Initiation mechanism and deformation tendency of a high-position landslide at Ningnan County, China

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Abstract. High-position landslides mainly occur in the upper part of the steep slope wherein the shear outlet is much higher than the toe of the slope. It often transforms into the rapid and long-runout debris flow, causing severe loss of life and property. This paper describes a high-position landslide that occurred on the right bank of the Heishui River in Songxian Town, Ningnan County, southwestern China, on June 28 and August 16, 2012, resulting in five deaths. Based on the field investigations, borehole drilling, in situ, and laboratory experiments, the initiation mechanism of the landslides are unraveled. Detailed crack surveys are conducted to identify the deformation tendency of this landslide in the future. The Baishuihe landslide originated on a 310 m-high hillside, which provided a favorable free surface for the landslide occurrence. The Baishuihe landslide is located in the influence zone of the Zemuhe fault, and the active fault activities dramatically contribute to the fragmented stratigraphic structures and well-developed minor structures. The initiation of the June 28 landslide is considered a long-term creep under the inner and outer integrations, while the consequent bedding slope and persistent precipitation are the primary factors. The failure of the August 16 landslide is analyzed using the retrogressive slide in the source area of the first landslide. The sustaining deformation of the landslide is controlled via cracks on the surface of the main deformation zone and hydraulic influences induced by rainfall. The slip process follows creep deformation and can be aggravated under rainfall. Based on the crack distribution, the potential instability volume is calculated as $1.66 \times 10^4 \text{ m}^3 \sim 5.4 \times 10^4 \text{ m}^3$. The Baishuihe landslide provides a crucial case study for evaluating high-position landslide and zoning risk areas in mountainous areas.

1. Introduction

High-position landslides are a common geological disaster in mountainous areas \cite{1,2}. Due to the high elevation of the source area, this type of landslide presents a greater challenge for disaster prevention and mitigation \cite{3,4}. Recently, the alpine regions of southwest China have experienced several high-position landslides. For example, the Ermanshan landslide of 2010 resulted in 20 casualties \cite{5}, the Sanxicun landslide of 2013 killed 166 people \cite{6}, the Xinmo landslide of 2017 caused 83 fatalities \cite{7}, and the Jichang landslide caused 51 casualties \cite{8}. These landslides manifest identical characteristics of high-position landslides and have devastating consequences. Landslides in slopes are often induced by...
rainfall due to pre-existing cracks [9][10]. Rogers and Selby (1980) analyzed several landslides in New Zealand induced by pore pressures within cracks after intense rainfall. Notably, cracks exert a strong influence on rainfall-induced destabilization behavior of slopes [11]. Hu (2005) discussed the effects of cracks and rainfall on slope stability, showing that the stability reduced with deeper and denser cracks, and the surface cracks generally produced shallow landslides [12]. Pre-existing cracks in the soil slope accelerated the slope failure by reducing the shear strength and increasing the hydraulic conductivity of unsaturated soil [13]. Survo et al (2013) performed Electrical Resistivity Tomography surveys, borehole tests, and geometrical surveys to emphasize the vital contribution of deep cracks in soil slopes in increasing their instability induced by rainfall [14]. Zhang et al (2012) systematically investigated the effect of cracks on soil slopes under rainfall conditions and concluded that oblique cracks were more likely to induce global landslides under rainstorms than the vertical cracks when located on the slope top [15]. Consequently, the development of crack deformation determines the behavior of a slope during rainfall. Therefore, it is important to observe the crack deformation response and failure mechanism of the slope.

