Scenario Simulation of The Geohazard Dynamic Process of Large-Scale Landslides: A Case Study of The Xiaomojiu Landslide Along The Jinsha River

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Scenario simulation of the geohazard dynamic process of large-scale landslides: a case study of the Xiaomojiu landslide along the Jinsha river

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Abstract

Large-scale landslides often cause severe damage due to their long run-out distances and having disaster chain effects. Scenario simulation has been adopted in the current work to analyze the Xiaomojiu landslide dynamic processes, such as sliding velocity, deposition characteristics, and flood outburst after a landslide-dam failure using Particle Flow Code (PFC-3D) which introduced the changeable friction coefficient and the HEC-RAS software. The landslide characteristics and topography data were obtained via field investigation, whereas high-resolution topographic data (0.17 m) was obtained using an Unmanned Aerial Vehicle (UAV). The results showed that: 1. The landslide presents a scallop shape with a length of 1566 m, a width ranging from 809~1124 m, and an area of 1.34×10^6 m^2. The average thickness and volume of the sliding body is approximately 40 m, 5.1×10^7 m^3. The InSAR deformation analysis showed that the Xiaomojiu landslide has a maximum annual displacement rate of 60 mm/y, and a maximum accumulation deformation of 180 mm since November 25, 2017. 2. From the landslide simulation results, the failure process of the Xiaomojiu landslide lasted for 65 s with a maximum velocity of 78.2 m/s. The deposited area is approximately 2023 m long, 900 m wide, with a maximum height of approximately 149 m. 3. After the landslide blocks the Jinsha River, a landslide-dammed lake with an elevation of 2940 m and a storage capacity of 4.13×10^9 m^3 is formed. The maximum peak flow rate of the breach is 12051.7 m^3/s, 43451.4 m^3/s, 148635.6 m^3/s, and 304544.7 m^3/s for the landslide-dammed failure degrees of
15%, 25%, 50%, and 75%, respectively. These results provide a scientific reference for the risk analysis and mitigation of the landslide.

**Keywords** Scenario simulation · Geohazards chains · Landslide failure · Flood simulation · Xiaomojiu landslide

1 Introduction

Large-scale landslides often cause severe damage due to their long run-out distances and having a significant disaster chain effect; thus, resulting in a large number of casualties, significant property loss, as well as damage to the ecological environment (Yin et al. 2016; Korup et al. 2019; Aslan et al. 2021). The complex geology and high-relief landform along the rivers indicate that a landslide has a large potential energy (Guo et al. 2020; Zhang et al. 2020; Gong et al. 2021). The failure and run-out process are complex and with the landslide materials traveling along the passway, resulting in a very high velocity with long run-out distances (Yang et al. 2014; Ge et al. 2019). Landslides that occur on both riverbanks produce landslide debris that can easily block the river and form a dammed lake. The water upstream of the dam body can then inundate residential areas and infrastructures. Moreover, the severity of dam failures and consequent flood bursts cause significant damage to downstream towns, transportation facilities, communication equipment, and the environment, thereby threatening the safety of human life (Liu et al. 2019; Fan et al. 2020a).

There are many catastrophic landslide occurrences globally, especially in the regions with landforms having higher elevation differences and frequent geohazards; thus, blocking rivers and forming landslide dams. For example, in 1933, a magnitude 7.5 earthquake occurred in Diexi, Maoxian County, Sichuan Province. This earthquake triggered a landslide that buried Diexi Town and blocked the Minjiang River, resulting in the formation of a dammed lake, which again broke and caused a massive flood killing more than 2500 people after 45 days (Zhao et al. 2019). In 2000, a landslide with debris spanning approximately $3 \times 10^6 m^3$ occurred in Yigong, Tibet, blocking the Yigong River, and forming a 130m high landslide dam. The outburst flood from the breakage of this dam was $1.24 \times 10^5 m^3/s$ causing significant loss downstream (Delaney et al. 2015). In May 2008, another large-scale landslide occurred in Tangjiashan on the right bank of the Tongkou River triggered by the Wenchuan earthquake. The landslide blocked the Tongkou River and formed a
landslide dam with a height that ranged from 82-124m tall and having a storage capacity of nearly $3 \times 10^9$ m$^3$. The landslide posed a significant threat to the lives of nearly a million people downstream (Cui et al. 2009). In October and November 2018, two landslides with volumes of $2.4 \times 10^7$ m$^3$ and $8.50 \times 10^6$ m$^3$ occurred in Baige Village along the Jiangda River. The landslides traveled a distance of 1,400 m and blocking the Jinsha River. This led to a rapid increase in the water content of the barrier lake ($3.85 \times 10^8$ m$^3$), causing devastating damage to coastal residents and infrastructure up to 1,000 kilometers downstream along the Jinsha River (Fan et al. 2020b; Zhang et al. 2020). Therefore, the formation and failure of landslides and landslide dams are sudden and extremely dangerous, and above all, it is extremely difficult to forecast and alleviate such catastrophes. Therefore, scenario simulation of the geohazards’ dynamics processes of large-scale landslides and geohazards’ chain of "landslide-blocking river-dam failure outburst flood" of the potential landslides is of utmost significance for the risk assessment and mitigation of the geohazard’s (Zhang et al. 2019; Liu et al. 2019; Fan et al. 2020a).

