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Research paper

A study of control scheme of debris flows and geological disasters in the Shiwei river basin

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Abstract: The basic characteristics of debris flows in the Shiwei river basin are summarized through the field investigation on debris flows in the Shiwei river basin and analysis on formation conditions of debris flows from three aspects, i.e. geological environment, geological structure and neotectonic movement, as well as seismic action. Based on this, the stability of landslide in the Shiwei river basin is analyzed and calculated, and the stability coefficient of landslide is obtained. The debris flows in the Shiwei river basin will directly damage and threaten the county town, while other geological disasters such as landslide, collapse, slope sliding & collapse and potentially unstable slopes will indirectly damage and threaten the county town. The landslide form is clear, and the landslide stability calculation shows that the landslide body is generally stable – basically stable, but partially unstable – less stable. The "blocking + discharging" comprehensive control scheme is proposed according to the formation conditions and development characteristics of debris flows in the Shiwei river basin, and the study findings can be used as a reference for similar projects.

Keywords: Shiwei river, debris flow, landslide, stability calculation, control scheme

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1. Introduction

The Shiwei river runs through the core area of Yunlong County in Yunnan Province, and there are complex geological conditions in the river basin, where the debris flow, landslide, collapse, slope sliding & collapse, potentially unstable slope and other geological disasters are developed due to multiple factors, including regional geological structure, formation lithology, landform, climate, rainfall and earthquake. For the whole county town, the main threat of geological disasters is debris flow of the Shiwei river. At present, many scholars have studied debris flow prevention and control as well as landslide body control, with many achievements. Shen et al. [1] studied a recent rockslide-debris flow in the northern Apennine Mountains in Italy. Ueta et al. [2] investigated particle movement characteristics of debris flow using the numerical method. Romero et al. [3] carried out detailed field mapping and study on geology, gully erosion characteristics and related hail & debris flow accumulation. Dash et al. [4] attempted to divide susceptible area of debris flow of Himalayas in Chamoli District, India. Andrade et al. [5] measured and studied the physical properties of debris flow using seismic apparatus. Yao et al. [6] analyzed the impacts of landform on the movement process of debris flow. Pal et al. [7] developed a sensitive risk model for debris flow movement. Dias et al. [8] investigated and compared the main trigger factors and geomorphic characteristics of two debris flow events in Brazil. Baselt et al. [9] focused on the study of runoff distance, fluidity and inundated area based on the experiment on massive stony debris flow. Kokuryo et al. [10] studied the safety evaluation methods of steel protection structure against massive debris flow.

It can be concluded from the current study status that how to effectively analyze and control debris flow is of great significance [11, 12]. Therefore, taking the control of debris flow disasters in the Shiwei river basin as an example, this paper analyzes the geological conditions and main characteristics of debris flow, calculates the stability of landslide and proposes corresponding control schemes. The results of this study may provide a reference for prevention and control of debris flow disasters.

2. Overview

The total area of debris flow in the Shiwei river basin is 42.03 km^2. The formative region has a catchment area of 36.79 km^2, historical annual average rainfall of 943.8 mm, an elevation of 1710–2490 m and an elevation difference of 780 m. The main gully has a length of 13.08 km, a bed gradient of 25–208‰ and an average gradient of 65.9‰. The moving region has an area of 3.28 km^2 and an elevation of 1662–1710 m. The main gully has a length of 1.37 m and a longitudinal slope of 35‰ at the gully bed, with many bends and river blocks at the upper reach. There is a small amount of supplemental debris along the gully bank. The accumulation region has an area of 1.93 km^2, an altitude of less than 1662 m and a topographical slope of 3–5°. The estimated reserves of loose solid matters are 87.6283 million m^3, in which, 5.979 million m^3 (accounting for 6.82‰ of the total amount) of such matters will be involved in debris flow. The debris flow in the Shiwei river basin is an active extra-large high-frequency micro-viscous debris flow of ravine type, main characteristic parameters of which are: fluid density of debris flow is 1.56 t/m^3; solid matter density is 2.6 t/m^3. The discharge of debris flow in the Shiwei river basin is respectively 147.5, 100.3 and 73.8 m^3/s at a frequency of 2, 5 and 10‰.