On 16 August 2012, at 09:20 am, a large landslide occurred in Ningnan County of Sichuan Province, southwestern China (27° 17′ 34.4″ N; 102° 33′ 51.6″ E), about 9.30 km southeast of the county center (Fig. 1). The landslide area is subjected to multiple episodes of landslides in 2012, mainly including two major events on July 28 and August 16. Both events initiated as a soil sliding and then transformed into debris flow that crossed and dammed the Provincial Road S212 and the Heishui River due to the steep-lower slope gradient. The landslide claimed the lives of two persons with three missing persons reports, and resulted in significant economic losses. Therefore, it is highly important to recognize the failure mechanisms and the development tendency of deformation of the debris flow. This paper is devoted to describe and delineate the Baishuihe landslide, a soil slide transformed into a debris flow. This study aims to provide support and methods for the identification and evaluation of such catastrophes by envisaging the regional context, failure mechanisms, and future deformation tendency of landslides.

2. Regional geological settings

The Baishuihe landslide is located in the northwest trending Heishui River valley, sandwiched between Daliang Mountain and Lunan Mountain (Fig. 1) and preponderated by alpine mountains with ridges and deeply incised valleys. Fluvial valley bottoms with steep and gentle slopes dominate the topography of the area immediately around the Baishuihe landslide. The landslide headscarp is retrogressed into Shali Bench (Fig. 2), a residential and cultivated area at an elevation of 1793 m ~ 1899 m with a slope gradient of 5° ~ 25°. The Heishui River elevation before the Baishuihe landslide occurred was approximately 1076 m. At the lateral boundary of the landslide, remarkable grooved landforms and ridges are seen.

The geology in the study area is characterized by complicated tectonic movements. Situated in the northeast of the Hengduan Mountains and the southeastern margin of the Tibetan Plateau, it mainly includes the N-S trending faults that are mostly distributed in the near-axis of the syncline. The Zemuhe fault, a NW regional fault in the southwest of Sichuan Province, is distributed along the Heishuihe in the study area. Affected by the Zemuhe fault, the rock mass in the landslide area is fractured with various degrees.

The bedrock in the study area consists of sandstone, shale of the Hongshiya Formation, lower Ordovician system, with an altitude of 9° ~ 45° < 45° ~ 50°, and the dolomite, shale, sandstone, and limestone of the Erdaoshui formation, upper Cambrian system, with an altitude of 352° < 20°. Moreover, there are local deposits of loose quaternary sediments. Residual deposits ($Q_{4}^{el+d}$), landslide deposits ($Q_{4}^{de}$), and alluvial-pluvial deposits ($Q_{4}^{pl}$) comprised of silt clay, broken gravel, and large boulders, are distributed on the surface of the study area.

The neotectonic movement in the area is intense, consisting of lifting and skew movements. The extrusion and cutting of the neotectonics caused severe damage to the stratum integrity, resulting in
crushed rock, and ultimately, landslide and rockfall. Moderate to strong earthquakes have occurred in Ningnan County around the Baishuihe landslide. Frequent earthquakes severely impacted the slope stability in the county causing the loosening of slope materials, formation of unloading zones, and increase in the sliding force, resulting in fatigue and damage to the slopes. In the aftermath of such events, the slopes mass weakens and they become highly susceptible to failure against heavy downpour and other similar activities.

The climate in the study area is characterized by distinct wet and dry seasons with the mean annual precipitation of 1024.2 mm, out of which approximately 70% of the rainfall occurs during the monsoon from June to September. Frequent agricultural practices in the Shali Bench, including tillage and irrigation (with an irrigated area of $23.3 \times 10^4$ m$^2$) result in loose soil structure in the slope, making it highly prone to sliding.

