1425 m, which is cut out on the section of the beltway around 1240 m. The initial movement direction of the debris flow is 210°, which is affected by the retaining wall and topography during the migration process. Close to the west, the migration direction turns to 185° and finally stops near Dongpogou. The height of the lowest point of the accumulation is about 1035 m, the vertical height difference is 395m, and the horizontal projection length is about 700m. According to its deformation, failure, and movement characteristics, the landslide can be generally divided into the slip source area (I area), the circulation scraper area (II area), and the accumulation area (III area).

4.1. Source area

The slip source area (I area) is located in the middle and upper part of the slope, with an elevation ranging from 1425 to 1240 m. The lower shear outlet is located near the section of the beltway, with
an elevation difference of 185 m. The main sliding direction of the sliding source area is 205°, the length is about 300m, the width is about 360m, and the area is about $10.0 \times 10^4 m^2$. The landslide is mainly composed of loose old landslide deposits and strongly weathered and broken basalt. Based on drilling exposure, the thickness of the landslide is about 40.0~76.0 m and the total volume is about $460 \times 10^4 m^3$. According to the description of local residents, prior to the occurrence of the landslide, the slope of the landslide source area was about 35°~40° on a near-linear steep slope, and no deformation and failure signs such as tensile crack and local subsidence were found at the trailing edge. After the occurrence of the landslide, the slide body in the source area is mainly based on the overall lower seat, and a belt-shaped slide wall with a height of about 10~17 m and a slope of about 50°~60° is formed on the rear edge (Fig. 5a and 5b). The sliding body can be roughly divided into two parts. One part of the sliding body (about $410.0 \times 10^4 m^3$) is accumulated in the sliding source area, and most of the original stratigraphic characteristics are retained. The original vegetation cover and many long cracks can be seen on the surface. After the body rushes out of the shear outlet, it disintegrates to form a debris flow.

**Figure 4.** Post-sliding geological map of Nantang landslide.

**Figure 5.** Photos showing the source area of the Nantang landslide. (a) Landslide body in source area. (b) Main scarp and tensile crack.

4.2. **Transportation area**
The transportation area (area II) is located in the middle of the landslide, with a slope of about 35°. The main channel for the main landslide to move rapidly along the main sliding direction after starting is mainly distributed in the elevation of 1240–1135 m with a projected area of about $5.7 \times 10^4 \text{m}^2$ (Fig. 6a and 6b). After the rock mass in the sliding source area slipped out, the original loose material on the slope surface was scraped and pushed to the lower part of the slope to accumulate, making the spatula grooves to be partially visible (Fig. 6c). According to exposure reveals, the thickness of the deposits in the circulation spatula area varies, gradually becoming thicker from the top to the bottom. The thickness is about 5–15 m, and the accumulation volume is about $57.0 \times 10^4 \text{m}^3$. The main composition is debris formed after the disintegration of the strongly weathered protolith (Fig. 6d). The slope of the landslide transportation area is steep, which has a certain acceleration effect on the debris flow. However, due to the influence of open terrain and rock disintegration, the scraper effect is relatively weak, mainly dominated by stacking.

Figure 6. Photos showing the track or transportation area of the Nantang landslide. (a) UAV image in track or transportation area. (b) Photos in track or transportation area. (c) The preexisting loose deposits by scraping. (d) Cataclastic basalt in track or transportation area.

4.3. Transportation area
As shown in Fig. 7, the accumulation area is located at the lower part of the slope, with trailing edge elevation of 1135 m, leading edge lowest point elevation of 1020 m, and relative height difference of 115 m. After the debris flow reached the accumulation area, the debris flow gradually closed from both sides to the middle due to the blocking effect of the highway retaining wall, and the movement direction changed from 205° to 190°, accumulating in the gentle slope section of the left bank of Dongpogou. The accumulation body is mainly composed of strongly weathered gravel soil, gravel, and basalt rock blocks separated from the original rock, forming a “cone-shaped” accumulation area with a slope of about 15–20°, burying a house and knocking down a large number of trees in the east ditch. Results from the DEM data analysis after landslide show that the projection area of the accumulation area is about $4.8 \times 10^4 \text{m}^2$, the average accumulation thickness is about 20 m, and the accumulation volume is about $96.0 \times 10^4 \text{m}^3$.

In summary, the residual volume of landslide source area is about $410.0 \times 10^4 \text{m}^3$, the volume of scraper accumulation area is about $57.0 \times 10^4 \text{m}^3$, the volume of accumulation area is about $96.0 \times 10^4 \text{m}^3$, and the existing loose accumulation in landslide area is about $563.0 \times 10^4 \text{m}^3$. According to the topography and geological data before and after the landslide, combined with the above analysis, the geological longitudinal profile as shown in Fig. 8 is obtained.
5. Factors that cause slope instability

5.1. Lithology and rock mass structure
Combined with the field investigation, the specific characteristics of the slope and rock mass are as follows:

(1) The basalt near the sliding source area has strong weathering (Fig. 9a). Through investigation, the weathering intensity of basalt varies greatly in different sections of the Dongpogou slope, and some sections have weak weathering degree and high strength, which can form a steep and dangerous rock mass. However, the weathering zone of basalt in the sliding source area is deep, the surface layer is clayized, the rock mass is fragmented, and the fractures are open with low strength. In addition, it should be noted that basalt contains about 10%–15% feldspar crystals, which were kaolinized by groundwater. As a result, the strength of basalt rocks was reduced, and the homogeneity of basalt was damaged due to the existence of feldspathic crystals, causing basalt rock mass to be susceptible to
fracture [9]. As a consequence, the basalt rock mass has gradually softened, and the shear strength of the rock structural planes has dramatically decreased.