3. Geology

3.1. Geological environment

3.1.1. Landform

Located in the longitudinal valley area of Lancang River in western Yunnan, the exploration area belongs to medium-high mountain geomorphology, with north-south Chongshan Mountains, Panshan Mountains, Qingshuilang Mountains from the west to the east, accounting for over 90% of the total area of the whole county. The Bijiang River valley is a north-south longitudinal valley, which is high in the north and low in the south. The Shiwei river basin belongs to medium-high ravine geomorphology, with complex topographical conditions, and is high in the east and low in the west. The main mountain is roughly parallel with the Shiwei river, and in approximately east-west strike. The highest part is the southeast tip of the Zijin Mountain with an altitude of 2,952 m, while the lowest part is at the confluence of the Shiwei river and the Bijiang River with an altitude of 1,625.5 m and the largest relative elevation difference is 1,326.5 m. Located on the depositional fan of debris flow between the Shiwei river and the Suolichang Valley, the town of Yunlong County is threatened by debris flow and landslides for a long time. In summary, the exploration area belongs to medium-high mountain canyon geomorphology characterized by intensive erosion, and is a typical V-shaped steep-slope narrow valley, which is characterized by intensive cutting, extremely developed V-shaped ravines, bank slopes of 30–60° on both banks and local bankslopes of more than 70°. The continuous action of steep slope and intensive undercutting of gully water leads to the gradual unloading, dumping, collapse, surface landslide and other actions of gully bank slope, which provides a provenance for the formation of debris flow. The landform of the Shiwei river basin is shown in Fig. 1.

Fig. 1. Landform of the Shiwei river basin

3.1.2. Formation lithology

The outcropping strata in Yunlong County are respectively Cenozoic Quaternary alluvial, proluvial, debris flow accumulated sandy soil, gravelly soil and clayey soil intercalated with gravel, strata of Tertiary Pliocene Sanying Formation, Eocene Guolang Formation, and Paleocene Yunlong Formation; strata of Mesozoic Cretaceous Jingxing Formation, Nanxin Formation, Hutousi Formation and Jurassic Bazhilu Formation.

The main outcropping strata are Quaternary loose accumulation horizon to upper Jurassic strata. Now, the strata are briefly described from old to new:

Upper Jurassic Bazhilu Formation (J_3b): Mainly distributed in the east of the Shiwei river basin, consisting of purplish-red mudstone and siltstone intercalated with sandstone, easily weathered residue, showing grayish-white and flatly striated striped images on aerial photo, with sparse dendritic drainage pattern and strong roughness on surface.

Lower Cretaceous Jingxing Formation (K_1j): Mainly distributed on the north and south banks of the upper reach of the Shiwei river. Lithology: the lower member is grayish-green, grayish-white fine-grained quartz sandstone, purplish-red mudstone, and siltstone, which have non-uniformly thick, stratified, and intercalated with calcareous conglomerate; the upper member is purplish-red mudstone and silty mudstone intercalated with fine sandstone.

Lower Cretaceous Nanxin Formation (K_1n): Mainly distributed on both sides of Gangouchang Valley Lithology: Medium coarse-grained sandstone, quartz sandstone intercalated with conglomerate, sandy conglomerate and a small amount of mudstone.

Upper Cretaceous Hutousi Formation (K_2h): Mainly distributed between Qingshiyan Valley and Huangsongpo Valley. Lithology: Light gray, brownish-red blocky feldspathic quartz sandstone.

Tertiary Paleocene Yunlong Formation (E_1y): Distributed on the north bank of the Shiwei river, namely Nuodeng Town, Xianglu Village and Heping Village. Lithology: brownish-red calcareous mudstone and siltstone intercalated with bluish-gray & yellowish-gray marlstone and containing salt mud conglomerate and gypsum.

