

Landslides (2020) 17:1935–1949
 DOI 10.1007/s10346-020-01394-7
 Received: 21 January 2020
 Accepted: 11 March 2020
 Published online: 8 April 2020
 © Springer-Verlag GmbH Germany
 part of Springer Nature 2020

Yueping Yin · Bolin Huang · Quan Zhang · Guoqiang Yan · Zhenwei Dai

Research on recently occurred reservoir-induced Kamenziwan rockslide in Three Gorges Reservoir, China

Abstract A landslide occurred in Kamenziwan, Zigui, the Three Gorges Reservoir area, located about 43 km from the dam on December 10, 2019. Due to a successful early warning system, no casualties were reported following the Kamenziwan landslide. However, roads, citrus groves, water supply lines, and 280-V power lines were damaged, resulting in a direct economic loss of 5.8 million RMB. This landslide is a newborn, wedge-shaped (apparent dip) red-layer rockslide, controlled by double-slip surface and covers an area of about $2.1 \times 10^4 \text{ m}^2$ and a volume of about $42 \times 10^4 \text{ m}^3$. The sliding mechanism includes leading-edge traction in the early stage and middle-rear gravity displacement in the late stage. The landslide movement was rapid, with a maximum sliding velocity of about 0.15 m/s, a movement time of more than 15 min, and a movement distance of about 18 m. Based on our investigation, the Kamenziwan landslide is not triggered by the reservoir water level and rainfall; indeed, this landslide has no obvious triggering factors. The results from our study suggest the long-term water level fluctuation in the Three Gorges Reservoir area has eroded the key anti-slip section in the middle-lower part of the Kamenziwan landslide, greatly accelerating its evolution process. The landslide that occurs “naturally”, due to the degradation of rock mass in the water level fluctuation zone, may be an important path for the development of new landslides in the later stage of water impoundment. The Kamenziwan landslide is of great reference value for understanding the development of a new type of reservoir-induced landslide in the Three Gorges Reservoir area. Comprehensive studies on this landslide help to identify potential geohazards, similar to Kamenziwan landslide, in the early stage of their development.

Keywords Three Gorges Reservoir · Kamenziwan landslide · Wedge-shaped red-layer landslide · Failure mechanism · Degradation of rock mass

Introduction

On December 10, 2019, at 16:50, a large displacement rock landslide (Kamenziwan landslide) occurred 2.1 km away from the town of Xietan, on the left bank of Xietan river, a secondary tributary of Yangtze River in Zigui County, Three Gorges Reservoir, China (Fig. 1). The Xietan Town and Shuping landslides are across the Yangtze river, and Kamenziwan landslide is located in a distance of about 3 km away from the Shuping landslide (Wang et al. 2008) and about 43 km from the Three Gorges Dam (Fig. 1). The recently occurred landslide is also about 6 km from the Qianjiangping landslide (Wang et al. 2004) and about 7 km away from the Shanshucao landslide, which are both located in the floodplain of the Qinggan river, another tributary of the Yangtze river.

Following the landslide, no casualties were reported, because of reliable procedures for early warning of landslide and performance of related controls in advance. However, the Kamenziwan landslide damaged a 135-m highway, affecting public

transportation of 12,300 people from 13 villages in the area. Moreover, 90 acres of citrus groves, water supply lines in town, and 280-V power lines were damaged, resulting in direct economic loss of 5.8 million. The failure of Kamenziwan landslide can be related to the degradation of rock mass in water level fluctuation zone, caused by periodic fluctuation of water level. Therefore, the breeding path of a new type of reservoir-induced landslide could have been developed in the Three Gorges Reservoir, causing occurrence of this type of landslide on a more frequent basis in the future. This explains the importance of conducting comprehensive research on this specific landslide.

Therefore, this study aims to (1) characterise the Kamenziwan landslide and describe its evolution, (2) analyse possible triggering factors (such as water level change, rainfall, and rock mass degradation) and failure mechanism, and (3) investigate the enlightenment of Kamenziwan landslide for identification of newborn landslide in the Three Gorges Reservoir area.

Geological settings and slope characteristics

The Kamenziwan landslide is located in the south-west limb of Zigui syncline, within Exi fold tectonic zone, which is an area with middle-high mountains and steep valleys. The elevation of the highest mountain in this region is about 1180 m above sea level (asl.), accompanied with the relative height difference of 300–1000 m. In the study area, the prevalent strata are the Middle Jurassic clastic sedimentary rocks (known as a red layer) (Xu et al. 2015), and the slope is generally between 20 and 40°. There are no major faults in this area, and the sedimentary strata are stable.

The outcrop strata mainly consist of the Middle Jurassic Shaximiao formations, which include interbed yellow-green medium-thick feldspar siltstone and fuchsia medium-thin silty mudstone, with a bedding attitude of $30\text{--}45^\circ \angle 30\text{--}45^\circ$. Kamenziwan slope is an oblique bedding, with a slope direction of 340°. In the Kamenziwan slope, there is a high correlation between micro-geomorphology and lithology. The sandstone outcrop area forms the ridge, while the mudstone outcrop area is relatively gentle (Fig. 2). A small distribution of residual sediment (Q^{el}) is observed on the slope, including mainly clay with gravel. The distribution area of Q^{el} is mostly mudstone outcrop area, formed a very gentle slope. As a whole, the middle-lower part of slopes is steep, with an average slope of about 40°, while the upper part of the slope is relatively gentle, with an average slope of about 30°. Except for the exposed sandstone cliffs and road scarp, the vegetation on the slope is well developed, and the slope is mainly covered by trees and citrus groves.

Regarding the attitude of the sliding rock mass in the Kamenziwan landslide, rock mass of the same layers as the slide mass is found at the outcrop of the excavated cliff of Wan-Weng road, at the trailing edge (Fig. 3). The rock mass is sandstone-silty mudstone with unequal thickness and non-interbedded

Recent Landslides



Fig. 1 The location map of Kamenziwan landslide. The left upper map shows the relative location between the Kamenziwan landslide and the Three Gorges Dam

deposition. On the outcrop, a continuous development of yellow medium-thick feldspar sandstone is observed, with well-developed

joints. According to the field investigation of the bedrock outcrop, there are three groups of structural planes developed in the rock

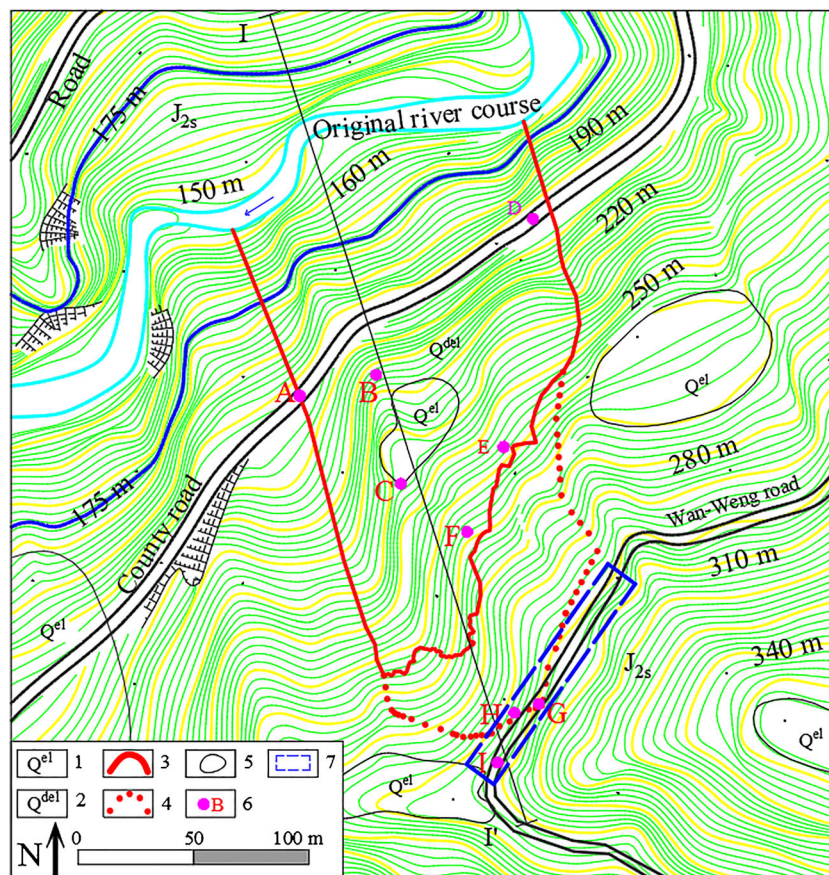


Fig. 2 The geological plan of Kamenziwan landslide. The landslide terrain is pre-destruction terrain. 1, residual deposit; 2, landslide; 3, the boundary of landslide; 4, the boundary of retrogressive zone; 5, geological boundary; 6 A–F are simple monitoring points for cracks before landslide; G–I are simple monitoring points for cracks after landslide; 7, landslide bedrock outcrop observation zone

