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The formation and failure process of Yigong landslide in Tibet Plateau

Jun Li[1,*], Ningsheng Chen[2], Yuandi Zhao[1], Weiyu Wang[1], Javed Iqbal Tanoli[3]

[1]*School of Civil Engineering, Sichuan University of Science & Engineering, Zigong, 643000, China*

[2]*Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China*

[3]*Department of Earth Sciences, COMSATS University Islamabad, Abbottabad campus 22060, Pakistan*

*Corresponding author: lijunxiaoyouxiang@163.com

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Abstract: Yigong landslide is located in Zhamunong gully, Yigong Township, Bomi County, Linzhi region in Tibet, the volume of which is $3\times10^8m^3$. Firstly, we analyse the formation mechanism of Yigong landslide in 2000, based on the field investigation and data collection. Secondly, we analyse the failure mechanism of Yigong landslide in 2000, combined with the mechanical test results of granite rock and stability calculation results of slumped mass (BH01). Under the combined effect of rapid incision and seismic activity in Yigong Lake zone, the basic factor of landslide formation is that the rock mass structure for controlled slope rock mass evolution has entered a stage of progressive failure in Zhamunong gully, and precipitating factors of landslide are excess melt-water and continuous rainfall under the temperature rise before landslide hazard happens, according to the results of the study. The formation process of landslide can be divided into 4 stages. (i) Trailing edge fracture of slope rock mass is in rapid development stage due to the effect of fast incision in the valley. (ii) The frequent seismic activities in Yigong Lake district facilitate the development and evolution of granite rock mass's structural plane; (iii) The combined effect of excess melt-water and continuous rainfall at the prophase of the disaster makes the high angle fissure in trailing edge of BH01 rock fall body further develop. (iv) The high-speed rock fall block of BH01 rock fall body triggers the liquefaction of detrital accumulation materials at the source of gully, which forms landslide and finally transforms into high-speed granular mass flows. The stability-losing distruction mechanism of landslide is as follows. Under the combined effect of many conditions, such as fast incision of valley in Yigong district, earthquakes, temperature change, and continuous rainfall and so on, the high angle fissure in trailing edge of BH01 rock fall body develops quickly, and continuous creeping deformation occurs in rock fall body along weak structural plane or fracture surface, forming mid 'locking section'. When the depth of cracking segment in trailing edge of BH01 rock fall body H_{cr} >363m or the length of rock mass's locking section L<455m, sudden brittle failure occurs in the mid locking section of BH01 rock fall body, and rock fall occurs in rock fall body.

1. Introduction

There was a giant landslide disaster (or Yigong landslide) in Zhamunong gully, Yigong town, Bomi county, Linzhi region, Tibet at 20:00:15 on April 9th, 2000 (Delaney and Evans, 2015; Evans and Delaney, 2011; Kang et al., 2017; XuQiang et al., 2012). The whole process included rock fall, landslide, debris flow, dammed lake, and outburst flood, which formed an exceedingly integrated geological chain process (Liu and He, 2018; Wang and Lu, 2002; Yin and Xing, 2012). Approximately 0.91×10^8m^3 granite rock slumped from the peak in the gully at an altitude of 5320m, causing strong power which take about 600×10^4m^3 debris materials depositing in the gully for a nearly century to the mouth of gully. And the loose debris materials blocked the Yigong Zangbo channel, forming the natural dam at an deposition volume of about 3×10^8m^3 which made the Yigong River become a dammed lake simultaneously. The rising speed of the Yigong dammed lake's level was 0.5m/d at the beginning, which reached 2.0m/d in the rainy season, making the volume of lake rising sharply from 7.07×10^8m^3 to 22.59×10^8m^3. The dam body in Zhamunong gully broke down with the strong effect of overflow in June 10th ,2000, forming super-large outburst flood, whose the maximum peak discharge in China was located in the Tongmai Bridge at the speed of 12×10^4m^3/s (Tewari, 2004). The outburst flood broke down some infrastructures in G318, such as the Tongmai Bridge, the Motuo Liberation Bridge, highway and so on, which was along the Yigong Zangbo River and the Parlung Zangbo River in China, making G318 interrupt for 76d. And it cause the direct loss of $ 280 million and 2 people died. According to the report of L'Agence France-Presse, the outburst flood killed 94 people of Lamaputra in the northern India, took the home of 2.5 million, and interrupted the transport connection of 7 states in the central India (Cheng et al., 2009; Liu et al., 2000).

At present, the common perspective for Yigong landslide refers to the high-place landslide, at the source of the debris flow basin, losing its stability and then forming high-speed landslide under the water hammer mechanism of pore water pressure (Jietang, 2002). Affected by strong rainfall and deep V valley, the high-speed landslide is converted to high-speed movement debris flow after moving a distance of 1-2 kilometers (Liu, 2002). So far there have been some achievements on the study of the landslide in Zhamunong gully (Hu et al., 2015; Kang et al., 2017; Mingjian et al., 2009; Zhou et al., 2016), but there still lacks a scientific and unified understanding on the formation mechanism of the landslide in Zhamunong gully, especially the formation mechanism and the stability-losing distruction of the landslide. Some scholars think that the main factor of the landslide in Zhamunong gully is the excessive and repeating melt-water and continuous rainfall in the region (Hu et al., 2015). And some scholars think that the main factor of landslide is related to terrain, structure and climate (Huang, 2003; Kang et al., 2017; Yin, 2013). These study results highlight the influence on Zhamunong gully, including short-term rainfall, temperature change at the beginning of disaster and so on. However, they ignore that the deformation of the landslide in Zhamunong gully is the geological process of long-term development and evolution under certain geological conditions. In other words, they ignore the factors of granite rock's structure plane with the geological evolution, including epigenetic deformation, the aging deformation of creep property and development phase of rock's destruction.

