Deformation Characteristics of Tianjiaba Landslide Induced by Surcharge

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Abstract: The Tianjiaba landslide on the Hang Rui expressway was located in the south of Sinan County, Tongren City, Guizhou Province. From the night of 2 July to the morning of 3 July 2011, numerous house cracks, foundation subsidence, and surface cracks suddenly occurred in the Tudiwan and Tianjiaba villages on the north and south sides of the management area. Based on the field geological survey, drilling, pit exploration, surface displacement, fracture observation, and deep displacement monitoring data analysis the deformation characteristics and causes of the Tianjiaba landslide were comprehensively analyzed. In this study, the landslide was divided into three areas, in which fracture group 3 was the most severe. Among the ten inclinometer holes, the sliding surface displacement of No.8 inclinometer hole was the largest, i.e., 25 mm. The sliding surface slopes of fracture groups 1, 2, and 3 were small, i.e., 12.25°, 4.97° and 6.62°, respectively. The results showed that the displacement values of different positions of the landslide were different, and the ground displacement value was larger than the sliding surface displacement value. The maximum displacement of the ground was 242.68 mm, which is larger than the maximum displacement of the inclinometer hole. Because the displacement of the upper part was greater than that of the lower part, bulging cracks formed in the lower part of the landslide. When the displacement of the upper part was less than that of the lower part, tension cracks formed in the lower part of the landslide. According to the surface cracks and displacement values of inclinometer holes on the sliding surface, the landslide was in the initial sliding stage and filling the platform of the management area on the hillside was the main cause of the landslide.

Keywords: Tianjiaba landslide; sliding surface; borehole; inclinometer; surface displacement observation point

1. Introduction

One of the main causes of a landslide is that the upper part of the slope is loaded to induce a landslide [1]. The deformation characteristics of the landslide are the core of slope stability evaluation, which has been widely investigated by researchers around the world for a long time [2,3]. According to the deformation and failure characteristics of landslides [4,5], the slope can be divided into three types: gradual change, sudden, and stable type. The sudden type of landslide is the most harmful to human beings.

When engineering construction is conducted in mountainous areas, high platforms or buildings are often developed on the slope to break the original equilibrium state of the slope and the slope can slide downward [6–9]. During a landslide a large number of cracks arise, such as tensile cracks in the back wall of the landslide, fan-shaped tensile cracks in the front edge, shear cracks in the perimeter of a landslide, bulging, and tension cracks in the landslide [10–13]. In soil landslides, the sliding direction of the landslides is usually perpendicular to the direction of tension and bulging cracks [14–16]. The strike of
shear fracture is usually perpendicular to the strike of the slope and, in most cases, it is relatively straight [7,17,18]. For rock landslides, the occurrence and nature of fractures are mainly controlled by structural planes [19–21].

The surface of tension and bulging cracks is rough, without scratches. The transverse tension crack is usually arc-shaped and generally extends longer than other cracks [22,23]. The longitudinal crack is relatively straight, often fusiform, with a short extension. The surface of the shear crack is smooth with obvious scratches. The strike of the shear cracks and scratches are consistent with the sliding direction of a landslide [24,25]. Many researchers evaluated the stability of landslides based on the width of cracks and sliding rate. They divided the development of the landslide cracks into initial deformation, constant velocity deformation, and accelerated deformation stage [26–28]. Although the cracks of some landslides are very wide, the sliding rate is stable and landslides are still in a stable stages. The fracture shape and deformation characteristics of sliding mass have guiding significance for landslide prevention and stability evaluation [29–31].

In this study, the Tianjiaba landslide in the north of Sinan County, Tongren City, Guizhou Province was the research object. According to the field geological survey, ground displacement observation points, and inclinometer tube displacement data, the deformation characteristics of the landslide were investigated. This study analyzes the displacement characteristics of landslide mass and the sliding surface. The results could guide landslide disaster prevention.