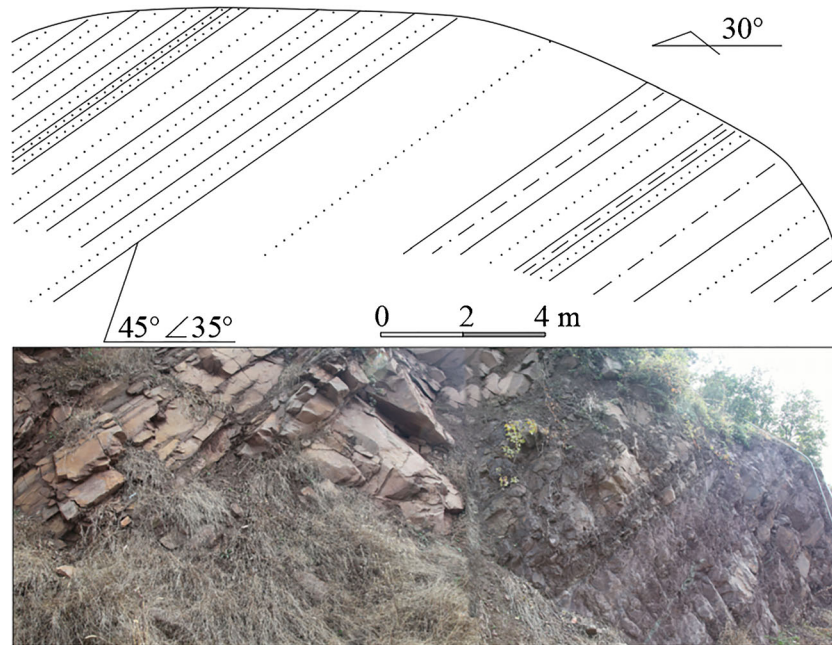


Fig. 3 The outcrop and sketch of sandstone-mudstone of unequal thickness in the same strata as the slide mass. See Fig. 2 for a specific location

mass. The structural planes in group A with an attitude of $270\text{--}290^\circ \angle 50\text{--}70^\circ$ are the major large structural planes. Occasionally, scratches with calcium crystal deposition are presented on this set of structural surfaces, suggesting possible movement occurrence in the slope history. The attitudes of the other two groups of small structural surfaces (group B and group C) were $230\text{--}250^\circ \angle 45\text{--}55^\circ$ and $325\text{--}340^\circ \angle 60\text{--}70^\circ$. Combination of these three groups of structural planes and beddings forms triangular prisms and rectangular columns. On the south of the outcrop, silty mudstone with

unequal thickness is observed; the middle layer of silty mudstone is indistinguishable, which can be crushed by hand and intensively weathered. Additionally, the structural planes of A and B groups are also developed in silty mudstone.

There are two roads in the slope area, including a highway and a dual carriageway road, called the Wan-Weng road. The highway was built around 20 years ago as the main road of the Xietan Town, with an elevation between 200 and 210 m asl. The Wan-Weng road, located on the top of the mountain, was excavated in



Fig. 4 The crack change in point E on November 28 (a) and December 7 (b). The crack was partially lowered by 5 cm on December 7

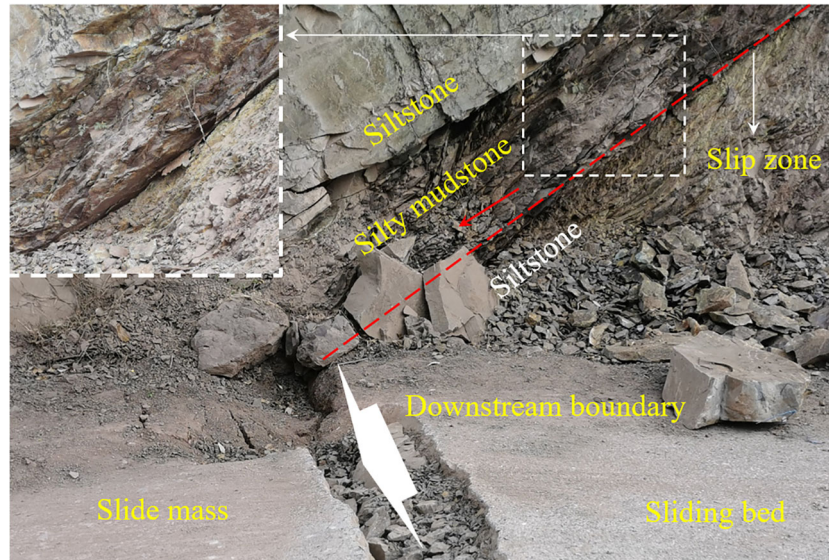


Fig. 5 Photos of the slip phenomenon and boundary cracks caused on November 29, clearly showing the lithology and rock mass structure of some slide mass, slip zone, and sliding bed

February–March 2019. No other major engineering activities took place on the slope long before the landslide occurred.

Landslide process

On November 20, 2019, some cracks on the highway were reported by villagers, which is to the location of the Kamenziwan landslide. During the investigation at that time, cracks were found in many places on the slope (see Fig. 2A–D), which were caused by slope sliding. According to the Three Gorges geological disaster monitoring and early warning network system requirements, simple monitoring points and corresponding inspection-monitoring system were established on the Kamenziwan landslide, in an early stage.

On November 28, inspectors found new cracks in another area (i.e. at point E in Fig. 4 a), and on November 29, the slope began to show significant deformation. The slide mass slipped slowly along the silty mudstone (weak plane) for about 20 cm after measured siltstone (Fig. 5), and the sliding direction was nearly consistent

with the slope direction (about 340°). After this slip, the leading edge was partially lowered by 5–30 cm, with a crack depth of 1.2 m. A tensile crack appeared at the downstream of the slope, with a strike of 315° and a width of 10–25 cm, and the downstream boundary of the landslide began to form. A near arc tensile crack appeared at the trailing edge of the landslide, with a trend of $150\text{--}225\text{--}275^\circ$ and a width of 5–25 cm, hence, forming the boundary at the trailing edge of the landslide.

The slope deformation has been intensified, since December 5. From 15:00 p.m. on the 5th to 9:00 a.m. on the 6th, the width of the tensile crack at the downstream of the landslide re-increased by 8 mm, increasing the width of the crack at the trailing edge of the landslide by 11 mm; furthermore, new cracks appeared on the highway. On December 7, obvious falling appeared at the crack of point E (Fig. 4b). Consequently, the surrounding roads were closed by the relevant authority, and the geological disaster warning was disseminated. On December 8, new cracks appeared in a new area (i.e. point F in Fig. 2).



Fig. 6 Photos of transverse cracks in the middle of the slide mass, taken on December 9



Fig. 7 The water in the river has a lot of foams before sliding on December 10

On December 9, accelerated deformation of the landslide was observed, where the falling deformation of the trailing edge cracks reached 20 cm, followed by the formation of many transverse cracks in the middle of the slide mass (Fig. 6). The leading edge of the landslide along the river showed swelling, and the crack of downstream boundary increased by about 12 cm. A connection existed between the cracks in the downstream side and the trailing edge of the landslide.

In the morning of December 10, the upstream boundary of the landslide formed and connected with the crack in the trailing edge. At this stage, the landslide boundary was fully connected. The sandstone cliff re-slipped briefly at a speed of about 0.8 cm/h. At the downstream boundary, the rock mass above the highway kept falling, generating the rock mass friction and fracture sound. The water in the river had a lot of foams, due to the inflow of rocks and the possible inflow of groundwater from the slide mass (Fig. 7). At 16:18, the Kamenziwan landslide began to show overall sliding.

A close monitoring of the process was backed by multiple witnesses and monitors to provide multi-angle and multi-period video shooting of the sliding process. Figure 8 shows the slip moment at the most violent moment of the landslide. In the moving process, the sidewall of the landslide continued to collapse, accompanied by loud rock fractures, collisions, and friction sounds. The surface of the slide mass was constantly pulled apart, drifting dust from the pulled cracks. The leading-edge slide mass pushed the water slowly, and the local rock mass disintegrated into the water, producing waves and shock waves, which turned into the turbid, at a later stage.