According to field investigation, the stability-losing of the landslide in Zhamunong gully is mainly controlled by granite rock' structure plane. So it is exceedingly necessary to reveal the geological evolution process of the landslide in Zhamunong gully going to final destruction phase, based on which the mutual relationship of landslide's formation process, earthquake and temperature change etc. and the stability-losing destruction of the high-place landslide are further studied. Aiming at scientific questions above, this passage analyzes the formation mechanism and stability-losing destruction of the landslide in Zhamunong gully, based on field investigation, rock mechanical test and the calculation results of the high-place landslide' s stability.

2. Study area

2.1 Geological background

Yigong Township, Zhamunong gully is located on the northwest of the South pangkwa peak and the left bank of Yigong Zangbo (Fig. 1a), whose topography is high in the West and low in the East with alpine landform. Its basin area is 29.4 km^2, and the highest altitude is 5 616.00m, the lowest altitude is 2 185.72m, and the relative height discrepancy is 3 430.28m. It develops a trumpet-shaped packing fan from mountain-pass of downstream to the mouth of gully in Zhamunong gully, which covers an area of 3.4km^2. The slope of Zhamunong gully is comparatively large, which is more than 45° usually. The gully bed's gradient ratio is large as well, and the average gradient ratio of the whole gully is 233‰, the largest is 646‰. The formation lithology of Zhamunong gully in Yigong is comparatively complicated, including the marble and schist of Pre Sinian, the Carboniferous limestone and slate, the Himalayan granite and the Carboniferous slate and variable sandstone from north to south (Fig. 1b). The quaternary loose material and accumulation material distribute widely in the mouth of main gully and the valley in the two sides of gully's bed, mainly including eluvium,flood alluvial,colluvial and the accumulation material of debris flow ect. The Zhamunong gully basin is passed through by three fault zones, which are relatively Jiali Deep Fault Zone (F_1), Dade-Anizha Fault (F_{22}), Danen-Zepu Fault (F_3). The basic structure of the three faults is described as follows. The Jiali Deep Fault Zone (F_1): It consists of two faults, new and old, which are parallel and single. There are a series of pass areas in the landform, distributing in the half-slope of Yigong Zangbo valley. The thick limestone and faulted-shattered zone distribute continuously along the fault zone, whose width can reach 1-2 kilometers. Because of the strong anti-weathering ability of limestone and shattered zone prone to weathering and eroding, strong contrast of landform is formed. Exceedingly fresh and large-scale deformation phenomenon cannot be seen in the neighborhood of the fault zone, and the exact location of the latest activity fault in the valley is unascertained. The entrenched meander, developing in early and middle Quaternary, is not transformed obviously by fault. Dade-Anizha Fault (F_{22}): Across the Yigong lake basin, the fault's trend is about NW60-70°. And its dip is comparatively steep, over 50° generally, tendency SW. The fault extends far in the Yigong lake basin, and its length is over 6km. A faulted-shattered zone distributes continuously along the fault, and its width is generally 10-100m. Across the upstream of Zhamunong gully, Dade-Anizha Fault's hanging wall is granite, while the foot wall is limestone. Controlled by the structure, the granite and limestone are very fragmented. Danen-Zepu Fault (F_3): Extending along the left bank of Zhamunong gully, the fault's trend is about NE 30-35°. And its dip is comparatively steep, over 40° generally. Many landslides are distributed in the fault zone, taking the shape of moniliform, which are mostly retrogressive landslides. Along the fault zone in the Zhamunong gully basin, the formations of granite and limestone appear, from north to south. Affected by the structure, the granite and limestone are comparatively fragmented.

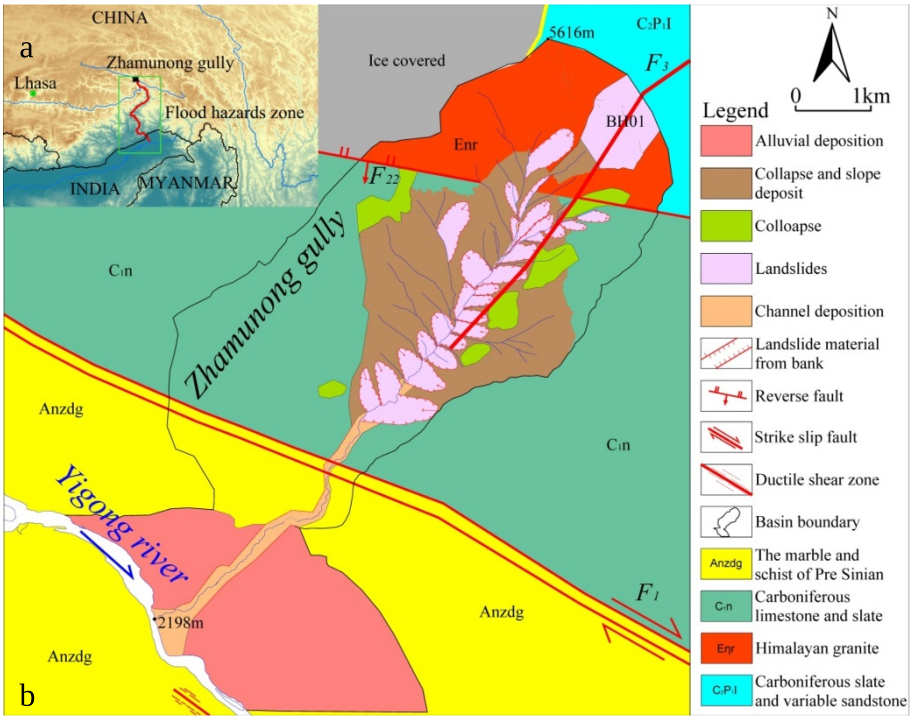

Figure 1: The extension (a) and engineering geological map (b) of Yigong landslide