2. General Situation of Engineering Geology in Landslide Area

2.1. Landslide Background

The landslide area is located in the intermountain depression between Tianjiaba and Tudiwan villages in the Sinan County, Tongren City, Guizhou Province, at the k1460–k1410 section of Hangrui Expressway (G56). Its geographic coordinates are 116°23′49.66″E and 39°54′59.50″N. To meet the needs of the project, a management area platform with a length of 220 m, a width of 120 m, and a height of 13–17 m was developed in the middle of the depression. The slope sliding occurred due to the platform in the filling management area and the excavation of a ramp and connecting line embankment on the north and south sides of the platform. From the night of 2 July 2011 to the morning of 3 July 2011, a large range of cracks occurred in the southwest corner of the filling platform and its outer side of Tudiwan and Tianjiaba villages. The cracks developed rapidly, leading to most of the houses becoming dangerous to occupy.

2.2. Topography and Geomorphology

The terrain of the landslide area is generally a dustpan like depression in the mountains. The north, east, and south sides of the depression are close to the bedrock ridges or hills; the terrain is relatively high, and altitude values are about 491 m. The slopes of the ridges or hills are between 35° and 50° and the west side is a gully and steep slope. The depression is a wide and gentle slope; the terrain is relatively low, and the altitude values are about 463 m. The upper slope is about 5° to 10°. The lower slope is slightly steep, about 10° to 25°. Figure 1 shows the outline of the landform.
2.3. Formation Lithology

In addition to artificial filling of the platform in the rear management service area, the overburden layer of the site consisted of eluvial and deluvial silty clay, mixed gravel clay, colluvial and deluvial gravel, block stone, and mixed silty clay gravel. The underlying bedrock consisted of a nearly horizontal occurrence of strongly weathered and moderately weathered mudstone with a strata dip angle of 230° to 270° and dip angle of 3° to 5° with argillaceous and layered structures. The fracture surface was severely stained by ferromanganese. The sliding zone soil was silty clay both above the bedrock surface and close to the bedrock surface. The silty clay was softened and argillized by groundwater to form a weak zone in the form of soft plastic to flow plastic. The buried depth was generally 5–19 m. The north, east, and south sides outside the landslide area were bedrock exposed areas, with local overburden thickness of 1–3 m and exposed bedrock in the gully. Figure 2 shows the core.
2.4. Meteorological and Hydrological Conditions

The site has a subtropical monsoon climate with annual rainfall ranging from 1100 to 1400 mm. The rainy season is mainly in the summer and autumn. Precipitation in spring and summer of 2011 was generally the same as in previous years, with intermittent rainfall for more than ten days in late June, providing effective recharge for surface water and groundwater. Groundwater in the landslide area was pore phreatic water in the Quaternary loose layer and bedrock fissure water.

Pore phreatic water in the Quaternary loose layer occurred in the overburden above the bedrock surface, with a buried depth of 0.9–8.8 m. It was supplied by the infiltration of the bedrock fissure water, atmospheric precipitation, and farmland irrigation water above the slope and then flew and discharged to low-lying areas.

3. Deformation Characteristics of Landslide

3.1. Outline of Landslide and Monitoring Scheme

The landslide was about 380 m long from east to west and 450 m wide from north to south. Restricted by topography to the north and bedrock surface to the south, the landslide was in an inverted pear shape with wide back and narrow front. Through field geological survey and surface displacement observation, the landslide was divided into three zones according to the extension direction of the fracture group. The main sliding direction of zone 1 was about 330 m long and 110 m wide, and the height difference between the front and rear was about 50 m. The front of zone 2 was integrated with zones 1 and 3. The main sliding direction was 290 m long, the rear part was 280 m wide, and the height difference between the front and rear was about 65 m. The main sliding direction of zone 3 was about 370 m long and 190 m wide, and the height difference between the front and rear is about 65 m.

Due to the limitations of a high and steep terrain, the monitoring methods were inclined hole displacement monitoring, surface displacement monitoring, surface crack monitoring, and manual inspection. The total station was used for surface displacement monitoring.