Based on Fig. 8, considering the road and sandstone cliff as the reference, the velocity and acceleration of the landslide in the overall sliding can be roughly obtained, using the relation of displacement, velocity, and time in Newton's law (Huang et al. 2012). At about 20 s, the sliding velocity reached its maximum, i.e. about 0.15 m/s (Figs. 9 and 10). During the 58 s, the average velocity of the landslide reached about 0.1 m/s. At about 60 s, the acceleration of landslide reached the maximum, i.e. about 0.1 m/s². From 16:18, the landslide began to move, and the landslide did not slow down until 16:31. Therefore, it can be estimated

that the whole movement time of the landslide was more than 15 min, with the average sliding speed of about 0.02 m/s. According to the Varnes classification, the landslide speed is classified as very rapid (Hungr et al. 2014). Since the movement speed did not exceed 1 m/s, the amount of water, flowing into the landslide, was limited, with no solid impulse wave, consistent with the conclusions of previous studies (Heller et al. 2009).

On the day of the landslide, the water level in the Three Gorges Reservoir was 174.6 m asl. Since October 31, 2019, the water level in the Three Gorges Reservoir has been slowly falling from 175 m asl. and fluctuating between 173.8 and 174.8 m asl. (Fig. 11). During this period, the maximum rate of water level rise was 0.17 m/day (occurred on November 29), while the maximum water level declining rate was 0.39 m/day (occurred on November 4). The average declining rate during the last 5 days before the landslide was 0.04 m/day. Based on the current literature, the rate of fluctuation of water level should not be enough to induce landslide (Tang et al. 2019; Yin et al. 2016). From November 30 to the day of landslide occurrence, the weather was sunny for 10 consecutive days, and no rain was reported in the area (Fig. 11). Moreover, the cumulative rainfall in the last 40 days before the landslide occurrence was only 24.4 mm, suggesting the low possibility of rain-induced landslides (Brooks et al. 1993; He et al. 2010; Xia et al. 2013; Yang et al. 2017). Consequently, it is very unlikely that the Kamenziwan landslide was triggered by the water level fluctuation and rainfall. In other words, no immediate and obvious triggering factors can be considered for this reservoir landslide.

Landslide features

Since the Kamenziwan landslide occurred, a full range of ground surveys and unmanned aerial vehicle (UAV) topographical surveys have been conducted (Fig. 12). A series of structural planes of group A constitute the main rear wall of the landslide and the upstream boundary of the landslide (Fig. 12b). The downstream boundary of the landslide is the sliding bed consisting of sandstone, most of which is exposed after sliding (Fig. 12c). The maximum elevation of the trailing edge of the landslide is 280 m. The

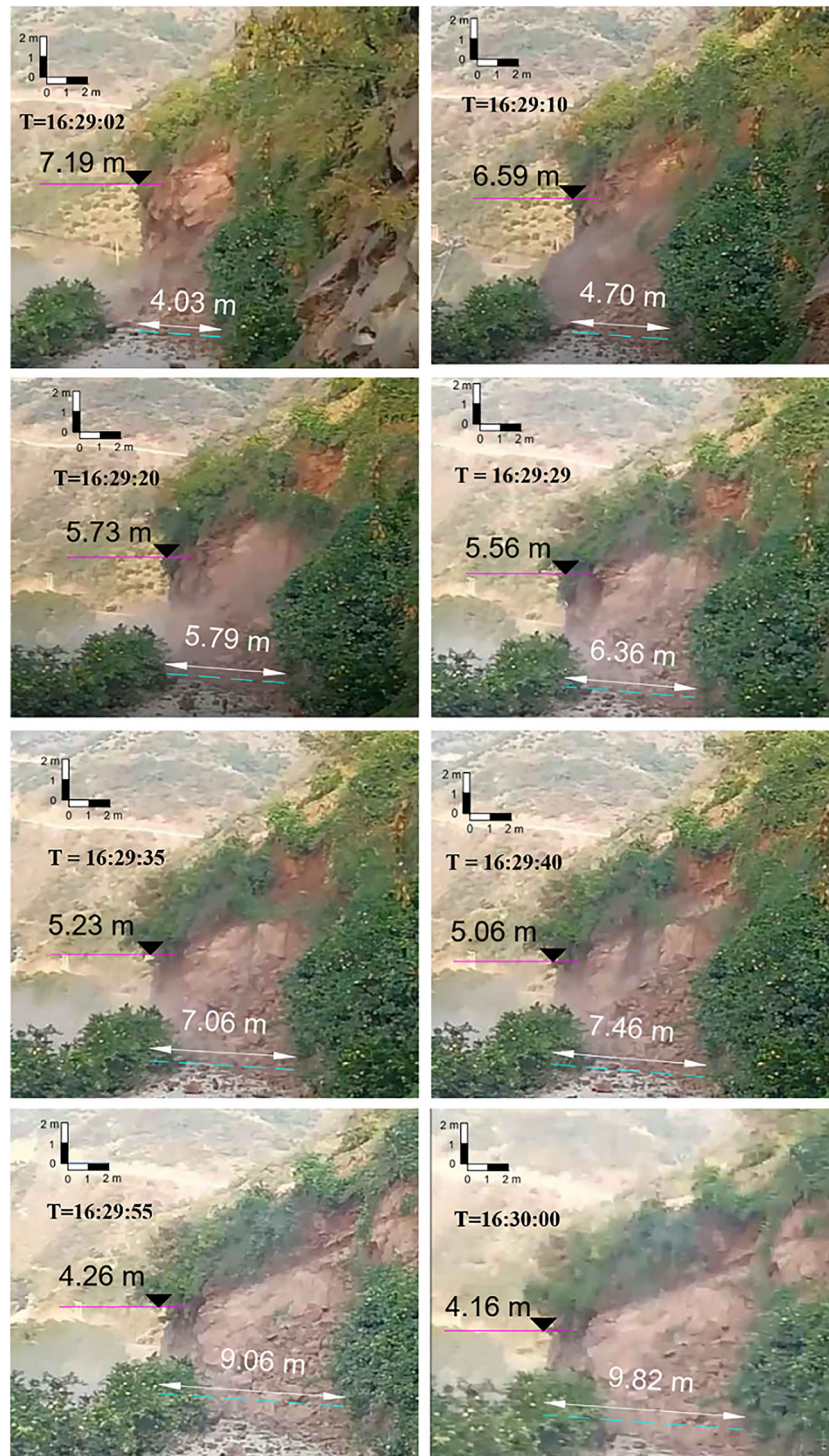


Fig. 8 Instantaneous photos of lateral motion of the Kamenziwan landslide. The video was filmed at 16:29 (photo taken by local patroller Chen YJ on date)

trailing edge is serrated, the boundary on both sides is flat, and the plane shape is approximately tongue shape. The width of the middle-lower part of the landslide is about 135 m, and the minimum width of the crown of the trailing edge is 40 m. Comparing the location of highway, the linear movement distance of the landslide is calculated, which is about 18 m, with horizontal movement distance of 15 m and vertical movement distance of 10 m.

In terms of the landslide images (Fig. 12), in the local area of the trailing edge, the local area of the leading edge, and the shear boundary of both sides, there are loose and overhead stone accumulation, with the internal cracks of the slide mass. However, the overall form of the slide mass remains unchanged, maintaining the roads, trees, and orange trees on the slide mass in their original conditions. This indicates that there is no collision, covering, and

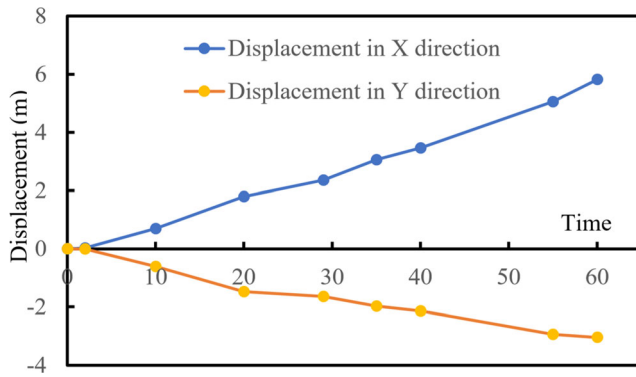


Fig. 9 Displacement time curve of the steep cliff on the highway. According to Fig. 8, the displacement of the steep cliff on the highway in the X and Y directions of the landslide is analysed. X and Y direction refers to the horizontal direction and vertical direction of the sliding direction. The negative displacement means the direction of motion is down

pushing of the internal blocks, caused by the movement difference inside the landslide (Wang et al. 2004), and no mixed accumulation of the slide mass is formed. Therefore, the slide mass has similar dynamic characteristic in the motion process, and the motion difference of each region is small, which is related to the uniformed slip zone and sliding bed.