With the advancement of computer simulation techniques and geohazard numerical simulations, they have the advantages of being less time-consuming, low cost, and the intuitive calculation results becoming the most effective method for studying the kinematic characteristics of landslides and the evolution of dam-breakage (Fan et al. 2017; Liu et al. 2015). Many scholars have studied large-scale landslide dynamics scenario simulations under different influencing factors (Bandara et al. 2015; Pastor et al. 2015; Yin et al. 2016; Gong et al. 2021) and flood evolution process simulations (Butt et al. 2013) based on numerical simulation methods in order to understand the mechanism of large-scale landslide failure and risk assessment. Numerical analysis has been widely adopted by several researchers in the past (1) To study the large-scale geohazard chain process based on post geohazards and comparing them with the geohazard characteristics in order to reproduce the geohazard chain process using a numerical simulation (He et al. 2015; Liu and He 2020). (2) Numerical simulation is also adopted to study the dynamic processes of the geohazards chain process under different triggering factors, such as the dynamic process of landslides caused by earthquakes (Sun et al. 2017; Wang et al. 2018; Sarma et al. 2020). Furthermore, groundwater affects the initiation process of a landslide as well as the landslide process caused by rainfall, loading, and unloading (Zhang et al. 2017; Zhang et al. 2019; Gong et al. 2020). (3) Numerical simulations were further used to carry out regional or single landslide scenario analysis, study the disaster loss
and the damage zone caused by the geohazards, and provide a reference for risk analysis, assessment zoning, and disaster relief route selection (Loreto et al. 2017; Fan et al. 2020b; Mao et al. 2020).

Scenario simulation of the dynamics of large-scale landslides and the detection of the long-runout of geohazard chains for a potential landslide is very important for risk assessment and the mitigation of the landslides, especially for site selection and planning of major projects (Liu and He 2020; Fan et al. 2020b). The current work aims to study a potential landslide, namely the XiaoMojiu landslide as the case study. The landslide characteristics and topography data were obtained through field investigations and UAV flights. The landslide model was built using high-resolution topographic data obtained from the UAV. The landslide failure process deposits, the landslide dam characteristics, and the dam-breakage flood evolution process were analyzed using PFC3D and HEC-RAS software.

2 Area setting

The Xiaomojiu landslide located in the east of the Qinghai-Tibet Plateau on the right bank of the Jinsha River in Jiangda County of the Tibet Autonomous Region (Fig. 1), is approximately 5 km upstream of the Baige landslide (E 98° 41’ 49″, N 31° 07’ 24″). Since the middle and late Pliocene era, due to strong uplifts of the Qinghai-Tibet Plateau, the height differences between both sides of the Jinsha River have become more prominent, and the valleys have been strongly cut (Chen et al. 2013), creating steep slopes. The landslide’s top and toe elevations are 3655 m and 2900 m, respectively; therefore, having a height difference of 755m. The toe of the landslide undergoes strong erosion by the Jinsha River and has a slope of approximately 30°-35°.

Fig.1 The Xiaomojiu landslide setting area characters (base data from https://geocloud.cgs.gov.cn/#/home)

The geological structure of the Xiaomojiu landslide is closely related to the tectonic evolution of the Qinghai-Tibet Plateau and is affected by the compression and collision of the Indian and the Asia-Europe plates. The eastern Qinghai-Tibet Plateau has strong tectonic deformation and uplift, making the eastern Qinghai-Tibet Plateau one of the most tectonically active areas. Typically, the faults and folds are found to be highly developed within this area (Cao et al. 2015). The concentrated development area of the unique geohazards formed by the action is primarily composed of
metamorphic basic-ultrabasic rocks, metamorphic clastic rocks, and marble mixtures (Fig. 2). The south-north ductile shear mylonite belt and the strong schistosis belt are highly developed with a series of east-west squeezed imbricated inverses and fold structures (Zhang et al. 2016). The above-mentioned geological background makes the Xiaomojiu landslide a typical high-steep valley structure consisting of a broken loose body structure that provides favorable topography and material for landslide failure.