Based on the field survey, combined with the landform and the macro deformation characteristics of the landslide, ten inclinometer holes, numbered JCK1–JCK10, were set.
up. Twenty-six surface displacement monitoring points were numbered N1–N26. There were 21 test pits numbered WT1–WT21, and eight boreholes numbered ZK1–ZK8. The deflectometer with guide wheel was used for the deformation measurement of the inclinometer. The total station equipment was Leica TCRP1201+R1000, with an accuracy of 1 mm.

Figure 3 shows the landslide zoning, inclinometer holes, surface displacement observation points, and borehole layout.

![Figure 3. Distribution map of surface displacement observation points and inclinometer holes.](image)

### 3.2. Deformation Characteristics of Surface Fractures

A landslide crack is an essential associated phenomenon in the formation and development of landslides. In the process of landslide movement, a crack represents a deformation trace of the landslide surface soil.

There were more than 100 main surface cracks in the landslide area with a length of 10–30 m, and several longer cracks were more than 40 m long. The width of ground cracks was generally 1–5 cm, and the width of house cracks was mostly between a few centimeters to 20 cm. Table 1 presents the observation data of 26 surface displacement monitoring points.
| Number | Location | Position | Observati Displacement on Times | Horizontal Displacement (°) | Maximum Ground Uplift (mm) | Maximum Ground Settlement (mm) |
|--------|----------|----------|---------------------------------|-----------------------------|---------------------------|-----------------------------|
| N3     | Fracture group 1 | Upper part of slope | 12 | 224 | 44.55 | 30 |
| N20    | Fracture group 1 | Lower part of slope | 16 | 280 | 85.51 | 17 |
| N2     | West side of management area platform | 19 | 262 | 113.16 | 19 |
| N16    | West side of management area platform | 2 | 62 | 121.26 | 13 |
| N1     | West side of management area platform | 9 | 266 |  | |
| N17    | Upper part of steep slope on the west side of platform in management area | 20 | 274 | 241.67 | 11 | 13 |
| N18    | Fracture group 2 | Upper part of steep slope on the west side of platform in management area | 20 | 271 | 108.34 | 29 | 17 |
| N19    | Management area platform southwest corner table | 20 | 274 | 88.02 | 88 |
| N5     | Slope toe at southwest corner of platform in management area | 20 | 253 | 131.02 | 18 | 39 |
| N15    | Slope toe at southwest corner of platform in management area | 20 | 253 | 242.68 | 2 | 35 |
| N14    | Upper part of slope | 20 | 241 | 72.28 | 7 | 21 |
| N13    | Upper part of slope (near JCK-1) | 20 | 246 | 74.55 | 46 | 29 |
| N4     | Middle and upper part of slope | 18 | 258 | 169.65 | 55 |
| N7     | South end of middle upper slope | 11 | 213 | 33.38 | 10 | 11 |
| N6     | Middle part of slope | 16 | 259 | 223.16 | 14 | 16 |
| N8     | Middle part of slope (near JCK-1) | 20 | 263 | 219.7 | 29 |
| N11    | Middle part of slope | 20 | 251 | 66.91 | 27 |
| N12    | Middle part of slope | 20 | 253 | 59.14 | 29 |
| N10    | Middle part of slope | 3 | 250 | 37.12 | 14 |
| N9     | Middle and lower part of slope | 20 | 277 | 221.2 | 7 | 28 |
| N25    | Gully center on the west side of slope | 16 | 296 | 76.94 | 14 |
| N26    | Upper part of steep slope on the west side of slope | 16 | 308 | 128.7 | 66 |
| N27    | Residual beam on the upper part of the southwest steep slope (near ZK6) | 16 | 292 | 102.69 | 25 |
| N28    | The upper part of the steep slope on the southwest side of the slope | 16 | 286 | 143.89 | 24 |
| N22    | Connecting line LK1 +040 embankmen t | South side of slope toe of LK0 + 940 Road | 16 | 280 | 64.94 | 26 |
| N23    | Gully intersection on the west side of slope | 11 | 309 | 53 | 22 |