The analysis of the UAV image is verified by tracking the downstream boundary of landslide. The sliding bed on the top of the slide mass is the same layer as the sliding bed on the highway cliff (Fig. 5). The sliding bed consists of a very flat yellow-green sandstone surface, with an attitude of $44^\circ \angle 36^\circ$. Striated scratches, slip zone, and polished surfaces are observed on local sandstone surfaces (Fig. 13). The slip zone contains purplish-red clay with crushed stones, which evolved from silty mudstone and can be easily found on the downstream sideslip bed, located between two yellow sandstone layers (Fig. 14). The total thickness of the silty mudstone is about 0.3–0.5 m, including the slip zone with a thickness of about 0.1 m and fractured silty mudstone, located above the slip zone. Due to intense extrusion, the slip zone has a sheet structure, with obvious scratches and polished surface. The striping trend of sliding bed and slip zone is $340\text{--}350^\circ$, indicating that the sliding direction is about 340° .

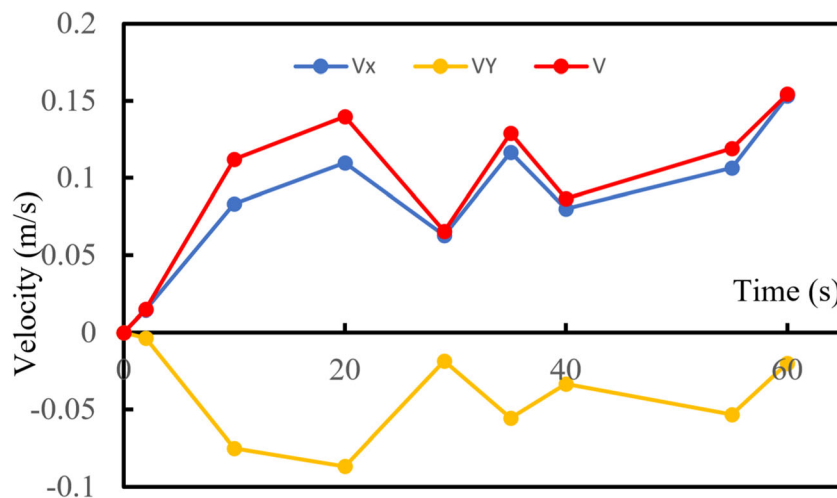


Fig. 10 The velocity process of landslide. According to Fig. 8, the slip displacement and time are analysed, and the instantaneous slip velocity can be obtained by calculating Newton's law of motion. V refers to the sliding velocity, and Vx and Vy refer to the horizontal and the vertical velocity of V, respectively. The negative velocity of Vy means the direction of motion is down

Obviously, this sliding direction (340°) is approximately 55° from the rock strata tendency ($30\text{--}45^\circ$), with an angle of approximately 70° from the structural plane of group A ($270\text{--}290^\circ$). Based on the stereographic projection analysis (Fig. 15), the sliding direction falls within the intersection line between the rock layer and the structure plane of group A (Stead et al. 2006). The Kamenziwan landslide is controlled by two sets of sliding surfaces of rock strata and the structural surface of group A; hence, the real sliding direction is the intersection line of these two sets of sliding surfaces (Fig. 15). Therefore, the Kamenziwan landslide is indeed a wedge sliding, controlled by two sets of sliding surfaces (Stead et al. 2006).

Although the slide mass slides in a wedge-shaped flume, formed in the structural surface and bedding of group A, it still slides along the bedding (Fig. 16) from the longitudinal profile, similar to the apparent dip slide. Based on the sliding bed and outcrop of underlying bedrock strata, it can be concluded that the shear outlet of the Kamenziwan landslide is located near the elevation of 174 m (Fig. 17). According to the profile estimation, the thickest part of the slide mass is about 30 m, and the average thickness is about 20 m. Therefore, the sliding area on December 10 can be calculated as $2.1 \times 10^4 \text{ m}^2$, with the landslide volume of about $42 \times 10^4 \text{ m}^3$.

After the overall sliding, the retrogressive zone is formed, where a large number of cracks are developed (Fig. 11). The highest crack is located on the Wan-Weng road, extending in a series of en echelon (Fig. 18). After the landslide, the retrogressive zone has experienced deformation. Until 1 p.m. on December 20, the crack has a maximum width of about 15 cm and a subsidence of about 18 cm. The retrogressive zone is determined by the boundary of the crack development zone (detailed region seen in Figs. 2 and 12). The area of the retrogressive zone is $0.6 \times 10^4 \text{ m}^2$, and the corresponding volume is about $12 \times 10^4 \text{ m}^3$, when calculated at an average thickness of 20 m.

After landslide, the relative displacement of G, H, and I crack points (Fig. 2) at the trailing edge is monitored (Fig. 19). According to the daily relative displacement, G and H cracks (Fig. 18) have been expanded and deformed rapidly every day, with the average deformation between 9.5 and 12.5 mm. The deformation of crack I is small, with an average deformation of 1.5 mm. The maximum

Recent Landslides

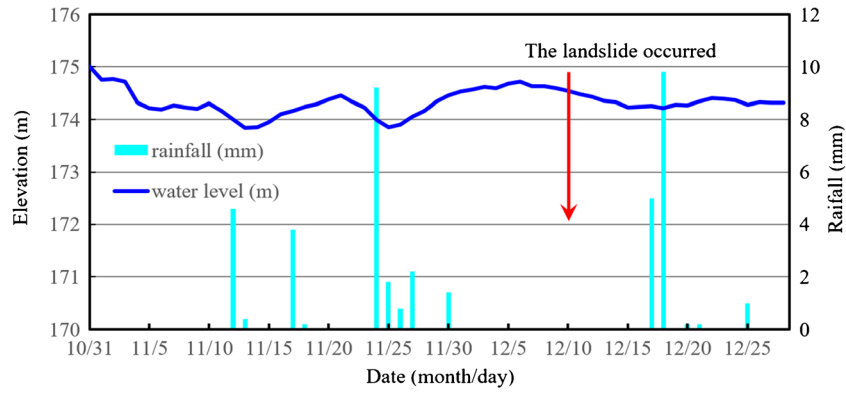


Fig. 11 Changes in water levels and rainfall, since October 31. Since November, the water level has been fluctuating slightly between 173.8 and 174.8 m, with the occurrence of mostly sunny days and limited rainfall, during this period