3. The 2012 Baishuihe landslide
The landslides occurred in 20 episodes in 2012, including two dominating distinct events: (1) the first main slide occurring on 28 June 2012 after intense rainfall, blocking the main road along the Heishui River, and the second failure happening on 16 August 2012, interrupting the road again and damming the Heishui River, resulting in a 4 m water level rise upstream, 3 hours cut-off of the river, 15 days of traffic jams, two fatalities, three missing persons reports, and damage to 38 houses [16]. According to the geological investigation, the length along the sliding direction of the August landslide was 1160 m and the average width was about 250 m, the area was approximately $32 \times 10^4$ m$^2$ with an average gradient of $28^\circ$ and the sliding direction of $52^\circ$ NE. The elevation was 1076 m to 2000/2010 m with a height difference of 924 m ~ 934 m. The drilling holes discovered that the preliminary sliding surface was the interface of the gravel soil and underlying bedrock, with an average depth of surface rupture being 18 m, and the volume was about $201 \times 10^4$ m$^3$. Based on a newly proposed update of the Cruden and Varnes [17] landslide classification system [18], the August Baishuihe landslide would be described as a soil slide-debris flow, which is characterized by slowly moving, retrogressive failure of debris on a steeply inclined slope.

The landslide was divided into three distinctive zones and several subzones, characterized by diverse styles of geomorphology, deformation, and material structure (Figs. 2, 3). Pertinent observations within each zone that contributed to our interpretation of the landslide behavior were present in Figure 2.
3.1. Zone A: deformation zone
We divided zone A into three subzones, A1, A2, and A3 in terms of the degree of crack development. Zone A was located at elevations ranging from 1710 m to 2000 m a.s.l (above sea level), stretched for 520 m along the sliding direction, was 250 m ~ 300 m wide, and had the main scarp at the front with numerous cracks, shear, and tensile failures. The thickness of the deformation zone was between 15.0
and 26.7 m with a mean thickness of 18 m and a volume of $176 \times 10^4$ m$^3$. Evidently, arc-shaped scarps and tensile cracks developed on the surface of the sliding body, illustrating that the cracks showed apparent zoning and time-series feature; thus, playing a vital role in dividing subzones and indicating the boundary.

Subzone A1 mainly consists of the source area of the landslide within the headscarp. The headscarp had a width of 150 m along the direction of 45° NW and a slope gradient of 41°. The lateral margin was also visible in the source area (Fig. 2a, b). After the landslide, several sliding masses were stranded in the source area (Fig. 2d) and eventually formed a platform (Fig. 2f). This subzone was located at an elevation of 1710 to 1855 m with a length of 235 m along the direction of 52° NE, an average width of 235 m, an area of $3.1 \times 10^4$ m$^2$, and a volume of $54 \times 10^4$ m$^3$. A large-scale coherent scarp (L4) showing tensile strength failure in the crown and shear failure in the left flank formed after the August landslide, which comprised of block gravel soil with an arc-like shape, a length of 360 m, a width of 0.1 m ~ 0.45 m, a dislocation height of 0.6 m ~ 4 m (Fig. 4, 5). Some secondary tensile cracks and feather-like fractures connected to the large scarp were developed, demonstrating that the slope was still undergoing creep deformation after the landslide. Moreover, on the left section of A1, a shear scarp (L3) subsided by 0.1 m ~ 3.8 m, with a strike of 25°, a length of 46 m, and a width of 0.02 m ~ 0.1 m. Otherwise, a tensile scarp (L6) located in the middle section of A1 subsided by 0.04 m ~ 0.45 m with a length of 243 m, a width of 0.1 m ~ 0.75 m, a depth of 0.6 m ~ 0.75 m, and an extension direction of 315°. Several cracks, characterized by various scales, conspicuous depth, and width, can be observed below the L4. The main cracks are listed in Table 1.

Borehole drilling was performed to identify the material composition of the landslide, involving the sliding mass, slipping zone, and sliding bed. The sliding mass mainly comprised of debris and soils with the parent rock of sandstone and mudstone (Fig. 6a, b). About 55% ~ 70% of the debris was gravels ranging in size from 2 cm ~ 8 cm, 15% rock blocks ranging in size from 0.2 m ~ 0.3 m, and several large, isolated boulders (up to ~3 m in size) were observed in this subzone. The outcrop at the headscarp and the boreholes ZK7 and ZK13 showed that the slipping zone mainly consisted of clay breccia with breccia content larger than 55%, clay content of 20% ~ 25%, and the silt content of 20% ~ 25% (Fig. 6c, d). The sliding bed was mainly composed of strongly weathered sandstone, argillaceous sandstone, and shale, interbedded with joints and well-developed fissures.