Tertiary Eocene Guolang Formation (E_2g): Close to the gully bottom on the south bank of the Shiwei river, and also intermittently exposed on the north bank of the Shiwei river. Lithology: There are brownish-red calcareous mudstone and siltstone intercalated with fine sandstone at the lower part, and non-uniformly thick interbeds of brownish-red, purplish-red silty mudstone, siltstone and sandstone at the upper part.

Quaternary strata (Q): Mainly distributed in the main channels of the Bijiang River and the Shiwei river, tributary valley sections, floodplains and slopes as well as foothills, and consisting of residual, deluvial, proluvial-alluvial, debris flow-accumulated cobble and gravel, blocky gravel, sand and clayey soil. Most of them are arable farmland, are marked in white and off-white during interpretation, and in patchy and horsetail pattern, with no vegetation and smooth image surface.

The formation lithology is the material basis for the development of geological disasters. The development and distribution of geological disasters are closely related to the distribution of formation lithology, and the lithological characteristics have a great influence on the types of geological disasters developed. The landslides developed in Yunlong County are distributed in the slope zones with developed elluvium-deluvial crushed stones and soil, as well as the slope zones composed of rock masses such as interbeds of thick-bedded sandstone and mudstone.

Brownish-red calcareous mudstone intercalated with thin-bedded sandstone: The mineral components of mudstone are mainly clayey minerals. Structurally, mudstone is argillaceous, while sandstone is sandy, with thin to medium-thick bedded structure. The rock mass is relatively complete, mostly columnar, and short-columnar. The stratum is thick, buried at different depths, and widely distributed.

The rock stratum in the exploration area has an occurrence of 200–225° ∠ 21–50°. Mainly outcropping at the middle & upper parts and both sidewalls of the slope in the exploration area, the rock masses are of medium-thick bedded structure and developed with fractures. The rocks at the upper part are intensively weathered and structured. The fractures of intensively weathered layer of mudstone are very well developed. The intensively weathered layer of bedrock is thick, being generally over 3–5 m thick and up to 10m at most. The sandstone has stronger weathering resistance than the mudstone.

3.2. Geological structure

Seen from tectonic structure, Yunlong County is located in the northern section of structural zone among three rivers (i.e. the Nujiang River, the Lancang and Jinsha River) in western Yunnan. Structurally, the northern margin of Lanping – Simao geotectogene is dominated by faults, followed by developed folds, with an overall structure of SN-NW strike. As a whole, it is an intensive compression-caused fault-fold zone. The deep and large fault zone of the Lancang River runs from the north to the south. The Mesozoic and Cenozoic strata in the area have a general strike of 280–310°, a dip of SW, and a dip angle of 34–50°. Faults are developed, with inter-stratum foldings in some sections. The structure is cut by faults and inter-stratum foldings to be monoclinic stratified type, broken and disordered, with a strike of 280–310° and a dip of SW.

3.3. Neotectonic movement and seismic action

In this area, the crustal movement in later and recent periods is mainly intermittent large-scale uplift. This area belongs to the northern section of structural zone among three rivers in western Yunnan, with intensive late activity and seismicity. The main external forces are denudation and erosion, with weak action of accumulation. Only a small amount of sediments are on both banks of the river, intermountain narrow striped area or flat dam area.

Located near the contact zone between the southeast side of Himalaya mass and Southeast Asia mass, Yunlong area sis overall in the uplift zone, where seismic activities are frequent. The exploration area is located in the northern section of structural zone among three rivers in western Yunnan, namely at the northern margin of Lanping – Simao geotectogene. The structural traces are mainly faults, with underdeveloped folds. The structural line is approximately in SN-NW strike, with intensive compression-caused faults and intensive neotectonic activities. There are frequent seismic activities, with totally 11 violent earthquakes recorded in 476 years from 1514 to 2011. Sensible earthquake occurs every year.