The district of Yigong, where Zhamunong gully situated in, belongs to block of Nyenchen Tanglha. Its tectonic deformation features in press-thrust and strike-slip. Because of the territorial activities of faults, the district of Yigong, relatively descending, is graben, while Zhamunong gully-Tongmai-Bomi district, relatively ascending, is horst (Fig. 2). Zhamunong gully is located in the compound position, where Jiali Deep Fault Zone and Yigong-Lulang strike-slip fault are intersected with an approximately right angle. At the source of the gully, there is early granite of Himalaya invading, then the gully is influenced by continuous tectonism, especially the composite control action by Jiali Deep Fault Zone, Dade-Anizha Fault, Danen-Zepu Fault, which contributes to the exceedingly developed joint fissure of granite rock in Zhamunong gully. The three mainly large joints are: Joint 1's occurrence is 203∠34º , Joint 2's is 94∠57º , and Joint 3's is 211∠86º (Fig. 3).

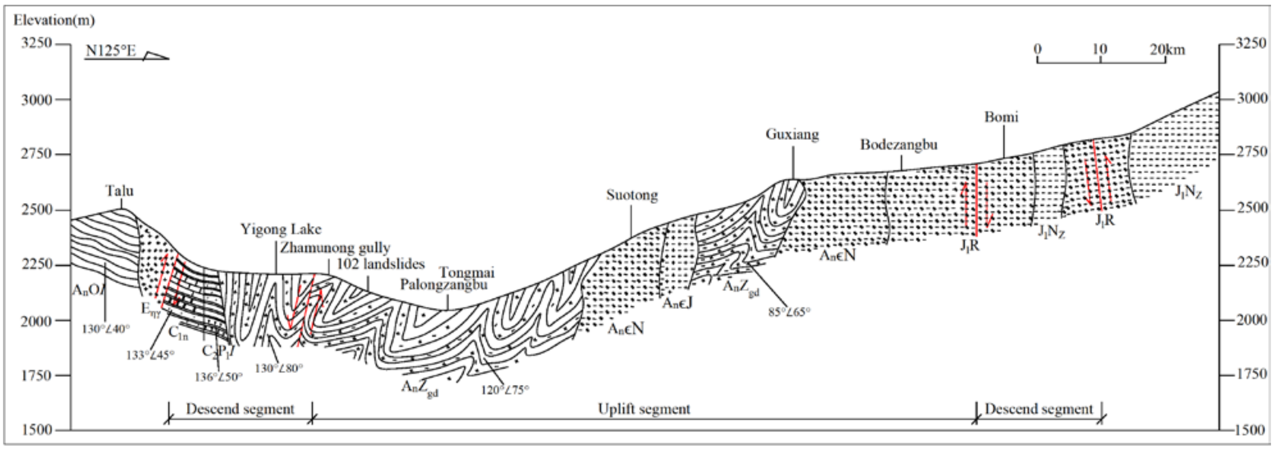

Figure 2: Cross-section of geotectonic profile in Yigong

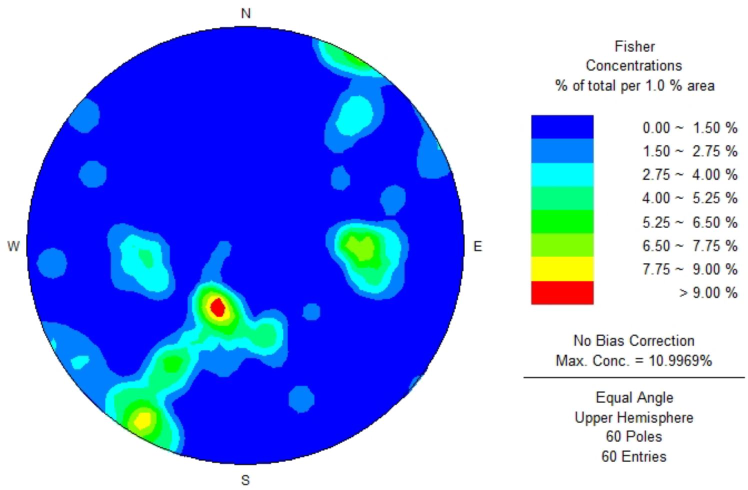

Figure 3: Joints statistic map of Zhamunong gully landslide.

It is dangerous to research granite's joint at the source of Zhamunong gully. Therefore Gongde granite, which is nearest to Zhamunong gully and easy-measured, is selected to do a research on district joint. The location's longitude is E94°43'18.65", latitude is N30°17'48.71", and the distance is 25km from the mouth of Zhamunong gully.