The study area has a semi-humid climate within the plateau cold temperate zone having an average annual temperature of 7.5°C and an apparent vertical climate zoning. The average annual precipitation is approximately 650 mm, and can reach a maximum of 1067.7 mm. Furthermore, the precipitation has the characteristics of uneven temporal and spatial distribution primarily concentrated in June, July, August, and September. Additionally, the groundwater in the study area is primarily bedrock fissure and pore water. The main sources of the water are precipitation and melting ice and snow. The bedrock fissure water is primarily distributed within the bedrock fissures (Chen et al. 2013).

3 Methods

3.1 Discrete element method

The discrete element method (DEM) is an effective method for dynamic landslide analysis (Cundall and Strack 1979). PFC3D makes the following assumptions: (1) The particle unit is rigid; (2) All contacts between the particles occur only in small areas which can be regarded as point contacts; (3) The contact model is a flexible contact, that is at a contact point there exists a certain overlap; (4) According to the force-displacement law, the size of an overlap is related to the size of the contact force; therefore all of the overlaps are smaller than the particle diameter; (5) The contact between the particles can establish the bonding characteristics. The particle motion characteristics are calculated using Newton’s second law of motion, whereas the law of force and displacement is used to update the position of the particles and describe the motion of the particles in the PFC3D discrete
element method (Equations 1, 2, Itasca Consulting Group, Inc 2006):

\[ F_i(t) + mg_i = \frac{m \Delta v_i}{\Delta t} \]  
\[ M_i = \frac{I \Delta \omega_i}{\Delta t} \]  

where \( i = 1, 2, 3 \) are the three directions of \( x, y, z \). \( F_i(t) \) is the unbalanced force of the particle at time \( t \), \( g \) is the acceleration of gravity, \( m \) is the particle mass, \( M \) is the unbalanced moment, \( \Delta t \) is the calculation time step, and \( \omega \) is the angular acceleration. Then, the particle displacement \( s_i \) and velocity \( v_i \) are:

\[ s_i(t + \Delta t) = s_i(t) + v_i(t)\Delta t \]  
\[ v_i(t + \Delta t) = v_i(t) + \frac{1}{m_i} F_i(s_i(t))\Delta t \]  

3.2 Determination of friction coefficient

Many scholars set the friction coefficient as a fixed value while studying the dynamic process of large-scale landslides using numerical simulations, and they rarely consider changes in the friction coefficient (Han et al. 2010). However, numerous study results have shown that the friction coefficient of the rock during the sliding process is indefinite (Han et al. 2007; Han et al. 2010; Yao et al. 2013; Dong et al. 2017). The friction coefficient of a landslide varies due to the dynamic expansion, water hammer effects, sliding separation, or saturated liquefaction. Other effects, such as the air cushion layer, excessive pore water pressure, and rolling friction reduction, causes a reduction in the friction coefficient resulting in the high-speed and long-run outs of the landslide (Han et al. 2007; Han et al. 2010; Yao et al. 2013; Dong et al. 2017).

Han et al. (2010) proposed an empirical equation for the steady-state friction coefficient (Equation 5) including the velocity based on a rock high-speed friction test, and the friction coefficient during the sliding process.

\[ \mu_{ss} = \mu_{ss.\ min} + \left( \mu_{ss.\ max} - \mu_{ss.\ min} \right) \exp \left[ \ln(0.05) \left( \frac{v}{v_p} \right) \right] \]  

where \( \mu_{ss} \) is the steady-state friction coefficient when the speed is \( v \), \( \mu_{ss.\ max} \) is the steady-state friction coefficient at a small slip rate, \( \mu_{ss.\ min} \) is the steady-state friction coefficient when
the speed progress to infinity, and \( v_c \) is the critical speed. When the speed is 0, \( \mu_{ss} \) is equal to \( \mu_{ss, \text{ max}} \); when the speed tends to be infinite, \( \mu_{ss} \) is equals to \( \mu_{ss, \text{ min}} \).

Based on the friction attenuation empirical formula proposed by Han et al. (2010), the present paper introduced a friction empirical formula showing how the friction coefficient changes with speed in the PFC3D model as well as simulating the landslides movement process. The flow chart is shown in Fig. 3.

The simple model is shown in Figure 4 and was used to verify the accuracy of the program. The experimental materials of Han et al. (2010) were selected as the material for this verification simulation. The physical parameters are shown in the Table 1. The final simulation result is shown in Fig. 5, verifying the reliability and accuracy of the program.