(2) The joint fissures of basalt rock mass are developed (Fig. 9b). In the eastern basalt area where the study area is located, the basalt rock mass often develops original columnar joints, cutting the rock mass into cataclastic or massive structures. The rock mass structure is relatively broken and has high water permeability. The instability of the sliding body after formation has extremely significant disintegration characteristics.

(3) There was a split physicochemical interlayer dislocation zone (Fig. 9c and 9d). According to the regional geological data and field investigation, the primary weak surface is developed in the basalt of Nantang landslide, mainly volcanic breccia or conglomerate debris. The volcanic breccia or conglomerate debris’s thickness is small and its mechanical strength is low compared with volcanic lava layer. It is easy to modify and wet slide when encountering water and often becomes the control type weak structural plane of basalt instability and sliding.

![Figure 9](image)

**Figure 9** Structural characteristics of basalt rock mass. (a) Strongly weathered basalt rock mass on upper section of beltway. (b) Cataclastic basalt is developed in structural plane. (c) Moist scarp of landslide. (d) Sliding surface from ZK06.

5.2. Continuous rainfall
The slope geological structure in the study area is susceptible to seasonal heavy rainfall, which mainly concentrates in May to August. Data from the Jincheng Precipitation Observatory near the landslide from May 1, 2017, to before the landslide shows that the cumulative rainfall in the 2 months before the landslide reached 299.2 mm, which was significantly greater than the rainfall in the same period in the region. There was a continuous rainfall process from June 18 to June 24, with the accumulated rainfall of 88.2 mm and the maximum daily rainfall of 42.9 mm (Fig. 10).

The main groundwater types around the sliding source area are elasic rock and volcanic rock bedrock fissure water, which is recharged by atmospheric precipitation. After the occurrence of the landslide, the residual mud-bearing wet sliding zone was visible at the trailing edge (Fig. 9c). Under the condition of continuous rainfall, rainwater infiltrates along the basalt joint surface and abundant groundwater forms pore water pressure in the rock fracture, further reducing the mechanical strength of the interlayer dislocation zone, so as to promote the expansion of the sliding surface and lead to the shear of the sliding front. Therefore, continuous rainfall is a factor that directly causes landslides.
Figure 10. Cumulative curve of rainfall prior to landslide occurrence in Jincheng town near the Nantang landslide. (Dataset is provided by National Meteorological Data Center. (http://data.cma.cn)

5.3. Excavation activities
The design subgrade width of beltway in Leibo County is 8 m, and the engineering construction needs excavation (Fig. 11). The maximum height of the cut slope is 24.3 m. During the construction period, the subgrade slope did not make relevant drainage facilities, only the lower section of beltway completed the lower shoulder and retaining wall construction. Due to the influence of road construction and continuous rainfall, local cracking and collapse deformation have occurred in the landslide area.

Figure 11. Nantang landslide is excavated due to the construction of beltway in Leibo County

The above analysis shows that the loose cataclastic basalt distributed in the sliding source area and the physical and chemical interlayer dislocation zone in the slope are the internal causes of landslide formation. The pore water pressure formed by the groundwater in the rock mass cracks caused by the continuous rainfall reduces the mechanical strength of the dislocation zone between layers, and the highway excavation further reduces the stability of the slope, which are the external causes of the landslide.

6. Suggestions for prevention and control of cataclastic basalt slope
The joint fissures of basalt are relatively developed. Rainwater is easy to infiltrate through rock fissures during rainfall, and the weak interlayer will soften when there is interaction with water, resulting in the decreased overall stability of the slope. Therefore, attention should be paid to the construction of the basalt slope (1) to strengthen the design of interception drainage. The water in the slope body should be constructed according to the principles of “detaching but not blocking” and “combining interception, drainage and guide” [10]. (2) The prevention and control process should be based on drainage engineering and combined with retaining wall, anti-slide pile, and other prevention and control measures. (3) Slope monitoring should be carried out when necessary to determine whether further engineering treatment is needed.

7. Conclusions
By means of satellite remote sensing, InSAR interpretation, UAV aerial survey as well as field investigation, visit, and exploration, the following conclusions are drawn:

(1) In March 2017, with the construction progress of the upper part of the beltway, a small range of collapse deformation first appeared but did not further expand. After the rainy season in June, only a new deformation instability region was added in the middle of the slope. Until July 1, obvious deformation began to appear in the leading edge of the landslide, damaging the whole body.

(2) According to the deformation, failure, and movement characteristics of landslide, landslide can be generally divided into sliding source area, transportation area, and accumulation area.

(3) Weathered and broken basalt and argillization zone are the internal causes of landslide formation, saturated loading, and infiltration softening caused by continuous rainfall, and highway slope cutting disturbances are the external causes of landslide.

(4) For weathered broken basalt slope, we should strengthen the interception and drainage design, take interception and drainage engineering as the main prevention and control measures, and monitor if necessary.

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