As shown in Figure 3 and Table 1 the N3 displacement observation point was located in the upper part of the slope, N20 was located in the lower part of the slope, and the elevation of the two points was in a continuous settlement. According to the observation data, the horizontal displacement of the lower part of the slope (N20) was more severe than that of the upper part (N3), and land subsidence of the upper part of the slope (N3) was more serious than that of the lower part (N20). The reason for the formation of zone 1 of the fracture group was the traction displacement of the LK0 + 805 culvert foundation of an excavation connecting line, which formed tension cracks (LK is the culvert mileage number.). There were more than 30 fractures in zone 1, which were mainly developed in the upper part of the slope, sporadically distributed in the lower part, and almost none in
the middle. The overall strike of the fractures was northwest-southeast (310° to 340°), and the sliding direction was about 230°.

Fracture zone 2 was developed in the lower part of the slope and the total number was less than that of zone 1 and 3 on the north and south sides, respectively. N2, N1, N18, and N17 observation points were located at the foot of the west slope and below the platform in the management area. The direction of ground displacement was 262–274°, and the maximum horizontal displacement was 241.67 mm (N17). The ground rose first and then subsided, and the maximum uplift was 29 mm (N18).

The observation points N19, N5, and N15 were located at the southwest corner of the platform and below the slope toe of the management area. The direction of the ground displacement was 274–253°, and the maximum horizontal displacement was 242.68 mm (N15). The ground first subsided, then rose, and continued to subside. The current settlement of the filled platform (N19) was 88.0 mm, and the current settlement below the slope toe was 39 mm (N5).

It can be seen from the observation data that the ground displacement direction of fracture group 2 was a radial displacement with the filling management area platform as the core. Horizontal displacement of the west side of the platform was basically the same as the southwest corner of the platform. The ground at the foot of the west slope and below (N2, N1, and N18) of the platform first rose and then subsided, while the ground at the southwest corner of the platform and below the foot of the slope (N5) first subsided, then rose, and then continued to subside.

The displacement direction of the zone 3 of fracture group was radial displacement with the filling platform as the core. Surface horizontal displacement was the largest in the middle of the slope (N6, N8, and N9) and near the platform of the management area (N6 and N4), while displacement was smaller in the upper and lower parts of the slope and far away from the platform of the management area. The upper and middle part of the slope (to the east of N9) first uplifted and then subsided, while the lower part of the slope (N26, N27 and N28) continued to subside. The causes of fracture group 3 were the subsidence or displacement of the platform in the management area that led to the ground surface upliftment and formed bulging (tension) fractures. Figure 4 shows the tension crack.

![Figure 4. Tension fracture in the zone 3 of the fracture group.](image)

3.3. Deformation Characteristics of Sliding Surface

Ten deep displacement (borehole) observation holes were arranged in this survey. Figure 5 shows the analysis results of observation data from the deep displacement observation holes. The JCK-2 inclined hole was cut short at 7 m on 23 July, the JCK-3 inclined hole was cut short at 9.5 m on 30 July, the JCK-6 inclined hole was cut short at 17.5 m on 30 July, the JCK-7 inclined hole was cut short at 11 m on 1 August, and the JCK-8 inclined
hole was cut short at 19 m on 30 July. JCK-2,3,6,7,8 inclinometer holes were all cut short at the sliding surface.

3.3.1. Deformation Characteristics of Sliding Surface of Fracture Group 1

There were two deep displacement observation holes in fracture group 1 area, JCK-8 and JCK-9. Among them, JCK-8 was located in the lower part of the slope and JCK-9 was located in the upper part of the slope. The displacement of the two inclining holes is shown in Figure 5.