### 3.3 Landslide simulation parameters

In the discrete element method, the macroscopic properties of a particle depend on its mechanical contact properties. A uniaxial compression numerical test was used to obtain the macroscopic properties of the rock mass mechanics of the particle’s combination. The size of the PFC3D simulation uniaxial compression test model was 100 mm in height and 50mm in radius (Fig. 6). The sample comprised of 7558 particles with a particle density of 2650 kg·m\(^{-3}\), the maximum and minimum particle size ratio was 4:3, the contact adopted a linear parallel bonding, the outside of the particles was restrained by the wall command, and the wall stiffness was 1/10 of the particles stiffness. Loading was controlled by assigning speed to the upper and lower walls.

Fig. 5 Plot showing the relationship between friction coefficient and speed

Fig. 6 The simulated triaxial test model
The microscopic parameters that need to be calibrated included the particle properties and the bonding relationships. The properties of the spherical particles are determined by three parameters: $k_n$, $k_s$, and $\mu$. The bonding relationship was determined by $\overline{E_c}$, $\overline{k_n/k_s}$, $\overline{\tau_b}$, and $\overline{\lambda}$. where, $k_n$ is the normal stiffness of the particle, $\overline{E_c}$ is the parallel bond modulus, $k_n/k_s$ and $\overline{k_n/k_s}$ are the ratios of the normal stiffness and the tangential stiffness of the particle and the bond, $\overline{\tau_b}$ is the parallel normal bond strength, $\overline{\tau_b}$ is the parallel tangential bond strength, and $\overline{\lambda}$ is the particle bond radius coefficient.

Table 2 Comparison of the uniaxial test between the numerical model and the laboratory experiment

The stress-strain curve was obtained through a uniaxial compression simulation test (Fig. 6). Table 2 shows the differences between the physical and mechanical properties obtained from the laboratory tests and numerical model parameters. The simulation test results fit very well with the laboratory tests. The uniaxial compression test parameters are considered to be the landslide simulation parameters (Table 3).

Table 3 Parameters of the triaxial test results

3.4 Building the Simulation Model

High-resolution three-dimensional terrain data (0.17 m) recorded by a UAV are used to build the landslide simulation model. Field investigation and remote sensing interpretation methods are also used to analyze the deformation characteristics of the slope; thus, combining the drilling data, the thickness of the deformation body is evaluated at 40-80 m with an average of 60 m. Additionally, to analyze the speed of different positions of the sliding body, four monitoring points were selected in the upper part (P1–P4), middle part (P5–P8), and the toe (P9–P12) of the sliding body in order to record the landslide speed change (Fig. 7).

Fig. 7 Simulation model of the Xiaomojiu landslide (base terrain from UAV obtained by authors)

3.5 Out-burst flood simulation

The HEC-RAS software, which uses a two-dimensional unsteady flow based on the Navier-Stokes
equation, is the most commonly used method for simulating outburst floods (Hydrologic Engineering Center 2012). Assuming that the fluid is incompressible, the mass conservation (continuity) equation is:

\[
\frac{\partial H}{\partial t} + \nabla \cdot (hu) + q = 0
\]  

(6)

Where, \( t \) is time, \( u \) and \( v \) are the velocity components in the \( x \) and \( y \) directions, and \( q \) is the confluence; therefore, the momentum equation is:

\[
\frac{\partial V}{\partial t} + V \cdot \nabla V = -g \nabla H + v \nabla^2 V - C_f V + f_k \cdot V
\]  

(7)

Where, \( u \) and \( v \) are the velocity components in the \( x \) and \( y \) directions, \( g \) is the acceleration due to gravity, \( v \) is the horizontal viscosity coefficient, \( c_f \) is the bottom friction coefficient, \( f_k \) and \( f_x \) are the Coriolis parameters in the \( x \) and \( y \) directions, respectively.

4 Characteristics of the Xiaomojiu landslide

4.1 Characteristics of Different zones

As per the plan shown in Figure 8, the Xiaomojiu landslide is a scallop shape with a length of 1566 m, a width of 809–1124 m, and an area of 1.34×10^6 m^2. The sliding direction of the landslide is NE46°. The average thickness and volume of the sliding body are approximately 40 m, and 5.1×10^7 m^3, respectively. According to landslide characteristics and the drilling data, the Xiaomojiu landslide can be divided into two major areas: the landslide scar area (I) and the landslide deformation area (II). The landslide deformation area can be further divided into the upper sliding deformation zone (II1), the middle compression deformation zone (II2), and the slope toe stress concentration zone (II3) according to deformation characteristics (Fig. 8).

Fig. 8 The landslide deformation zone and side view of the landslide (base imagery and terrain from UAV obtained by authors)

The landslide scar area has a total length of approximately 2500 m, an area of 3.3×10^5 m^2, and an average height difference of about 105 m. The bedrock of the scar area remains bare, and the vegetation coverage is minimal. After the landslide, the boundary of this area became very clear, and the rock mass was significantly broken. Several gullies were formed in this area, and the ridges
in the northern area collapsed locally due to erosion, revealing that the first failure occurred a long
time ago (Fig. 9).