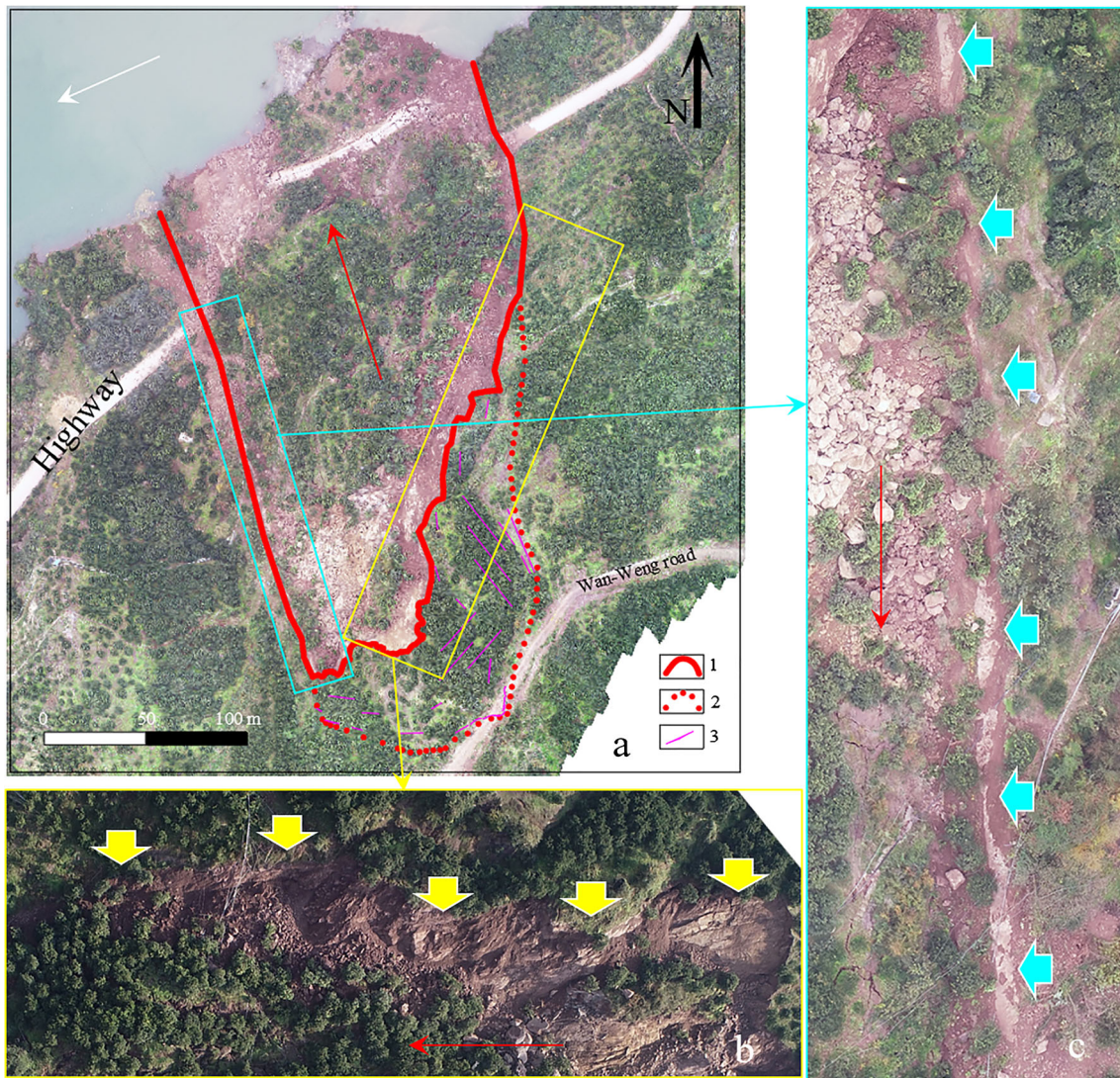


Fig. 12 The UAV images of the Kamenziwan landslide. Red solid line represents the landslide borderline, red dashed line demonstrates the border of retrogressive region, and the magenta lines represent cracks. **a** Shows the crack layout of the whole region and retrogressive region after the landslide. **b** Shows the landslide trailing edge and upstream boundary, and yellow arrows indicate the exposed area of group A structure surface. **c** Shows the sliding bed on the downstream side, and the cyan arrows indicate the exposed area of the same siltstone bedding



Fig. 13 The remaining fuchsia slip zone on the sliding bed-yellow sandstone surface, with a large area of polished surface and striated scratches on the slip zone (photo taken by Bolin Huang after failed)

relative deformation rate of these three cracks has reached up to 17 mm/day, on December 12 (Fig. 20). However, due to the short monitoring time and only relative displacement monitoring, the stability trend of the retrogressive zone cannot be determined.

Failure mechanism

After the deformation on November 20, the relative displacement monitoring of the A–F crack points (Fig. 2) was conducted. Figure 21 shows the relative displacement time curves of crack measuring points. Point A is located in the highway at the leading edge of the landslide, while points E and F are located in the trailing edge of the landslide. In terms of relative displacement, the relative deformation of point E exceeds the relative deformation of point A, in a later stage. On December 10, rapid deformation was observed at point A. Based on the relative deformation rate of cracks (Fig. 22), point A has the highest deformation rate at first. After point E started to deform, its deformation rate exceeds the deformation of point A. In the afternoon of the landslide occurrence, the deformation rate at point A accelerated clearly.



Fig. 14 Photos of slide mass, slip zone, and sliding bed in the trailing edge. Right-upper map is the photo of slip zone, with a large area of polished surface and striated scratches (photo taken by Bolin Huang after failed)

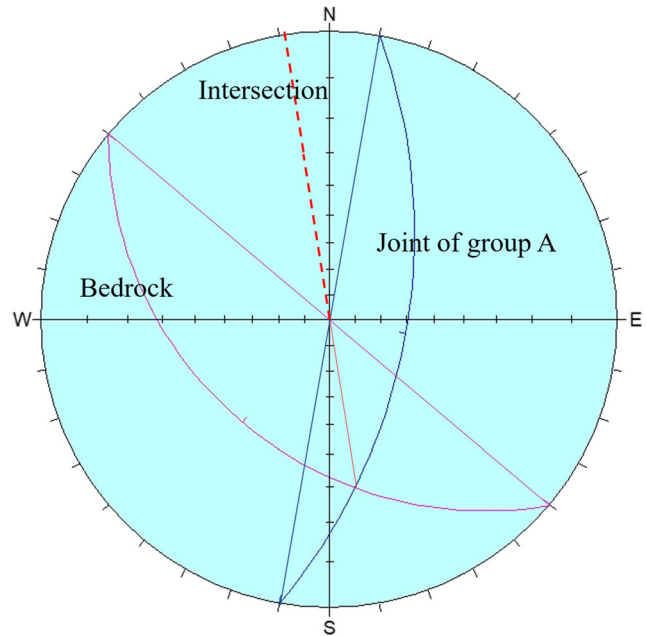


Fig. 15 Stereographic projection analysis of the double sliding surfaces of Kamenziwan landslide. The red line demonstrates the intersection of two sets of sliding surfaces, and the dotted line represents the actual sliding direction

As it is very dangerous, only point A was monitored on December 10, the day the landslide failed.

From the above analysis, the relative displacement monitoring can also reflect the deformation process of the landslide. In consideration of the spatio-temporal location of the crack, the landslide deformation occurred first at the leading edge, followed by its occurrence at the middle and trailing edges. In terms of the deformation extent, the deformation of the trailing edge exceeds that of the leading edge. Therefore, the sliding of Kamenziwan landslide is caused by the traction of the leading edge and the thrust of the middle-rear part. Indeed, the leading-edge traction is crucial to the landslide initiation. It took 8 days from November 20 until the cracks appeared on the highway at point E of the trailing edge, which was the crucial period for the traction-type process. After the formation of cracks at the trailing edge, the gravity shift in the middle-rear parts began to play a major role.

It is significant to explore the damage mechanism of the leading edge in Kamenziwan landslide. Figure 23 shows the leading-edge photo of the landslide in July 2019, suggesting that siltstone and mudstone (slip zone) are exposed below 175 m asl. In terms of micro-geomorphology, a small “sea cliff” is formed above 175 m. Below the elevation of 175 m, the strata above the sandstone in sliding bed are eroded, completely. The erosion of rock mass causes the landslide to lose a key anti-slide section, exposing the slip zone to form shear outlet. The elevation of 145 to 175 m corresponds to the water level fluctuation zone of the Three Gorges Reservoir, where periodic changes in the surface water level cause periodic changes in the groundwater level. Generally speaking, the groundwater fluctuation zone, caused by reservoir water fluctuation, is mainly concentrated in the middle-lower part of the slide mass (Tang et al. 2019; Yin et al. 2016; Xia et al. 2013; He et al. 2010).

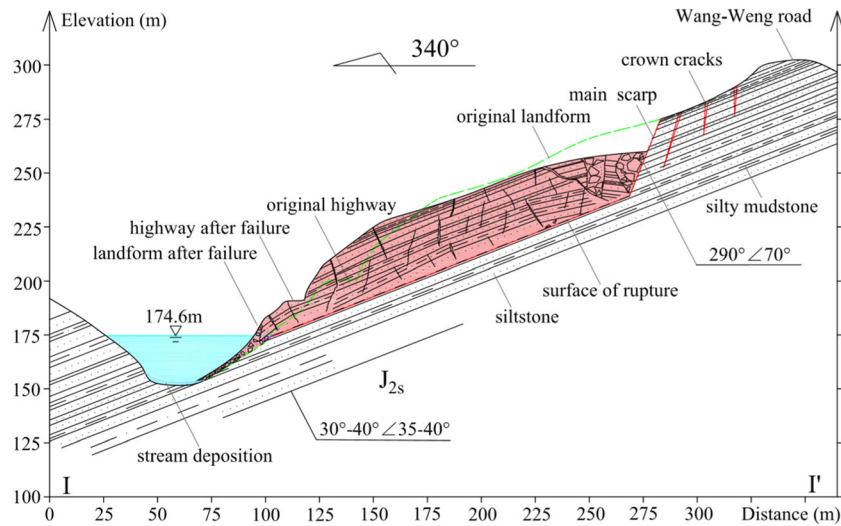


Fig. 16 Engineering geological profile of Kamenziwan landslide. The water level on the day of the landslide is 174.6 m

The periodic fluctuation of water level leads to the degradation of rock mass, including the degradation of quality and physical and mechanical properties of the rock mass (Huang et al. 2019). According to the studies of Deng et al. (2016) and Liu et al. (2018), strong degradation of siltstone and mudstone is reported, which is associated with the water level fluctuation and wetting-drying cycles. Indeed, the porosity of the rock enhances and the mineral alternation occurs, resulting in the formation of clay minerals. Moreover, the mechanical strength of the rock decreases, resulting in the average compressive decline rate of 3% for each wetting-drying cycle. It should be considered that rock mass degradation is a cumulative damage process. Since the 175-m asl. impoundment in 2008, there have been more than 11 cycles of water level changes. Therefore, the degradation of rock mass in the fluctuation zone of surface and groundwater (middle-lower part of landslide) is the key factor for the failure of the leading part of Kamenziwan

landslide, which is considered one of the important forming factors of the landslide (Huang et al. 2019).