The deformation law of inclinometer hole JCK-8 was obvious, while that of the deformation of inclinometer hole JCK-9 was chaotic. The deep displacement direction of JCK-9 was 216° and the maximum deep displacement was 4.0 mm. The bottom of the displacement layer was 14.0 m deep. The displacement surface was a mixed silty clay gravel layer. The deep displacement direction of JCK-8 was 228° and the maximum displacement was 25.0 mm. The bottom of the displacement layer was 19.0 m deep, and the displacement surface was a moderately weathered mudstone layer.

It can be seen that: the upper part of the slope (JCK-9), where the fracture group was located, displaces along the mixed silty clay gravel layer, and lower part of the slope displaces along the moderately weathered mudstone layer facing the excavation connecting line LK0 + 805 culvert foundation. The depth of the displacement surface was 14–19 m, the slope of the displacement surface (JCK9-JCK8) was 12.25°, and displacement of the lower slope (JCK8) was more severe than that of the upper slope (JCK9).

3.3.2. Deformation Characteristics of Sliding Surface of Fracture Group 2

There were three deep displacement observation holes in the fracture group 2 area, numbered JCK-4, JCK-6, and JCK-7. The data of each inclined hole are shown in Figure 6.
The deformation law of inclinometer hole JCK6 was obvious, while that of JCK7 and JCK4 above the sliding surface first decreased and then increased. The deep displacement direction of fracture group 2 was 280–301° and the deep displacement value was between 10.5 and 15.0 mm. The bottom depth of the displacement layer was 11–17 m, and the displacement surface was the strongly weathered mudstone layer of mixed silty clay gravel layer. The slope of the displacement surface was 4.97° (JCK6–JCK7), and the azimuth displacement on the slope (JCK6) was more severe than that on the bottom (JCK7 and JCK4).

The reasons for the deformation of fracture group 2 are that the platform displacement in the management area compressed the front of the slope toe, resulting in surface uplift and bulging (tension) fractures.

3.3.3. Deformation Characteristics of Sliding Surface of Fracture Group 3

There were five deep displacement observation holes in the fracture group 3 area, numbered JCK-1, JCK-2, JCK-3, JCK-5, and JCK-10. The data of each inclined hole are shown in Figure 7. Among them, JCK-1 was located in the middle and upper part of the
slope, JCK-2 and JCK-3 were located in the middle part of the slope, and JCK-5 and JCK-10 were located in the middle and lower part of the slope.

Figure 7. Deformation characteristics of the sliding surface of fracture group 3.
The deep displacement direction of the upper part of the slope (JCK1) in zone 3 of the fracture group was 336°, the maximum deep displacement was 7.0 mm, and the bottom depth of the displacement layer was 10.5 m. The deep displacement direction of the middle part of the slope (JCK2 and JCK3) was 320°–323°, the maximum deep displacement was 15.0 mm (JCK2), the bottom depth of the displacement layer was 7.0 (JCK2)–9.5 m (JCK3), and the upper part of the slope was in the mixed silty clay gravel layer. The deep displacement direction of the middle and lower part of the slope (JCK5 and JCK10) was 281° and the maximum deep displacement was 15.0 mm (JCK10). The bottom depth of the displacement layer was 6.0 (JCK5)–13.5 m (JCK10). The displacement surface was in the mixed silty clay gravel layer (JCK5) and the layer of moderately weathered mudstone (JCK10).

The depth of the displacement surface in zone 3 of the fracture group was 6.0–13.5 m, the slope of displacement surface was 6.62°–4.64° (JCK1, JCK2 and JCK10), and the displacement of the middle upper slope (JCK2 and the lower slope JCK10) was the largest, measuring 15 mm.

The reasons for the formation of fracture group 3 were the settlement of the platform in the management area that compressed the surrounding area (or the foot of the slope), resulting in the uplift of the ground in the upper and middle parts of the slope leading to the occurrence of bulging (tension) fractures.