The upper sliding deformation zone (Ⅱ1) is primarily distributed in the area with an elevation
of 3326–3462 m and a slope of 22°. The longitudinal length and lateral width of this zone are 319 m
and 280–680 m, respectively. Additionally, the area and the volume of this zone are 1.7×10^5 m^2 and
6.5×10^6 m^3, respectively. The zone is comprised of six-level arc-shaped steps due to the deformation
(Fig. 10). The steps are 91–257 m long, 22.4–64.0 m wide. The vertical dislocation of the steps ranges
from 12.6 to 43.5 m.

The middle compression deformation zone (Ⅱ2) is primarily distributed in the area with an
elevation of 3127–3326 m and a slope of 38°. The longitudinal length and lateral width of this zone
are 385 m and 1010 m, respectively. Furthermore, this zone has an area of 3.6×10^5 m^2 and a volume
of approximately 2.5×10^7 m^3. Under the squeezing action of the upper sliding deformation zone
(Ⅱ1), the structure of the rock mass in this zone is significantly broken and weathered with the local
convex landform. There are well-developed tension cracks in the southwestern edge of the
deformation zone, providing a path for rainwater infiltration. Moreover, a secondary landslide has
been found in this area whose length is 246 m, width is approximately 310 m and, a height difference
of 131 m (Fig. 11). The secondary landslide is a sign of shallow slippage due to road excavation.

The slope toe stress concentration zone (Ⅱ3) is a distributed area having an elevation of 2900–
3127 m and a slope of 35°. This zone has a longitudinal length of 450 m, and lateral width of 1150
m. The area of this zone is 4.7×10^5 m^2 and the volume is approximately 2.1×10^7 m^3. Several local
landslides occurred due to erosion by the Jinsha River. The maximum height of the landslide is
approximately 89 m (Fig. 12).
Fig. 12 The slope toe stress concentration zone (base imagery from UAV obtained by authors)

4.2 Deformation characteristics

76 SAR images were collected from the ALOS-2 satellite for the current study between 2017 and 2020. The SAR images were processed using terrain correction, time-space decoherence factors, and an atmospheric delay phase process (Zhao et al. 2016; Liu et al. 2021), thus obtaining the landslide's annual displacement rate since 2017 (Fig. 13a). Fig. 13b shows the displacement of the Xiaomojiu landslide since November 25, 2017. The maximum annual displacement rate of the landslide is 60 mm/y. Since 2017, the deformation rate of the landslide has typically increased tending to aggravate the deformation. The maximum deformation reached a value of 180 mm over a 3 year period. During this period, the slope deformation was primarily concentrated in the middle and upper parts of the slope, indicating that the landslide is induced by gravity or fault activity and has an apparent nature of instability.

Fig. 13 The deformation characteristics of the Xiaomojiu landslide using InSAR (base imagery from UAV obtained by authors)

5 Results

5.1 Dynamic characteristics

Fig. 14 shows the dynamic process of the Xiaomojiu landslide, whereas Figure 15 shows the friction coefficient distribution of the landslide at different times with the changeable friction coefficient. The landslide motion lasted for about 65 s and comprised of three stages: initiation phase (Fig. 14a-b, Fig. 14a-b), acceleration phase (Fig. 14c-d, Fig. 14c-d), and deceleration accumulation phase (Fig. 14e-f, Fig. 15e-f). At the initiation phase, the sliding body began to slide slowly along the bedrock. The landslide showed an overall instability failure after 4 s with a friction coefficient of 0.25–0.35. At 12s–26s, the sliding body accelerated sliding along the bedrock, and the potential energy of gravity converted into kinetic energy. At this time, the sliding body started to block the river. The landslide toe particles rushed into the channel first and reached the peak velocity. The friction coefficient attenuated to 0.10–0.15. During 26–64 s, the landslide was in the deceleration
accumulation stage. The sliding body passed through the river channel with the front-edge particles blocked by the mountain on the opposite bank. The energy consumed due to collision, tumbling, and friction started to decelerate. The sliding body accumulated on the opposite side of the mountain slope and on both sides of the rivers. The speed of the upper particles of the landslide decreased rapidly, and the coefficient of friction increased rapidly until it reached a maximum value of 0.50. At 64s, most of the particles stopped moving.