Table 1. Cracks in subzone A1

| Name | Nature | Characteristics |
|------|--------|-----------------|
| L2   | Tensile| Strike of 128°, length of 65 m, subsidence of 0.05-0.25 m; width of 0.05-0.55 m. |
| L5   | Tensile| Strike of 312°, length of 298 m, subsidence of 0.5-0.40 m; width of 0.05-0.25 m. |
| L7   | Tensile| Strike of 333°, length of 145 m, subsidence of 0.05-0.25 m; width of 0.15-0.20 m. |
| L12  | Tensile| Strike of 75°, length of 43 m, subsidence of 0.02-0.45 m; width of 0.02-0.05 m. |
| L13  | Tensile| Strike of 25°, length of 102 m, subsidence of 0.05-0.1 m; width of 0.08-0.17 m. |
| L14  | Tensile| Strike of 85°, length of 15 m, subsidence of 0.01-0.03 m; width of 0.05-0.15 m, depth of 0.35-0.40 m. |
| L15  | Tensile| Strike of 73°, length of 120 m, subsidence of 0.5-0.35 m; width of 0.05-0.40 m. |
| L16  | Tensile| Strike of 350°, length of 30 m, subsidence of 0.42 m; width of 0.14-0.30 m, depth of 0.70 m. |
| L17  | Tensile| Strike of 320°, length of 50 m, subsidence of 1.44 m; width of 0.70 m. |
| L24  | Tensile| Strike of 310°, length of 13 m, width of 0.06-0.15 m, depth of 0.05-0.13 m. |
| L25  | Tensile| Strike of 350°, length of 17 m, subsidence of 0.1-0.4 m, width of 0.03-0.12 m. |
| L26  | Tensile| Strike of 350°, length of 13.5 m, subsidence of 0.1-0.4 m. |
| L27  | Tensile| Strike of 290°, length of 42 m, subsidence of 0.05-0.3 m. |
| L28  | Tensile| Strike of 290°, length of 23.5 m, subsidence of 0.1-0.3 m |
| L30  | Tensile| Strike of 340°, length of 7.5 m, width of 0.06-0.11 m, depth of 0.05-0.10 m. |
| L31  | Tensile| Strike of 340°, length of 15.5 m, width of 0.04-0.13 m. |

Subzone A2 is located at elevations ranging from 1855 to 1900 m (Fig. 2, 3). This subzone is 125 m in length along the direction of 45° NE, 250 m in mean width, $4.8 \times 10^4$ m$^2$ in area, $107.5 \times 10^4$ m$^3$ in volume, with a moderate deformation degree. Some cracks with shorter length and width, and unremarkable displacement than those in subzone A1, developed in this region (Table 2). Additionally,
tensile cracks in the residential buildings contributed to their collapse. We also observed several signs of deformation, such as damaged houses, tilted poles, and ruptured pools (Fig. 2g, 2h, 2c). Therefore, this subzone has the significant potential to fail, if not primary.

**Table 2. Cracks in subzone A2**

| Name | Nature | Characteristics |
|------|--------|-----------------|
| L8   | Tensile| Strike of 320°, length of 150 m, subsidence of 0.2-0.45 m; width of 0.05-0.35 m, depth of 0.30-0.80 m. |
| L9   | Tensile| Strike of 325°, length of 50 m, subsidence of 0.10-0.50 m |
| L10  | Tensile| Strike of 265°, length of 110 m, subsidence of 0.20-1 m; width of 0.05-0.15 m. |
| L18  | Tensile| Strike of 320°, length of 21 m, subsidence of 0.89 m; width of 0.05-0.15 m. |
| L19  | Tensile| Strike of 50°, length of 5.2 m, subsidence of 0.12 m. |
| L20  | Tensile| Strike of 250-290°, length of 20 m, subsidence of 0.46 m. |
| L32  | Tensile| Strike of 320°, length of 75 m, subsidence of 0.30-0.60 m. |
| L11  | Tensile| Strike of 115°, length of 58 m, subsidence of 0.13-0.35 m; width of 0.02-0.15 m. |