2.2 The movement zone of landslide

According to accumulation features and material movement of different position in the Zhamunong gully landslide disaster, the landslide can be divided into three areas, which are the area of BH01 rock fall, running area of debris flow and accumulation area of debris flow (Fig. 4). The area of BH01 rock fall is located in the source of Zhamunong gully, and about 4500-5320m in altitude, with a height difference of 820m. The rock fall body is wedge-shaped in general, and the bottom structure appearing after rock fall, shapes as V-type hanging valley, which is steep in two walls. And the air face formed newly by the posterior wall of hanging valley is relatively gentle in gradient, 46° on average, inclining from NE to SW. The trailing edge, against peak, is nearly erect steep wall, which is comparatively flat on the surface. Danen-Zepu Fault (F_3) passes through the area of BH01 rock fall, Dade-Anizha Fault (F_{22}) also passes through inferior mountain body in the area of BH01 rock fall (Fig. 5). Affected by the two faults, the rock body's joint fissure, which is in the area of BH01 rock fall, is very developed, mainly developing joint inclining to south. Running area of debris flow is a canyon segment formed from the mouth of Zhamunong gully to landslide, whose length is 3500m and height difference is about 1500m. The two sides of gully's groove are 45-60° in gradient, showing cliffs and steep walls in part. The bottom of gully inclines from NE to SW, in relatively gentle trend. Near the north of groove, the width of valley bottom is around 50m and height 150m, and the width of upper part is around 150m. The south of groove, the width of valley bottom is around 150m, and the width of upper part is around 300m, with a height close to the north. There is lots of early clastic rock fall material. Accumulation area of debris flow is located in deposition fan of Zhamunong gully's primary mouth, and in the two banks of Yigong Zangbo. Accumulation material of debris flow forms a deposition fan body similar to the shape of trumpet, which is 8~10° in gradient on average. Movement material of debris flow accumulates in the mouth of gully, whose front part always reaches Xianglongnongba debris flow deposition fan, which is in the opposite bank of Yigong Zangbo river bed, forming natural dam body and blocking Yigong Zangbo. The largest accumulation width of accumulation body's front part reaches to 2.5km, while the accumulation width of trailing edge is merely 300m. The total length reaches to 4.5km, from the front to trailing edge. The material composition of accumulation body is comparatively complicated, more than 90% of which is granite and merely 10% is metamorphic rock. The diameter of rubble is generally 30cm—50cm. The middle part of accumulation body is rubble accumulation area, 80% of which is over 3m in diameter, the two biggest of which are 42m and 44m in diameter. In the rubble accumulation area, the direction of long axis is completely consistent with movement direction, and diameter of rubble shows gradually decreased trend along the movement direction of debris flow.

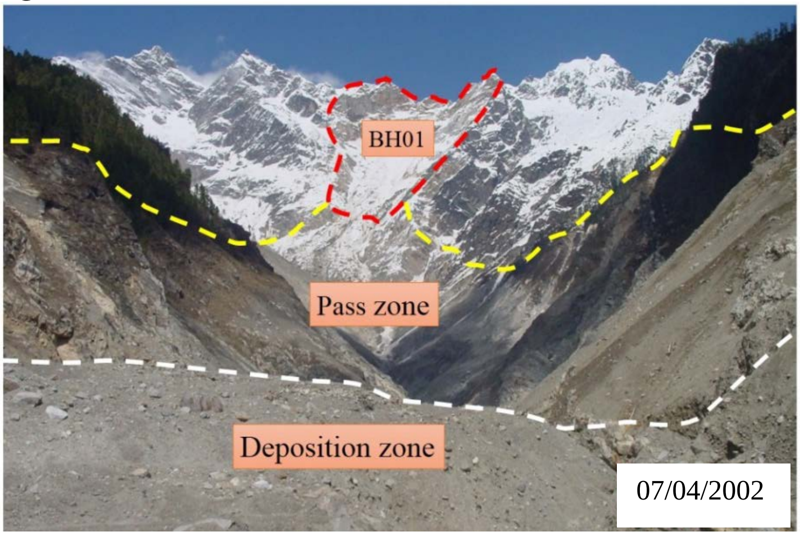

Figure 4: The movement of Yigong landslide in Zhamunong gully

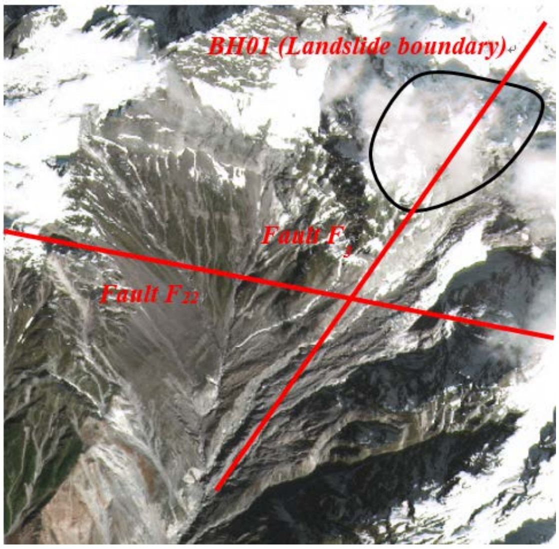

Figure 5: The relative position of BH01 and Fault in Zhamunong gully

3. Dynamic process and failure mechanism of rock mass in Zhamunongong gully

3.1 Dynamic process of rock mass developing in Zhamunongong gully

The landslide in Zhamunongong gully is very special and huge, which causes disasters not only forming a very intact geological disaster chain but also showing dynamic process different from generally great landslide. In 1902, there was a huge landslide in Zhamunongong gully, whose scale reached to $6\times10^8 m^3$. However, during a hundred years, it broke out large-scale landslide, which is obviously unusual. The dynamic process of landslide in 2000 must be very special, and intrinsic and external motive condition must be very active in the region. According to geological data of Yigong district and the results of field investigation, the dynamic process of Zhamunongong gully's landslide in 2000 can be concluded into the three aspects as follows.