The slip zone is considered an important key factor for landslide. The slip zone in Kamenziwan landslide consists of fuchsia clay. Based on the scanning electron microscopy (SEM) images (Fig. 24) and X-ray diffraction (XRD) analyses, the slip zone mainly consists of quartz and montmorillonite. Montmorillonite has strong swelling and water absorption capability, which resulted in the characteristics of easy sludge and softening. The presence of these types of minerals in the slip zone makes it more susceptible to landslide.

Field investigation shows that multiple movements have occurred along the slip zone. After a careful cleaning of the downstream part of the slip zone, two different sets of scratches were observed on the sliding bed (Fig. 25). Group S1 corresponds to the direction of the landslide movement, with a strike of about 340°, and the strike of group S2 is about the true tendency of rock strata,



Fig. 17 The full-face photo of the Kamenziwan landslide. The white arrows indicate the position of the slide bed, suggesting that the landslide shear outlet is near 174 m



Fig. 18 Retrogressive zone photo. The crack on the left side extends very long, about 15 m, and the crack on the right side is only visible on the road surface. G and H are the measuring points of crack relative displacement

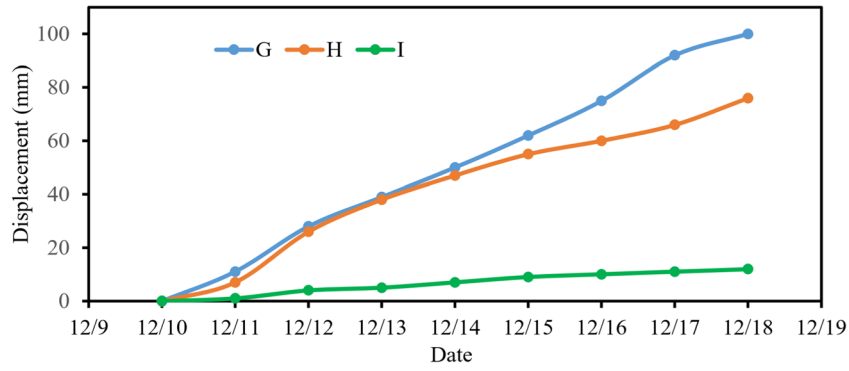


Fig. 19 Relative displacement time curve of the cracks on retrogressive zone

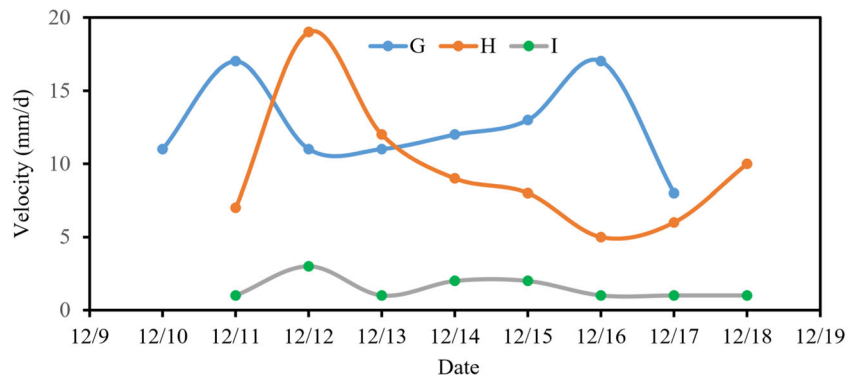


Fig. 20 Relative deformation rate time curve of the cracks on retrogressive zone

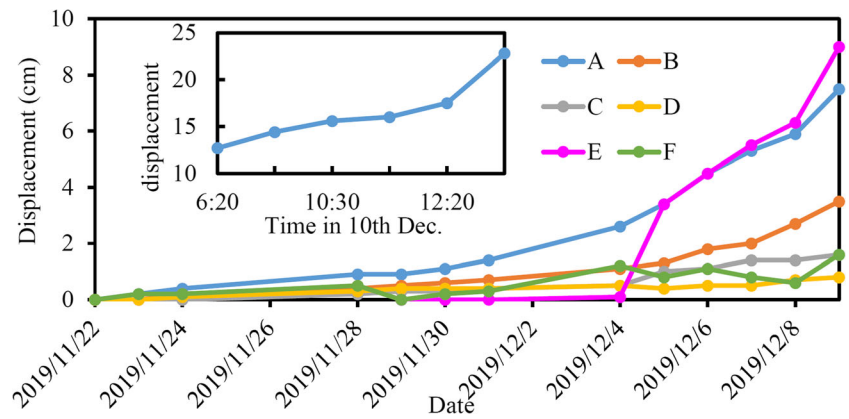


Fig. 21 The relative displacement time curve of A-F monitoring points. The small figure shows the deformation of crack A monitoring point before sliding on December 10

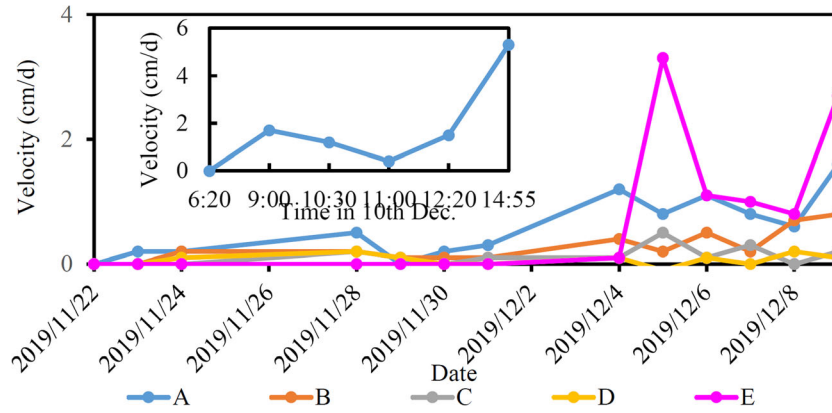


Fig. 22 The relative displacement velocity time curve of A-F monitoring points. The small figure shows the deformation of crack A monitoring point before sliding on December 10

which is 40°. This means that the slope has been creeping along this “slip zone”, towards the true tendency in the early stages. In other words, the formation of the slip zone can be related to the early movement. The movement is probably tectonic movement, causing the weak layer to form an interlayer shear zone (Wang et al. 2004), which then evolves into the slip zone (Li et al. 2007). After 175-m impoundment, the degradation of rock mass in water level fluctuation zone accelerates the evolution of weak layer to the slip zone.

Discussion

Based on our observation, the wedge-shaped or apparent dip sliding of Kamenziwan landslide is related to the slope structure and rock mass structure. When the rock is inclined and the

bedding slide is blocked, the slope will also slide in the apparent dip, the same as what happened in the cases of Jiweishan landslide and Shanyang landslide (Yin 2010; Xu et al. 2010). In terms of the inclined limestone slope, Yin (2010), Xu et al. (2010), and Li et al. (2016) proposed methods for early identification of potential catastrophic geohazards.