Subzone A3 is located at elevations ranging from 1900 to 2000 m with a length of 160 m along the direction of 45° NE, an average width of 190 m, an area of $2.9 \times 10^4$ m$^2$, a volume of $14.7 \times 10^4$ m$^3$, and slight deformation degree. A minor-scale tensile crack was observed with an extension direction of 151°, a length of about 102 m, a width of 0.03 m ~ 0.22 m, and a subsidence of 0.08 m ~ 0.27 m (L1) (Fig. 4).

The site investigation revealed that zone A had a different degree of deformation. Severe deformation and failure occurred between the headscarp and the large-scale scarp (L4), where various scale scarps and tensile cracks with large length and displacement were developed. Moderate to slight deformation took place in the trailing edge of L4. Hence, subzone A1 was the most aggravated by meteorological effects, and intensive soil reclamation further reduced the slope strength, which may have dire consequences. The subzones A2 and A3 have the possibility to fail subsequently in response to the unloading and retrogression from subzone A1 in vexing circumstances.

**Figure 4. Cracks distribution in zone A above the headscarp of the August 16 landslide**

3.2. Zone B: propagation zone

The propagation zone extends between the toe of the rupture surface at an elevation of 1710 m and 1150 m with a longitudinal length of 1070 m, an average thickness of 4 m, an area of $15 \times 10^4$ m$^2$, and a volume of about $60 \times 10^4$ m$^3$ (Fig. 2). During the failure, transportation of displaced material entrained highly weathered bedrocks.

3.3. Zone C: deposition zone

The displaced material mainly deposited at elevations ranging from 1150 to 1060 m, forming a T-shaped debris deposition fan (Fig. 2e, 2i). This zone had a length of over 300 m along the sliding direction and approximately 580 m along the river valley, an average thickness of 10 m, and an estimated volume of $87 \times 10^4$ m$^3$. Due to the narrow shape of the river valley with steep slopes on both flanks with slope gradients of 30° ~ 50° in conjunction with the relatively shallow river, the landslide resulted in the blockage of roads and the Heishui River, up to 600 m and 100 m, respectively. The river water level suddenly rose by 4 m, forming a barrier lake.
4. Factors contributing to the landslide

On some occasions, historic deformation of the slope induced tensile and shear failure but had not caused mobilization of hundreds of meters. Our geographical survey specifies the mechanism for the initiation of the 2012 landslides and identifies certain contributing factors. The primary causes are as follows:

The saltation of topography. The landslide is located on the right flank of the Heishui River with a gentle slope on the upstream side, developed into a settlement. In contrast, the topography immediately turns steep in the landslide area. The gentle-upper and steep-lower topography of the alpine canyon facilitates the landslide formation by providing the favorable free surface condition for the sliding of the upper loose soil.

The fragile geological structure. The slope materials are subjected to tectonic effects, such as the Zemuhe fault, resulting in loose and fractured geological structure, which is sensitive to external factors. Based on the borehole drilling and field outcrop results, the sliding mass is mainly composed of gravelly soil with argillaceous sandstone as the parent rock. The particle size is about 2–8 cm with a maximum size of 3 m. The sliding mass content contains 70%–85% of gravel and 10%–15% of pebble. The material in the slip zone is composed of brown-yellow breccia containing clay with the breccia content of about 55%–60% and the clay content of about 40%–45%.
**Anthropogenic activity.** Recurrent destruction of vegetation and simultaneous irrigation of crops by the residents result in the promotion of the soil weight and reduction in its shear strength, making it highly vulnerable to recurrent failures.