3.1.1 The phase of valley quickly cutting driving rock mass to generate deformation and rupture

The development of high slope in natural valley has a feature of three-phase, which are epigenetic reformation, time-dependent deformation and unstable failure. Similarly, the development of landslide in Zhamunongong gully has a typical feature of three-phase. Located in the southeast of Tibetan Plateau, Zhamunongong gully is a front zone of the most violent collision and deformation between Indian plate and Eurasian plate. The uplift rate of Yigong region is10-30mm/a since 1Ma, and the uplift rate is the biggest since 150 thousand years. In the downstream of Parlung Zangbo basin, including Yigong region, the river incision rate is 6.3mm/a (Lang et al., 2013) , 73, 000 years before present. It shows the river incision rate is lower than its uplift rate in Yigong region, and the continuous uplift of mountain body contributes to the increase of absolute elevation in Yigong region, then the gorge of Yigong Zangbo gets deeper and deeper, which lead to the stress release of mountain slope in Zhamunongong gully. The stress release drives slope rock mass to generate deformation and rupture, and its direction of deformation is nearly vertical to air face, trend of rupture parallels to air face. For example, the investigation finds that there is a granite body with a trend of SSW, whose structural plane is comparatively developed and the occurrence of fracture plane is 211º∠86º. Because of the non-tensile property of granite body's structural plane, the slope body in the area of BH01 rock fall rips along the steep fracture(211º∠86º), forming unloading cranny and forming the stability-losing fracture of trailing edge in the area of BH01 rock fall ultimately. With the process of slope's epigenetic reformation led by incision of valley, it generates geometrical boundary condition going against the stability of rock mass's structure in the area of BH01 rock fall, such as fracture of trailing edge, slow-inclined structural plane in the front and so on. This time the stress field of slope in the area of BH01 rock fall is mainly self-weight stress field. Under the drive of mountain body's self-weight, the rock mass can generate continuous loading transformation and time-dependent deformation along the structural plane, especially loading transformation of developed structural plane of slow-inclined angle(203∠34º)in the slope lowering the strength property of slope's structural plane in the area of BH01 rock fall, which provides conditions for the continuing deformation of slope. A scholar point that the stress of outer-side rock mass can decrease and that of inner-side rock mass can rise correspondingly in the valley when the fault is developing in steep dip and coastwise slope. Across the Zhamunongong gully basin, Dade-Anizha Fault (F_{22}) is a thrust fault. Because of the release of fault's stress, the outer-side granite rock mass can generate unstable failure and form a certain air face in the middle part of Zhamunongong gully's mountain body. The formation of air face accelerates the self-weight deformation of rock mass in the area of BH01 rock fall, which results in continuing time-dependent deformation of slope.

3.1.2 Frequent earthquakes facilitate the further development of rock slope

Located in the west-side of tectonic knot, the east-side of Himalaya, Zhamunongong gully, influenced conspicuously by surrounding strong earthquakes, has many seismic activities, occasionally earthquakes of $M_s\geq6.0$. According to recorded information, there were 66 earthquakes in total affecting this region from the year of 1950 to the day of April 9th, 2000, of which affected remarkably were Chayu earthquake of $M_s=8.6$ in 1950 (the intensity in Zhamunongong gully reached to 9°) and Naqudangxiong earthquake of $M_s=8.0$ in 1951 (the intensity in Zhamunongong gully reached to 6°). The Yigong Lake basin, where Zhamunongong gully located in, mainly generates small and moderate earthquakes. From the day of February, 23th, 1950 to the day of April 9th, 2000, 17 earthquakes occurred in the Yigong Lake basin, of which the smallest earthquake magnitude was M_s=4.1 and the biggest was M_s=5.5, with 76.4% earthquakes of M_s=4.5. The frequent earthquakes in this region facilitate the formation of landslide disaster in Yigong. The earthquakes affecting rock slope is reflected on the one hand that the earthquakes can make originally small-scale joint fissure in the slope transfix and form large-scale joint fissure, meanwhile the reflection and refraction of seismic wave at discontinuous medium surface in the rock mass may generate new fissure in the inner rock mass, which further damage the integrity of rock mass's structure. On the other hand, the seismic displacement response of joint-granite's rock slope mainly is in horizontal directional role in the process of granite rock's deformation and failure, and the unstable failure of rock is a result of sudden release of energy in rock. Through field samples, MTS815 Flex Test GT Rock Mechanics Testing System, made in the US, was used indoors for the uniaxial test of field granite rock, by which the elastic modulus of granite in the area of BH01 rock fall was measured to be 9.78GPa, density, tensile strength and Poisson ratio were measured to be 2.63 g/cm^3, 84.93 MPa, and 0.29, respectively. The testing results show that the granite in the area of BH01 rock fall belongs to hard rock. Hard rock has a good condition of storing energy, so frequent earthquakes in the region make the granite in the Zhamunongong gully basin store plenty of the energy of elastic strain. In conclusion, frequent earthquakes in Yigong Lake facilitates inner evolution of rock mass in the area of BH01 rock fall, which makes the rock mass more broken, on the one hand. On the other hand, because of the granite, in the area of BH01 rock fall, has a good property of storing energy, the rock slope in the area of Yigong rock fall can release the huge energy of earthquake storing suddenly to lead to the brittle failure of granite rock when the rock slope goes into a progressive phase of failure.