4. Cause Analysis and Prevention of Landslide

4.1. Analysis on the Cause of the Landslide

The deformation and failure of a landslide are caused by both internal and external factors. The main reasons for the landslide sliding are as follows:

1. Topographically, the landslide area was a dustpan-like depression between mountains, which makes it easy to collect and infiltrate with atmospheric precipitation, so the groundwater is rich. The front edge of the landslide was close to the deep cutting valley and there was a steep slope, which provides a free surface for possible sliding.

2. In the stratum structure, the underlying mudstone belongs to aquifuge, and the bedrock surface is relatively gentle, which makes it easy to enrich the infiltrating water near the mudstone surface, thus forming a weak zone. Mudstone inclination was 230° to 270°, which is basically consistent with the slope inclination, and it can collect the bedrock fissure water and the groundwater on the top of the rock in the far mountains on the north side of the landslide area. These conditions make the site itself a potential geological disaster-prone area.

3. Heavy loading on the back slope because management area site was filled with more than 80,000 m³ in the middle toll management area at the back of the slope, a large number of 3–4-story buildings were constructed by villagers at the middle and rear of the slope, and local subgrade filled at the connecting line all loaded the middle and rear part of the landslide and promoted the slope sliding.

4. There was local excavation near the leading edge. The front edge of the slope formed two local free faces due to the reconstruction of a village road and the excavation of GLK0 + 800 culvert and LK0 + 805 culvert (GLK is the culvert mileage number.), which reduced the slope’s stability.

5. Change of the groundwater runoff channel. Due to the high fill and impact rolling technology in the toll management area, the runoff channel of groundwater in the landslide area was changed, which made the groundwater flow to the middle of the landslide area, bypass the platform of the management area, and directly flow to the gully on the west side of the landslide area. The change in the groundwater runoff channel made the soil near the new runoff channel soften and produced a seepage hydrodynamic pressure. The sliding of block 1 and block 3 was promoted.
4.2. Landslide Prevention

Through systematic analysis and research on the geological environment, groundwater action, and the landslide deformation and development process, the deformation mechanism and sliding cause of the landslide were recognized. According to the characteristics of landslide and hazard objects, comprehensive treatment measures such as reducing fill, grading retaining, backfill back pressure, and interception and drainage were suggested as follows:

1. Moving the platform in the management area out of the landslide area to minimize the filling at the back of the landslide, and moving the excess earth fill out of the landslide area.
2. Considering the large area of the landslide, numerous houses, and the fact that there are two secondary connecting roads on the landslide mass that cannot be moved to other places, in order to directly protect the highway and residential buildings a row of antislide piles with a section of $2 \times 3$ m and a pile length of 24–28 m were set in the middle of zone 1, with a total of 11 piles.
3. A row of antislide piles with a section of $2.2 \times 3.2$ m and a pile length of 26–30 m were set under the central management platform of zone 2, with a total of 26 piles.
4. A row of antislide piles with a section of $1.8 \times 2.7$ m and a pile length of 18–20 m were set in the middle of zone 3, and a row of antislide piles with a section of $1.8 \times 2.7$ m and a pile length of 22–26 m were set outside the secondary highway in front of zone 3, with a total of 25 piles. Table 2 presents the summary of antislide piles at different crack groups.
5. To utilize the extrusion from blocks 1 and 3 to the middle of the sliding body, and to deal with the surplus earthwork from the platform in the original management area, a row of sheet pile walls was set in front of areas 1 and 2, and back pressure backfill was conducted after the sheet pile. 24 piles are set, with a section of $1.8 \times 2.7$m.
6. Backfill and seal the surface cracks and set up perfect drainage measures. The drainage measures consisted of the intercepting drainage ditches inside and outside the landslide and paving of the original large seepage ditch.

| Fracture Group | Pile Size  | Pile Length | Number of Piles | Location of Piles                      |
|---------------|------------|-------------|-----------------|----------------------------------------|
| Fracture group 1 | 2 × 3m      | 24–28m      | 11              | Middle part of fracture group 1        |
| Fracture group 2 | 2.2 × 3.2m  | 26–30m      | 26              | Below the management platform in the middle of zone 2 of fracture group |
| Fracture group 3 | 1.8 × 2.7m  | 18–20m      | 30              | Middle part of fracture group 3        |
| Fracture group 3 | 1.8 × 2.7m  | 22–26m      | 25              | In front of zone 3 of fracture group   |

According to the relevant monitoring data, the landslide has no new deformation, and the landslide has become stable, which meets the relevant requirements of highway design.