5. **Failure mechanisms of the 2012 Baishuihe landslide**

The 2012 Baishuihe landslide occurred on a slope with a history of prior deformations. The landslide area has experienced creep deformation since 2006 when several cracks and slumps started appearing. We categorized the landslide failure sequence into three distinct stages:

The first stage of movement is the creep deformation in zone A. The topography in zone A is characterized by slopes with gentle top and steep bottom with the rear edge gradient of 27° ~ 35°, middle edge gradient of 18° ~ 25°, and front edge gradient of 40°. Furthermore, stress concentration often occurs at the junction of the steep and gentle parts. When the shear stress in the toe of the slope exceeds its shear strength, shear failure occurs at the toe, followed by upward propagation of the shear zone, eventually resulting in slope deformation. These processes can operate independently but also simultaneously and synergistically. Geologically, zone A was affected by the Zemuhe fault, resulting in the deterioration of the rock mass, conducive to the deformation of slope via external factors. Therefore, tensile cracks and slight surface disruption started developing in this region in 2006, and some local collapses occurred.

We identified stage 2 as the rainfall-induced progressive slope failure. As described by a villager, approximately 20 minor-scale collapses occurred before the June landslide, indicating that zone A was marginally stable, following the observed displacements of L4 in April 2012. Soils of these movements were probably eroded during rainfall, widening the cracks facilitating the infiltration of water. Then the water content of soils increased and the effective friction angle and cohesion reduced. Meanwhile, the failure surface progressed. Creep deformation of the soil mass into the saturated state has contributed to the June event, interacting with the steep geomorphology, and mobilizing the slide debris as a debris flow.

Stage 3 was considered a combined effect of unloading and rainfall. Initial mobilization of the June landslide debris debuttressed zone A. Therefore, the remobilization triggered by intense precipitation occurred subsequently. The slope gravity, water content, and pore water pressure increased substantially under torrential rainfall, dramatically destabilizing the slope. Stage 3 involved retrogression into Shali Bench from the June landslide headscarp in a slow series of extensional failures. The initiation of the August event started at 9:20 am, blocking the road and river at 10:40 am, which persisted for more than an hour. The August event attributed to a high-position, slowly moving multi-stage debris flow. Special terrain conditions play a significant role during the mass movement process. Several bedrocks and deposits of the June event were impacted and scoured by the sliding mass, resulting in the transition into a debris flow. Deposits on the opposite bank of the river are lower in elevation, and the slope remains intact with low impact damage.

6. **Prediction of the development tendency of the deformation**

Based on the field investigation, the statistical analysis of the deformation characteristics of the slope was performed. The results are shown in Fig. 7. Owing to the August landslide, a circular chair-like terrain with a width of 220 m formed, and the L4 subsided by about 0.8 m simultaneously. The crack L4 subsided by 4 m. After large-scale cracks formed in subzone A1 in mid-October, tensile cracks started to appear in the subzones A2 and A3. Externally, these cracks were smaller than the cracks in the subzone A1. Notably, the slope was undergoing creep deformation, and the partial failure could not be ruled out during intense rainfall. Meanwhile, the average annual rainfall in the study area was 1024.2 mm. In the recent years, extreme weather conditions in Ningnan County have been frequently observed, such as the rainfall reaching 1300 mm in 2012. Therefore, there is a strong possibility of continuous heavy rainfall near the landslide area in the coming years.