3.1.3 The increase of temperature and rainfall lead to the rock mass's critical state of stability

According to the information of investigation, there has been intermittent small caving in the gully a year of landslide in Zhamunongong gully occurring before, which shows that the stability state of mountain body in the area of BH01 rock fall has tended from stability to instability gradually and the landslide has gone into final phase of progressive failure. From the change chart of daily average temperature and daily precipitation during March 1st to April 9th in 2000 (Fig. 6), we can see that the temperature rises gradually from March 1st to April 9th, with an average temperature of 5.6℃ from March 1st to April 9th close to annual average temperature; cumulative rainfall of Zhamunongong gully basin is 94.4mm, with daily average rainfall is 2.95mm. The temperature rising gradually and sustained rainfall action facilitate the development of stability-losing failure process of Zhamunongong gully landslide. Firstly, the place with altitude of 4500–5320m in Zhamunongong gully is a congelifraction zone developed by contemporary periglacial geomorphology, with bare bedrock, and the joint fissure of rock develops strongly by strong action of freeze-melting circulation. When the temperature lowers to below 0℃, the water going into the fissure of granite rock can freeze, and the volume of ice enlarging can drive the fissure to expand and deepen. When the temperature rises to above 0℃, the ice in rock fissure can melt, and the rock mass generates pore water pressure, leading the shear strength of rock mass to decrease. Such repeated action makes the fissure in rock mass expand and deepen constantly until becoming the fissure in transfixion level. Secondly, the increase of temperature leads to the acceleration of ice-melting, and melt-water and surface water infiltrate into rock mass's structural plane along the fissure with the increase of rainfall. Especially, when the surface runoff infiltrates into weak intercalation, the rock in weak intercalation is immersed and softened by water for a long time, which lowers the shear strength and friction coefficient between layers. The decrease of granite's mechanical strength can lead to the formation of landslide in Yigong easily. Therefore, the combined effect of excess ice-melting and sustained rainfall, led by the change of temperature for months, facilitates the formation of Zhamunongong gully landslide.

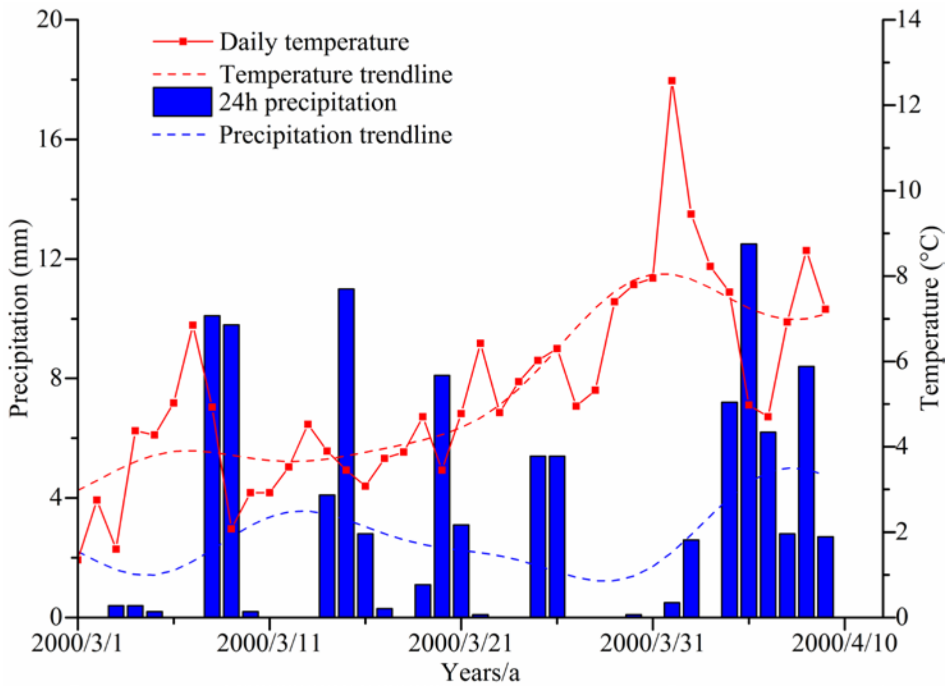

Figure 6: Temperature and precipitation change during 3/1/2000-4/9/2000

3.2 Dynamic process of BH01 rock fall body in Zhamunongong gully

3.2.1 The mechanical parameters of granite rock mass and the analysis of rock fall body's key boundary conditions

Figure 7: The test equipment and the samples of granite

MTS815 Flex Test GT Rock Mechanics Testing System, made in the US, was used for strength testing of field granite rock (Fig. 7). The samples of rock are got by drilling in huge boulder area accumulated by debris flow in downstream of basin, and each specimen Φ50mm with a height of 100mm. The granite rocks, strong weathered, moderately weathered and slightly weathered, are used for rock mechanics testing. There are 12 experiments in total, of which strong weathered granite c=9.69MPa, ϕ=58.27° (Table 1).