5. Discussion

The cracks on the landslide body are in a dynamic change. Some cracks continue to settle, and some cracks rise first and then settle. The fracture itself is also experiencing the process of occurrence, development, disappearance, and the continuous generation of new fractures. The crack development is related to landslides, and the current development of cracks can only reflect the landform conditions of landslides at this stage. The slope of sliding surface of fracture groups 1, 2, and 3 was small, which was 12.25°, 4.97°
and 6.62° to 4.64°, respectively. The upper slope was about 5–10°, the lower slope was slightly steep, about 10–25°, and the underlying bedrock dip angle was 3–5°. Considering the terrain, stratum, and dip angle of the sliding surface, this site was not a landslide site. However, more than 80,000 m² of filling at the back of the slope and the excavation at the front of the slope have changed the hydrogeological conditions of the site.

According to the engineering geological mapping, the landslide cracks were mainly distributed in the upper and middle parts of the slope when the ground surface cracks first occurred and then gradually occurred in the middle and lower parts of the slope. Cracks on the site have been in a state of slow widening and increasing, which indicated that the displacement of the slope was reflected in the creeping compression. Therefore, it was determined that the landslide was in the initial sliding stage.

6. Conclusions

Through the analysis of ground displacement observation points and deformation of inclinometer holes, the following conclusions are drawn:

1. The surface crack width was larger than the sliding surface displacement of the inclinometer hole. Among the 10 inclinometer holes, the sliding surface displacement of JCK-8 was the largest, which was 25 mm. Among the 26 surface displacement observation points, the displacement of N15 was the largest, which was 242.68 mm.

2. The depth of the displacement surface in zone 1 of the fracture group was 14–19 m, and the slope of sliding surface (JCK9-JCK8) was 12.25°. The reason for the formation of this group of cracks was that the excavation of the LK0 + 805 culvert foundation of the connecting line caused the formation of tension cracks in zone 1 of the landslide crack group.

3. The section with a gentle sliding surface was mostly the antisiding section, and the cracks on the ground were not developed. The slope of bedrock layer in zone 2 of the fracture group was steep up and down, the middle part was gentle, and the slope of sliding surface was 4.97° (JCK6-JCK7). The upper part of the slope was prone to integral displacement when the surface load increased, thus there were fewer cracks in the upper part of fracture group 2. The lower part of the slope was prone to traction displacement and more tension cracks when the excavation was partial.

4. There were few cracks when the entire landslide body moved. When the displacement of the upper part was greater than that of the lower part, bulging cracks often formed in the lower part of the landslide body. When the displacement of the upper part was less than that of the lower part, tension cracks formed in the lower part of the landslide body. Zone 3 of the fracture group moved along the mixed silty clay gravel layer in the middle and upper part of the slope (JCK2–JCK2, JCK10 and JCK5) and along the moderately weathered mudstone layer in the middle and lower part of the slope (JCK10). The depth of the displacement surface was 6.0–13.5 m, and the slope of displacement surface (JCK1, JCK2 and JCK10) was 6.62–4.64°. The displacement of sliding surface in the upper part of the slope (JCK1) was less than that in the middle and upper part of the slope (JCK2) and that in the middle part of the slope (JCK3 and JCK5) was less than that in the lower part of the slope (JCK10). Displacement of JCK2 and JCK10 was 15 mm. Thus, there were bulging cracks in the upper part of the slope, tensile cracks in the lower part, and bulging cracks and tensile cracks in the middle part.

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