Since the distribution and characteristics of cracks were investigated in conjunction with the failure mechanisms and landslide characteristics, the temporal and spatial failure evolution of the Baishuihe
landslides were analyzed according to the nature of cracks. The results are shown in Fig. 8. The volume of the potential failure slope body was $1.66 \times 10^4 \text{ m}^3 \sim 54 \times 10^4 \text{ m}^3$. Areas A, B, and C, with a total volume of $14.6 \times 10^4 \text{ m}^3$, were most likely to experience failure. After the disintegration of the front portion, it might cause the consecutive failure of area D, with a volume of $7.16 \times 10^4 \text{ m}^3$. Due to the failure of areas A, B, and C, the region within the crack L6 could be affected under traction. The sliding of area D might result in the instability of area E, subsequently, causing cracks L8 to L32 to further deform and penetrate in depth, thereby forming a new arc-shaped tensile failure. Thus, the influence zone of zone A instability is the circle arc formed by cracks L8 to L32. Additionally, the deposits of the August landslide were stranded within the slope surface without deforming significantly. However, due to the steep slope gradient and loose deposits, the blocks, and gravels might fall along the surface under the external agents, threatening the pedestrian safety of the road. Moreover, the deposits might convert into the slope debris flow, causing serious consequences. In summary, the deformation of the Baishuihe landslide was characterized by a remarkable variety of temporal and spatial distribution. The displacement rate varied with the rainfall. The landslide is in a temporary stability phase in its natural state. With the advent of the rainy season, the signs of deformation on the landslide could be further aggravated. Zone A will be unstable first with multiple large-scale sliding of the land during the rainy season. Therefore, it is advisable that the landslide monitoring be enhanced and some countermeasures be taken to stabilize the potential slide mass. Arguably, in the following years, intermittent minor and middle-scale events were reported, with larger ones in September 2015 and May 2016 after torrential rainfall. Thus, a remedial measure should be established before the catastrophic events, preventing the blocking of the roads and the river.

For the quantitative analysis of the deformation tendency of the residual slope, an integrated monitoring system was designed and installed, consisting of surface displacement monitoring stations and inclinometers in boreholes. Based on the monitoring data, no deteriorative deformation was observed, and the ground surface displacement and the cumulative deformation of the surface crack monitoring were non-significant. Until April 30, 2013, the cumulative displacement of the ground surface was the largest (12.4 mm) in the area A1, and the cumulative subsidence was 4.1 mm. Inclinometers were installed in several boreholes (ZK02, ZK05, and ZK12) (Fig. 3). The results showed that the monitoring point 3 (borehole ZK12) on the 1–1’ section had a large deformation at a depth of 29 m, the single displacement was large, about 5 mm, and the cumulative horizontal displacement was 16.5 mm (Fig. 9), which indicated that the sliding surface had been formed spontaneously. Monitoring point 2 (borehole ZK5) had a single horizontal displacement near 20 m depth, and the cumulative horizontal displacement was 5–13 mm. The potential slip surface as the basis for the judgment of the slip surface depth is close to that exposed by drilling. Therefore, the
monitoring data provided a reference for quantitative evaluation of the deformation tendency of the landslide.

**Figure 9.** Depth–displacement curve of monitoring points 1, 2, 3 in the boreholes ZK02, ZK05, ZK12, respectively.

7. Conclusions

In this paper, the 2012 Baishuihe landslide is taken as the case study, and a field investigation, photographic interpretation, and geological mapping were performed to analyze the failure mechanism and deformation tendency of the landslide.

We identified three distinctive zones and several subzones of the landslide area, characterized by diverse geomorphic expressions owing to different styles of geological materials and deformation degree. The results suggest that the landslides comprised of multiple-stage failures, with the first stage including a creep deformation in the zone A, the second including a rainfall-induced progressive slope failure, and the third including retrogression of the slide into the crack L4. The probability of rapid-moving and integral destabilization of the slide is very small. However, excess displacement may occur under torrential rainfall. There multiple large-scale sliding masses of the landslide could be formed during the rainy season. Therefore, enhanced deformation monitoring should be performed; some remedial countermeasures should be conducted to prevent any tragic event. The practical situation indicates that the prediction on the tendency of the deformation is appropriate.

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