**Fig. 14** The dynamic process of the Xiaomojiu landslide (a. t=4s b. t=12s c. t=26s d. t=39s e. t=53s f. t=64s, base terrain from UAV obtained by authors)

**Fig. 15** The changing characteristics of the friction coefficient during dynamic process (a. t=4s b. t=12s c. t=26s d. t=39s e. t=53s f. t=64s, base terrain from UAV obtained by authors)

Fig. 16 shows the plot of the speed vs. average speed of the monitoring points in different parts of the landslide. Comparing the average velocities of different parts of the sliding body, it was found that the particles of the upper-part (P1-P4) of the landslide had three sharp rises and drops in velocity before reaching the peak velocity. The velocities of the toe (P9-P12), middle- (P5-P8), and upper-part particles (P1-P4) of the landslide reached peak values in 26 s, 34 s, and 42 s, respectively. Due to the significant height difference in the movement path of the upper-part particles (P1-P4) of the sliding body, the peak velocity was significantly greater than the peak velocities of the toe (P9-P12) and middle-part (P5-P8) particles. For example, the peak velocity of the P1–4 monitoring points was 61.4 m/s, the peak velocity of the P5–8 monitoring points was 70.1 m/s, and the peak velocity of the P9–12 monitoring points was 78.2 m/s.

**Fig. 16** The point velocity of the Xiaomojiu landslide

5.2 Characteristics of the Deposited Zone

Fig. 17 shows the characteristics of the deposited zone with a changing friction coefficient. From the perspective of the plane distribution, the landslide traveled a distance of approximately 780 m, and the total area of the deposits was approximately $7.9 \times 10^5$ m$^2$. The deposited area presented an uneven oval shape, thin on both sides and thick in the middle. The maximum thickness was 149 m.
According to the simulation results, the deposited area blocked the Jinsha River to form a huge landslide dam. The landslide dam was spindle-shaped with a maximum thickness of 149 m. The elevations of the left and right banks were 2940 m and 3000 m, respectively. A dam break model was established based on the above profile.

**5.3 Outburst flood simulation**

According to the landslide simulation results, the height of the landslide dam blocking the Jinsha River was between 2940 and 3000m. The dam height that was considered the final submerged elevation was 2940 m, and the maximum storage capacity was $4.13 \times 10^9$ m$^3$. Considering the average annual flow in the upper reaches of the Jinsha River to be 957.3 m$^3$/s, the dammed lake was estimated to overflow after 50 days. To further analyze the floods from different scenarios of the landslide dam failure, we simulated and will discuss four types of scenarios: 15%, 25%, 50%, and 75% dam failure.

Fig. 18 shows the flow discharge process of the different scenarios of landslide dam failure. The floods from different scenarios of the landslide dam failure evolved as a single waveform. The flow discharge increased rapidly and reached a peak within 30 minutes. The flow discharge then decreased slowly, and after 24 hours, the decrease was more than 90%. The maximum flow discharge of the dam breach was 12051.7 m$^3$/s, 43451.4 m$^3$/s, 148635.6 m$^3$/s, and 304544.7 m$^3$/s for 15%, 25%, 50%, and 75% of the dam failure, respectively, which exceeded even the ten-thousand-year return flow of the Jinsha River at the landslide site.

Next, four sections that are downstream of the Jinsha River, namely the Sichuan-Tibet Line (Z1, 69km), the Lawa Hydropower Station (Z2, 140 km), the Batang Hydropower Station (Z3, 163 km), and the Zhubalong Jinsha Bridge (Z4, 180 km) were selected for flood analysis. The flood discharge process of each section for different scenarios of landslide dam failure is shown in Figure...
It can be seen from the figure that the flood discharge first increased rapidly, then reached a peak flow value, and finally decreased slowly. The flood discharge curves for different scenarios of the landslide dam failure have similar characteristics: the peak discharge gradually decreases along the way, the discharge process spreads downward in a single peak form, and the farther the distance from the dam, the wider the peak shape. As shown in Table 4, each section’s peak flood and arrival time are related to the different scenarios of the landslide dam failure. As the degree of dam failure increases, the flood peak discharge of each section also increases, and the shorter the time it takes the flood to reach each section. For 75% dam failure, the peak flow discharge of each section was the largest and the arrival time was the fastest. Conversely, for 15% dam failure, the peak flow discharge of each section was the smallest, and the time to reach each section was the slowest.

Table 4 Flood discharge and arrival time at different sections and for different dam failures

6 Discussions

Numerical simulation of geohazard chains is considered the most effective method to reveal the dynamics of landslides and the scenario analysis of potential landslides (Mao et al. 2020; Liu and He 2020). In this area, most of the published articles focused mainly on the simulation analysis of the dynamic process of post landslides as well as studying the initiation mechanism and characteristics of post landslides (Yang et al. 2014; Delaney et al. 2015; Yin et al. 2016; Ge et al. 2019; Guo et al. 2020). In contrast, only a handful of studies concerning the dynamic process and scenario analysis of potential landslides can be found. Moreover, the friction coefficient is often treated as a constant having a fixed value during the process of numerical simulation, which is not true (Han et al. 2007; Yao et al. 2013; Dong et al. 2013). Based on the existing research and the friction attenuation characters obtained from the high-speed rock friction test, the current study has proposed that the friction coefficient is related to the landslide’s speed, and therefore, is included in the landslide simulation. Furthermore, the simulation of the decrease in the friction coefficient and the aggravation of the high-speed motion phenomenon in the landslide process.