Table 1: The testing results of strong weathered granite rock's mechanical parameters under condition of saturated water

Number of sample	Confining pressure	Density/g/cm^3	σ_1-σ_3/MPa	Cohesive Strength c/MPa	Internal friction angle/°	Elastic modulus E/GPa	Poisson ratio μ
3-1	1	2.64	79.04	9.69	58.27	9.78	0.29
3-2	3		102.37				
3-3	5		140.48				
3-4	7		148.88				

Attention: σ_1 in table 1 is the principal compressive stress, σ_3 is the confining pressure, c is the cohesion strength of rock mass, and ϕ is the internal friction angle of rock mass.

3.2.2 The length of critical locking section of BH01 rock fall body

The key of landslide's formation in Zhamunongong gully is that BH01 rock fall body slips along the plane of weakness and generates rock fall. According to standard of Technical Specification for Landslide Control Engineering Design and Construction (DZ0240—2004), the calculation equation for the stability of BH01 rock fall body having high angle fissure in trailing edge is shown as equation (1). Equation (2), (3), (4), (5) are detailed calculation equation of every force in equation (1).

$$F = \frac{F_K}{F_S} = \frac{(W\cos\alpha - Q\sin\alpha - V\sin\alpha - U)\times tg\phi + cL}{W\sin\alpha + Q\cos\alpha + V\cos\alpha} \tag{1}$$

$$V = 0.5\times\gamma_w h_w^{\ 2} \tag{2}$$

$$U = 0.5\times\gamma_w L h_w \tag{3}$$

$$Q = \zeta W \tag{4}$$

$$W = \frac{\rho v g}{L} \tag{5}$$

$$H_{cr} = 0.5763H - 27.0092 \tag{6}$$

In equation (1), F is the stability coefficient of rock fall body, and the rock fall body has already tended to critical stable state, F=1; F_K is the anti-sliding force, KN/m; F_S is the sliding force, KN/m; c is the cohesion force of rock mass in sliding surface of rock fall body, KPA; φ is the internal friction angle of rock mass in sliding surface of avalanche mass, °; L is the length of locking section (the non-perforated length of rock fall body 's fissure surface), m; V is the fissure water pressure, KN/m; U is the uplift pressure along slip surface, KN/m; Q is the earthquake force, KN/m, ζ is the level coefficient of earthquake, divided ranks according to standard of geotechnical exploration and anti-seismic intensity, level earthquake coefficient ζ is valued 0.255; α is the dip of sliding surface, valued 36.5°. W is the self-weight of rock fall body, KN/m; ρ is the density of granite,kg/m^3; v is the volume of rock fall body,m^3; g is the acceleration of gravity, h is the depth of the fissure in trailing edge,m; h_w is the water-filling height, m, valued 0.2h in natural time and 0.3-0.5h when it is rainstorm. According to the information of rainfall, there is heavy rainfall before rock fall, so h_w is valued 0.5h. H_{cr} is the depth of the fissure in rock fall body's trailing edge, m. H is the height of slope from front of rock fall body to the fissure in trailing edge, m. The calculation parameters of BH01 rock fall body's stability are valued as table 2.

Table 2: The value table of calculation parameters of BH01 rock fall body's stability

Parameters(Unit)	Values	Parameters(Unit)	Values
Density of Granite ρ (kg/m^3)	2640	level coefficient of earthquake ζ	0.255
Density of Water γ_w (KN/m^3)	10	Dip of sliding surface α (°)	36.5
Cohesion strength c (KPA)	9690	H_{cr} (m)	363
Internal friction angle φ (°)	46.616	h_w (m)	181.5
H	676m		

Because there is no condition to get granite samples of BH01 rock fall body's structural plane, the choice of mechanical parameters of granite rock mass should consider the transfixion degree of fissure, the filling degree of fissure and the development degree of fissure, reduced according to the reduction requirements of rock mass's mechanical parameters in *Technical Specification for Construction Slope Engineering* (DB50/330-2002). The rock mass is comparatively broken at the source of Zhamunongong gully, so the internal friction angle's reduction factor of BH01 rock fall body's rock mass is valued 0.8, and the internal friction angle of avalanche mass's sliding surface after reduction is 46.616°. When the rock mass in cracking segment of rock fall body's trailing edge cracks to 363m and front locking section transfix, the rock fall body reaches to limit equilibrium state. According to equation (1), when the length of locking section L=455m, the rock fall mass is in the state of critical stability. When the trailing edge and front edge of rock fall body further crack, the length of rock mass's locking section L<455m or the depth of cracking segment in trailing edge H_{cr} >363m, rock falls occurs in BH01 rock fall body.