Terrain and geomorphology characteristics in Kamenziwan slope and adjacent areas can provide enlightenment for early identification of similar potential geohazards. Figure 26 shows some typical topographic and geomorphic characteristics of the 600-m area, near the Kamenziwan landslide. Before sliding, the Kamenziwan slope was a prominent ridge, with two free sides and one siltstone ridge. However, after instability, the geomorphology of Kamenziwan landslide changed into the siltstone ridge clip groove. It is obvious that this area is a stepped geomorphology, with a large number of micro-geomorphologies on the sides of the siltstone ridge clip grooves. On the one hand, the formation of groove micro-geomorphology occurred due to easy weathering of siltstone. On the other hand, it could be caused by landslides in sandstone, which occurred in the historical period. Especially in this area, there are a large number of grooves, with the features of

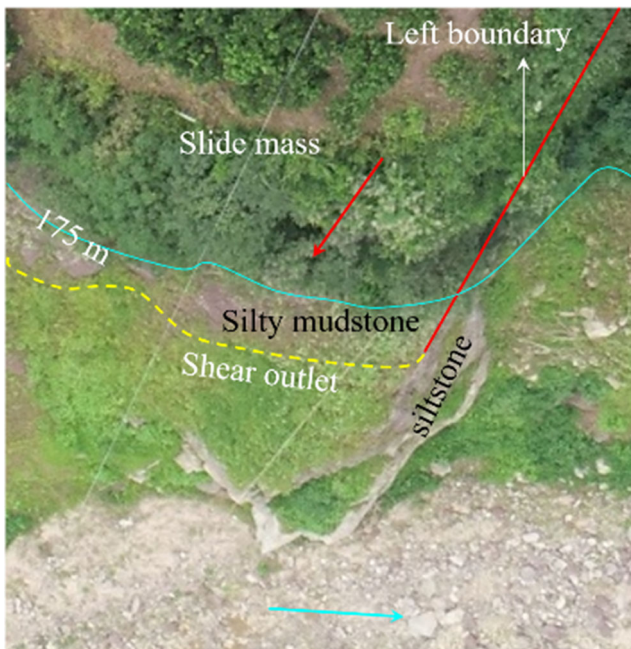


Fig. 23 Photo of the water level fluctuation zone before the Kamenziwan landslide (July 10, 2019)

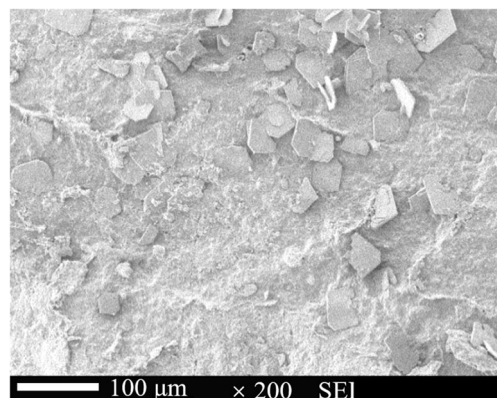


Fig. 24 Scanning electron microscopy image of the montmorillonite minerals, intersected in hexagonal slices

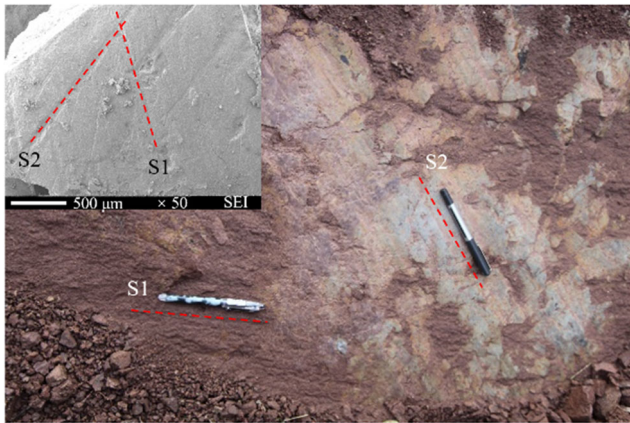


Fig. 25 Two sets of scratches on the yellow slide bed. The direction of the pen indicates the direction of the two groups of scratches

ancient landslides, such as gentle leading-edge platforms and chair-like geomorphology at the trailing edges (Ahmed and Rogers 2016), suggesting they were formed by historical landslides. Because this accumulation slope, formed by the historical failure of rock landslide, is gentle, and the loose accumulation thickness is not large and the stability is good, these historical landslides have not been identified yet. After the occurrence of multi-layered rock landslide, the stepped geomorphology will be formed (Xu et al. 2015). Therefore, in this area or similar areas, features such as near-parallel stepped geomorphology, bedding, oblique bedding, or apparent dip bedding geomorphology in the area cause potential geohazards in the adjacent bedrock mountains on both sides

of the area, similar to Kamenziwan. When the slope base of these potential geohazards is located in the water level fluctuation zone, further investigation and monitoring are required, in order to minimise the impacts of such a hazard on the environment and society.

When soft and hard sandwich-like red layer develops in bedding or inclined bedding, rock landslides are usually prone to occur. Therefore, the red layers in the Three Gorges Reservoir area correspond to the densely developed areas of rock landslides (Tang et al. 2019; Xu et al. 2015; Wang et al. 2004). Important information on the sandwich-like rocky landslide of the Three Gorges Reservoir is listed in Table 1.

As it can be seen from Table 1, the occurrence of the sandwich-like red-layer rocky landslide in the early stage is related to the first water impounding (Wang et al. 2004; Tian and Lu 2012). After impounding for a period, the water level fluctuations, in response to the superposition of heavy rainfall, are considered the inducing factor of these kinds of landslides (Yin et al. 2016; Huang et al. 2015; Xu et al. 2015), which are a typical form of reservoir-induced landslides. Currently, there are no obvious triggering factors in Kamenziwan landslide. However, 11 years of reservoir/groundwater level fluctuations have resulted in the erosion of slope base and rock mass degradation of the middle-lower part of the slide mass, causing the leading-edge traction. The long-term periodic water level fluctuations cause a disadvantageous time effect, namely water level fluctuation zone rock mass degradation. Furthermore, the hydrophilicity of clay minerals in the red layer causes continuous downgrade of the quality and physical-mechanical properties of the rock mass in the water level fluctuation zone. Finally, rock mass degradation accelerates the slope evolution towards the instability. This “naturally occurring”

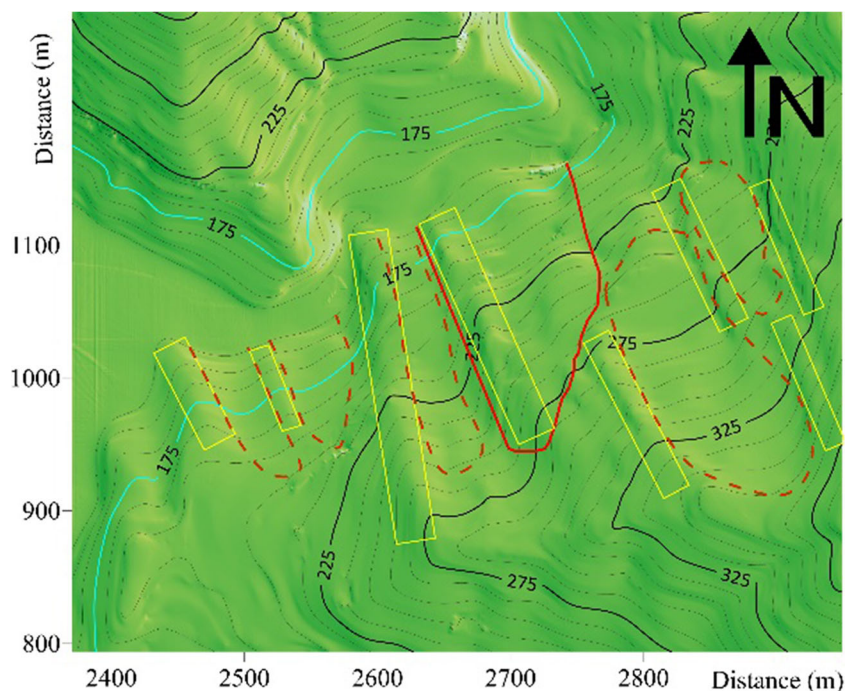


Fig. 26 Identification instructions of Kamenziwan landslide. Topographic map and shadow image, before sliding. The yellow frame represents the ridgeline, the red solid line demonstrates the Kamenziwan landslide, and the red dashed line refers to the grooved landform, which may represent the history rocky landslide area

Table 1 Bedding or inclined bedding red-layer rock landslide, occurred after water impoundment

Landslide name	Date	Volume	Inducing factors
Qianjiangping landslide	2003.7.14	2400×10^4	30 days after the Three Gorges Reservoir was first impounded to 135 m (Wang et al. 2004)
Nierwan landslide	2008.11.9	180×10^4	On the day of its occurrence, the Three Gorges Reservoir was first impounded to 172.8 m (Tian and Lu 2012)
Shanshucao landslide	2014.9.2	46.5×10^4	Heavy rainfall and water level raise with the velocity of 3.8 m/day from the 1st to the 2nd of Sep. 2014 (Huang et al. 2015; Xu et al. 2015)
Huangjuebang landslide	2015.6.18	66×10^4	Heavy rainfall and water level drawdown with the velocity of about 1 m/day from earlier June 2015 (Yin et al. 2016)

landslide due to the degradation of rock mass in the water level fluctuation zone can be also considered as a type of reservoir-induced landslide, which could be one of the main forms of a reservoir-induced landslide in the later stage of water storage in the future and one of the important paths of newborn landslide generation.