Fig. 19 shows the characteristics of the deposited zone which included both the friction attenuation empirical formula (model 1) and the fixed friction coefficient (model 2). Concerning
plane distribution, the lateral deposited length of model 1 was larger than that of model 2. However, due to the obstruction of the mountain on the opposite bank, the difference between the horizontal and vertical accumulation lengths of the two models was not notable. The edges of the accumulated bodies along the two sides of the river channel appeared to be discontinuously distributed. In contrast, the distribution of model 1 was uniform, indicating that the model combined with the changeable friction coefficient and depicted high mobility and continuity of the landslide.

Fig. 19 The different deposition characteristics of the Xiaomojiu landslide with changeable and fixed friction coefficients (base imagery and terrain from UAV obtained by authors)

Comparison of the dynamic process of the landslide with the changeable and fixed friction coefficients revealed a distinct speed difference in the landslide during the movement process for the varied and fixed friction coefficients. The maximum speeds of the landslide with changeable friction coefficient were 55m/s, 63m/s, and 65m/s of the toe, middle, and upper parts of the landslide, respectively, which were higher than those with fixed friction coefficient (31m/s, 33m/s, and 42m/s, Fig. 20). The speed of the landslide after the introduction of the varied friction coefficient was much higher than that of the landslide with a fixed friction coefficient. This indicates that the dynamic movement of the landslide after the introduction of the friction attenuation formula gained more dynamic characteristics.

Fig. 20 Average velocities of different parts of the Xiaomojiu landslide with changeable and fixed friction coefficients

7 Conclusions

In summary, the current study has established a landslide mode using high-precision three-dimensional topographic data (0.17 m) obtained by UAV. Through scenario simulation, the specific dynamic processes of the Xiaomojiu landslide were studied. More specifically, sliding velocity, deposition characteristics, and flood outbursts after landslide-dam failure were analyzed using PFC3D introducing the changeable friction coefficient and the HEC-RAS software. The primary conclusions derived from this work are as follows.

(1) According to the characteristics of the Xiaomojiu landslide, the landslide was divided into
two areas: the landslide source area and the landslide deformation area. The landslide deformation area was further divided into the upper slumping deformation zone, middle compression deformation zone, and the slope toe stress concentration zone. The Xiaomojiu landslide has a maximum annual displacement rate of 60 mm/y and the maximum accumulate deformation has been 180 mm since November 25, 2017, according to the InSAR deformation analysis.

(2) The failure process of the Xiaomojiu landslide lasted for approximately 65 s, and the maximum velocity was 78.2 m/s. According to the simulation, the deposited area was approximately 2023 m long, and 900 m wide, with a maximum depth of approximately 149 m.

(3) The landslide-dammed lake formed by the Xiaomojiu landslide failure had a storage capacity of $4.13\times10^9$ m$^3$, and the maximum peak flow discharge of the breach was 12051.7 m$^3$/s, 43451.4 m$^3$/s, 148635.6 m$^3$/s, and 304544.7 m$^3$/s for landslide-dam failure degrees of 15, 25, 50, and 75%, respectively. The flood peak discharge and arrival time of each downstream section was at 69 km, 140 km, 163 km, and 180 km downstream distance from the landslide dam.

Authors’ contributions Jianqi Zhuang, Kecheng Jiua, and Jiewei Z zhan designed the analysis, developed the model code and performed analysis. Yi Zu, Chenglong Zhang, Jiaxu Kong, Chendui Du and Shibao Wang curated data and field investigations. Jianqi Zhuang, Jianbing Peng and Yanbo Cao prepared the manuscript with contributions from all co-authors.

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Data availability The data that support the findings of this study are available from the corresponding author, Jianqi Zhuang, upon reasonable request.
Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Human and animal rights This research does not involve human or animal participants.

The authors declare that they have no conflict of interest.