Table 3: The calculation table of BH01 rock fall body' stability

Stable state	Seismic force Q (KN/m)	Gravity W (KN/m)	Fracture water pressure V(KN/m)	Sliding surface water pressure U(KN/m)	Sliding resistance force F_K (KN/m)	Slippage F_S (KN/m)	Stability coefficient F	L (m)
Critical stability	4077881	15991690	164711	412755	12922659	12922659	1	455

According to rock mechanics test and the calculation results of rock fall body's stability, Under the combined effect of many conditions, such as quick cutting of valley in Yigong district, earthquakes, temperature change, continuous rainfall and so on, the high angle fissure in trailing edge of BH01 rock fall body develops quickly, and continuous creeping deformation occurs in rock fall body along weak structural plane or fracture surface, forming mid 'locking section'. The continuous creeping deformation of avalanche mass leads the rock mass, of high angle fissure in trailing edge and front slow-inclined fracture surface, to further decline its strength. When cracking segment of trailing edge deepens to a certain depth, the stress accumulation of 'locking section' makes granite mass of BH01 rock fall body go into the progressive failure stage. When the depth of cracking segment in trailing edge H_{cr} >363m or the length of rock mass's locking section L<455m, sudden brittle failure occurs in the mid locking section of BH01 rock fall body, and rock fall occurs in rock fall body (Fig. 8). Under the action of gravity, BH01 rock fall body impacting loose detrital material in the gully with huge kinetic energy, which suddenly loses stability. And the loose detrital material can be taken quickly and spade and erode the mountain body in the two sides of gully, and then transform into granular mass flows, under the impact action of huge rock mass's continuous rock fall subsequently.

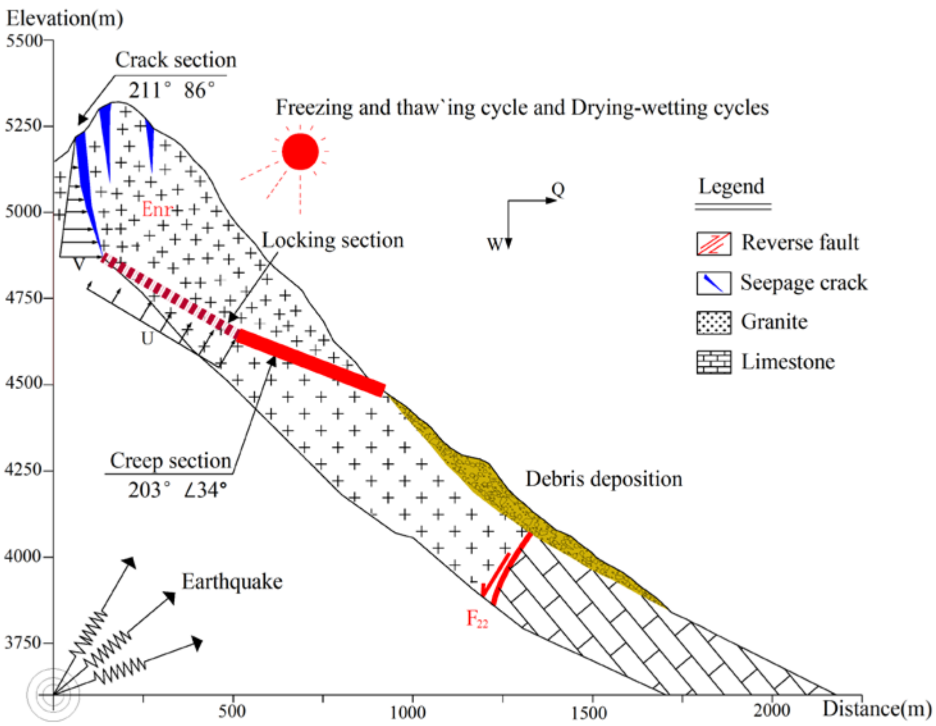

Figure 8: Model of sliding-tension-shearing failure

4. Conclusions

The results of study show that the formation of Zhamunongong gully landslide is the interaction of active intrinsic and external motive in Yigong district. The quick cutting of Yigong Zangbo forms the controlled structural plane of slope rock mass, which develops quickly under the drive of mountain body's self-weight. Across the Zhamunongong gully basin, Dade-Anizha Fault (F_{22}) has a property of thrusting, which makes the mid mountain body of Yigong form an air face and provides terrain condition for the development of Yigong slope. The frequent seismic activities in Yigong district play a developmental and stimulative role in the controlled structural plane of Zhamunongong gully slope rock mass. Finally, under the combined effect of excess melt-water and continuous rainfall at the prophase, sudden brittle failure occurs in BH01 rock fall body of Zhamunongong gully, which causes a series of geological disasters, such as landslide, debris flow, dammed lake, outburst flood and so on. The formation mechanism of Zhamunongong gully landslide can be divided into the four following phases: (i) The quick development phase of slope rock mass's high angle fissure in trailing edge because of the quick cutting of valley; (ii) The frequent seismic activities in Yigong Lake district facilitate the development and evolution of granite rock mass's structural plane in the basin on the one hand, on the other hand, they make creep occurs in the slope rock mass along the structural plane outside the slow-inclined slope; (iii) The combined effect of excess melt-water and continuous rainfall at the prophase of the disaster makes the high angle fissure in trailing edge of BH01 rock fall body further develop; (iv) The high-speed rock fall block, in the area of BH01 rock fall, triggers the liquefaction of detrital accumulation materials at the source of gully, which forms landslide and finally transforms into high-speed granular mass flows influenced by trap topography at the source of gully. The stability-losing distruction mechanism of landslide is as follows. Under the combined effect of many conditions, such as quick cutting of valley in Yigong district, earthquakes, temperature change, and continuous rainfall and so on, the high angle fissure in trailing edge of BH01 rock fall body develops quickly, and continuous creeping deformation occurs in rock fall body along weak structural plane or fracture surface, forming mid 'locking section'. When the depth of cracking segment in trailing edge H_{cr} >363m or the length of rock mass's locking section L<455m, sudden brittle failure occurs in the mid locking section of BH01 rock fall body, and rock fall occurs in rock fall body.

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