Conclusions

Following a comprehensive field investigation of the Kamenziwan landslide, which occurred on December 10, 2019, the process, characteristics, and mechanism of landslide are analysed in detail. The Kamenziwan landslide is a newborn landslide, which is of great significance for understanding the development of a new type of reservoir-induced landslide in the Three Gorges Reservoir area. Based on field investigation and analysis, the main findings of this study are as follows:

1. The Kamenziwan landslide is a wedge-shaped (apparent dip) red-layer rock landslide, controlled by two sliding surfaces. The downstream side of the landslide is bounded by a siltstone stratum, while the upstream side is bounded by the structural surface. The downstream slip zone of fuchsia clay is formed by the silty mudstone that has experienced multiple movements throughout the history. The landslide volume is estimated about $42 \times 10^4 \text{ m}^3$, resulting in a fractured retrogressive zone with volume of $12 \times 10^4 \text{ m}^3$.
2. The landslide deformation occurred on November 20, developing cracks from the leading edge to the trailing edge. The sliding mechanism of the landslide is the leading-edge traction in the early stage and the middle-rear gravity pushment in the later stage. The maximum sliding rate of the landslide is estimated about 0.15 m/s, the movement distance of the landslide is around 18 m, and the movement duration is more than 15 min.
3. The Kamenziwan landslide is not induced by the reservoir water level and rainfall, and no obvious triggering factors can be considered, in this regard. However, the long-term water level fluctuations in the Three Gorges Reservoir area have eroded the key anti-slip section below the elevation of 175 m asl., revealing the slip zone. Therefore, the degradation of the rock mass in the surface and groundwater fluctuation zone (middle-lower part of the landslide) has greatly accelerated the evolution process of Kamenziwan landslide. The landslide that occurs due to the degradation of rock mass in the water level fluctuation zone may be one of the important paths for

developing the new reservoir-induced landslides in the later stage of water impoundment in the future.

4. An early warning was successfully disseminated in the case of Kamenziwan landslide, minimising the potential casualties. However, it is still necessary to carry out early identification of the landslide potential geohazards in the soft and hard red-layer clastic rock areas, as they may occur more frequently in this area. Similar to the Kamenziwan landslide, the free bedding layer or oblique bedding layer bedrock slopes on both sides should be considered potential geohazards.

Acknowledgements

The authors would like to thank Professor Ye Yicheng and Professor Ma Xiaohan from the Hydrogeological Team of Hubei Province, China, and a local villager named Chen YJ for providing early information on the Kamenziwan landslide.

Funding information

This work was supported by the National Key R&D Program of China (ID: 2018YFC1504803 and 2018YFC1504806), project from the China Geological Survey (ID: 20190637), and the Geological Hazard Prevention and Control Project for Follow-Up Work of the Three Gorges Project (000121 2019C C60 001).

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

References

- Ahmed MF, Rogers JD (2016) Regional level landslide inventory maps of the Shyok River watershed, Northern Pakistan. *Bull Eng Geol Environ* 75(2):563–574
- Brooks SM, Richards KS, Anderson MG (1993) Shallow failure mechanisms during the Holocene: utilisation of a coupled slope hydrology-slope stability model. In: Allison R, Thomas D (eds) *Landscape sensitivity*. Wiley, Chichester, pp 149–175
- Deng H, Zhou M, Li J et al (2016) Study on deterioration of mechanical properties of red bed soft rock under water-rock action. *Chin J Rock Mech Eng* 35(S2):3481–3491 (in Chinese)
- He K, Wang S, Wen D, Wang S (2010) Dynamic features and effects of rainfall on landslides in the Three Gorges Reservoir region, China: using the Xintan landslide and the large Huangya landslide as the examples. *Environ Earth Sci* 59(6):1267–1274
- Heller V, Hager WH, Minor HE (2009) *Landslide generated impulse waves in reservoirs—basics and computation*. Thesis for Master, ETH, Zurich
- Huang B, Yin Y, Liu G, Wang S, Huo Z (2012) Analysis of waves generated by Gongjiafang landslide in Wu Gorge, Three Gorges Reservoir, on November 23, 2008. *Landslides* 9(3):395–405

- Huang B, Zheng W, Yu Z, Liu G (2015) A successful case of emergency landslide response - the Sept. 2, 2014, Shanshucao landslide, Three Gorges Reservoir, China. *Geoenviron Disasters* 2(1):18–27
- Huang B, Yin Y, Zhang Z, Wang J, Qin Z, Yan G (2019) Study on deterioration characteristics of shallow rock mass in water level fluctuation zone of karst bank slopes in Three Gorges Reservoir area. *Chin J Rock Mech Eng* 38(9):1786–1796
- Hungr O, Leroueil S, Picarelli L (2014) The Varnes classification of landslide types, an update. *Landslides* 11(2):167–194
- Li S, Li X, Wu J, Liu Y (2007) Evolution process and pattern of sliding zone in large consequent bedding rock landslide. *Chin J Rock Mech Eng* 26(12):2473–2480 (in Chinese)
- Li B, Feng Z, Zhang Q, Zhao C, Yan J (2016) Study on the disaster mode and early recognition of the great landslide hazard in Karst Mountain area. Science Press, Beijing
- Liu X, Yuan W, Fu W et al (2018) Porosion evolution law of sandstone dissolution under dry-wet cycle. *Chin J Geotechnical Eng* 40(3):527–532 (in Chinese)
- Stead D, Eberhardt E, Coggan JS (2006) Developments in the characterization of complex rock slope deformation and failure using numerical modelling techniques. *Eng Geol* 83(1–3):217–235
- Tang H, Wasowski J, Juang CH (2019) Geo-hazards in the Three Gorges Reservoir Area – Lessons Learned from Decades of Research. *Eng Geol.* <https://doi.org/10.1016/j.enggeo.2019.105267>
- Tian ZG, Lu SQ (2012) Analysis on formation mechanism and stability evaluation of Nierwan landslide in the Three Gorges Reservoir area. *Resource Environ Eng* 26(3):236–239
- Wang FW, Zhang YM, Huo ZT, Matsumoto T, Huang BL (2004) The July 14, 2003 Qianjiangping landslide, Three Gorges Reservoir, China. *Landslides* 1(2):157–162
- Wang F, Zhang Y, Huo Z et al (2008) Movement of the Shuping landslide in the first four years after the initial impoundment of the Three Gorges Dam Reservoir, China. *Landslides* 5(3):321–329
- Xia M, Ren GM, Xin L (2013) Deformation and mechanism of landslide influenced by the effects of reservoir water and rainfall, Three Gorges, China. *Nat Hazards* 68(2):467–482
- Xu Q, Fan X, Huang R, Yin Y et al (2010) A catastrophic rockslide-debris flow in Wulong, Chongqing, China in 2009: background, characterization, and causes. *Landslides* 7(1):75–87
- Xu G, Li W, Yu Z, Ma X, Yu Z (2015) The 2 September 2014 Shanshucao landslide, Three Gorges Reservoir, China. *Landslides* 12(6):1169–1178
- Yang B, Yin K, Xiao T, Chen L, Du J (2017) Annual variation of landslide stability under the effect of water level fluctuation and rainfall in the Three Gorges Reservoir, China. *Environ Earth Sci* 76(16):564
- Yin Y (2010) Mechanism of apparent dip slide of inclined bedding rockslide—a case study of Jiweishan rockslide in Wulong, Chongqing. *Chin J Rock Mech Eng* 29(2):217–226 (in Chinese)
- Yin Y, Huang B, Wang W et al (2016) Reservoir-induced landslides and risk control in Three Gorges Project on Yangtze River, China. *J Rock Mech Geotech Eng* 8(5):577–595

Y. Yin · B. Huang (✉) · **Q. Zhang**

Hubei Key Laboratory of Disaster Prevention and Mitigation,
China Three Gorges University,
Yichang, 443002, China
Email: 344043292@qq.com

Y. Yin

Technical Guidance Center for Geological Disasters,
Ministry of Natural Resources,
Beijing, 100081, China

G. Yan

China University of Geoscience,
Wuhan, 433002, China

Z. Dai

Wuhan Center of China Geological Survey,
Wuhan, 433002, China