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## Tables:

### Table 1 Parameters of the model

| Parameters | Density (kg/m³) | Young's modulus (GPa) | Uniaxial compressive strength (MPa) | Poisson's ratio |
|------------|-----------------|-----------------------|-------------------------------------|-----------------|
| value      | 2500            | 30                    | 75                                  | 0.25            |

### Table 2 Comparison of the uniaxial test between the numerical model and laboratory experiment

| Density (kg/m³) | Young's modulus (GPa) | Uniaxial compressive strength (MPa) | Poisson's ratio |
|-----------------|-----------------------|-------------------------------------|-----------------|
| Laboratory test | 2650                  | 19                                  | 64              | 0.27            |
| Simulation test | 2650                  | 18                                  | 64              | 0.26            |

### Table 3 Parameters of the triaxial test results

| Simulation parameters | Value |
|-----------------------|-------|
| $k_n$/MPa             | 6.7   |
| $k_n/k_s$             | 1     |
| $\mu$                 | 0.3   |
| $\lambda$             | 1     |
| $E_c$/GPa             | 3.1   |
| $k_n/k_s$             | 1.2   |
| $\bar{\sigma}_n$/MPa | 71    |
| $\bar{\tau}$/MPa     | 71    |

### Table 4 Flood discharge and arrival time at different sections and for different dam failures

| distance from dam (km) | Peak flood discharge (m³/s) | Arrival time (h) |
|------------------------|-----------------------------|------------------|
| 15%                    | 12051.7                     | 0                |
| Z1                     | 9447.3                      | 2.5              |
| Z2                     | 8747.9                      | 5.8              |
| Z3                     | 7901.5                      | 8.0              |
| Z4                     | 7644.6                      | 10.0             |
| 25%                    | 43451.4                     | 0                |
| Z1                     | 34965.2                     | 2.3              |
| Z2                     | 30488.1                     | 5.3              |
| Z3                     | 28993.0                     | 7.6              |
| Z4                     | 27898.7                     | 9.6              |
| 50%                    | 148635.6                    | 0                |
| Z1                     | 124254.5                    | 2.1              |
| Z2 | 140 | 108373.8 | 5.0 |
| Z3 | 163 | 103557.7 | 7.3 |
| Z4 | 180 | 99338.2  | 9.3 |
| 75% |  
| Dam site | 0 | 304544.7 | 0  |
| Z1 | 69 | 228908.2 | 1.9 |
| Z2 | 140 | 222692.0 | 4.9 |
| Z3 | 163 | 210628.3 | 7.2 |
| Z4 | 180 | 204134.3 | 9.1 |
Figures:

Fig. 1 The Xiaomojiu landslide setting area characters (base data from https://geocloud.cgs.gov.cn/#/home)
Fig. 2 Geological characteristics near the Xiaomojiu landslide (base data from https://geocloud.cgs.gov.cn/#/home)
Fig. 3 Flow chart of the friction coefficient changes with speed

Input $v_c$, $\mu_{ss \text{min}}$, $\mu_{ss \text{max}}$

Calculate all contacts

Is it ball-facet contact

Get the particle velocity of pointers contact. end1: $v_1$, $v_2$

Calculate $\mu_{ss}$

Run the model

End

Fig. 4 A simple model to verify the accuracy of the program

Input ball $0.1 \text{m}$, surface $0.5 \text{m}$, angle $20^\circ$
Fig. 5 Plot showing the relationship between friction coefficient and speed

Fig. 6 The simulated triaxial test model
Fig. 7 Simulation model of the Xiaomojiu landslide (base terrain from UAV obtained by authors)

Fig. 8 The landslide deformation zone and side view of the landslide (base imagery and terrain from UAV obtained by authors)
Fig. 9 The landslide scar area (base imagery from UAV obtained by authors)

Fig. 10 The upper sliding deformation zone (base imagery from UAV obtained by authors)
Fig. 11 The middle compression deformation zone (base imagery from UAV obtained by authors)

Fig. 12 The slope toe stress concentration zone (base imagery from UAV obtained by authors)
Fig. 13 The deformation characteristics of the Xiaomojiu landslide using InSAR (base imagery from UAV obtained by authors)

Fig. 14 The dynamic process of the Xiaomojiu landslide (a.t=4s b.t=12s c.t=26s d.t=39s e.t=53s f.t=64s, base terrain from UAV obtained by authors)
Fig. 15 The changing characteristics of the friction coefficient during dynamic process (a. t=4s b. t=12s c. t=26s d. t=39s e. t=53s f. t=64s, base terrain from UAV obtained by authors)

Fig. 16 The point velocity of the Xiaomojiu landslide
Fig. 17 The deposition characteristics of the Xiaomojiu landslide (base imagery and terrain from UAV obtained by authors).

Fig. 18 Flood discharge processes for different dam failures at different sites (a, 15% dam failure; b, 25% dam failure; c, 50% dam failure; d, 75% dam failure)
Fig. 19 The different deposition characteristics of the Xiaomojiu landslide with changeable and fixed friction coefficients (base imagery and terrain from UAV obtained by authors).

Fig. 20 Average velocities of different parts of the Xiaomojiu landslide with changeable and fixed friction coefficients.