4. Basic characteristics of landslides in the Shiwei river basin and analysis

In the Shiwei river basin, there are totally 71 geological disasters, including 3 debris flows, 8 landslides, 2 collapses, 46 slope slidings & collapses and 12 potentially unstable slopes. In addition, there are 32 gullies developed, 68 artificial side slopes and 16 artificial spoils. Landslide, collapse, slope sliding & collapse, potentially unstable slope and artificial spoil provide material sources for debris flow in the Shiwei river basin. The scouring of heavy rain, flood and debris flow provides a lot of material sources for debris flow, and it is possible to suddenly slide into the Shiwei river, forming blocking debris flow.

4.1. Formation conditions of debris flow

Located on the left bank of the Bijiang River, the Shiwei river runs overall from the east to the west, with a basin area of 42.03 km^2, the highest elevation of 2,952 m, the lowest elevation of 1,625.5 m, an elevation difference of 1,326.5 m. The main gully has a length of 13.08 km, an elevation of 1,627.5–2,490 m, a bed gradient of 25–208‰ and an average gradient of 65.9‰. The ravine is deep & V-shaped, and its flow conditions enable surface water collection in a short time. Its rapid water flow intensively erodes the bank slope, and the gully bed is seriously damaged, especially the slumped mass substances in the provenance area. Seven V-shaped branch gullies are developed mainly on both banks.

According to the ravine shape, the Shiwei river has formation conditions for debris flow. According to the topographical and geomorphic characteristics of the Shiwei river basin, loose sediment exists, so for debris flow, the Shiwei river can be divided into three functional areas, i.e. formative region, moving region and accumulation region. The various functional areas of the Shiwei river are detailed as follows: (1) The section at an elevation of 1710–2490 m is the formative region; (2) The section at an elevation of 1662–1710 m is the moving region; (3) The section from the elevation of less than 1710 m to the bed of the Bijiang River is the accumulation region (Table 1). Various functional areas have quite obvious differences in landform, but the average gradient of river bed is slightly difference.

Table 1. Characteristics of various functional areas of the Shiwei river

Functional area	Gully length (m)	Highest point (m)	Lowest point (m)	Average gradient (‰)	Topographical conditions
Formative region	13080	2490	1710	59.6	V-shaped gully, a slope of 30–50° on both banks and curved gully bed
Moving region	1370	1710	1662	35.0	Wide and gentle U-shaped gully, a slope of 30–50° on both banks, and straight river bed
Accumulation region	1240	1662	1627.5	26.2	Transversal slope of less than 5°

The moving region has an elevation of 1662–1710 m and a total length of 1.37 km. The gully bed has a small longitudinal gradient, which is about 35‰ on average. In this section, the ravine is relatively wide and gentle, and the gully bed is relatively straight. Double V-shaped drainage channels have been built in the transition section between the moving region and the accumulation region (Fig. 2), and bed fixing dam and check dam have been built in the lower middle and lower reaches of the moving region (Fig. 3). The overall geomorphic characteristics of this area are the gentle topographical slope, which is 20–50° on both sides. Quaternary sediments on the slope surface are mainly elluvium-deluvial deposits, alluvial-proluvial deposits of gully and debris flow deposits. Vegetations are dominated by herbaceous plants and planted arbors. The gully bed is about 10–30 m wide, and filled with blocky gravel as well as drift cobble and gravel, which are lithologically sandstones, with an average particle size of 0.3 m and good roundness. Angular – sub-round boulders with a particle size of more than 2 m are occasionally seen. Due to the existing corresponding control measures, the moving region does not have typical characteristics of moving region of debris flow gully, and will not obviously accelerate the debris flow.

(a) (b)

Fig. 2. Shape of ravine in moving region

The particle size of blocky stone on the surface is more than 2000 mm. This blocky gravelly soil layer is about 1.0–5.0 m thick (Table 2).

The catchment area of the Shiwei river basin is 42.03 km^2. The main gully with a ravine bottom elevation of more than 1625.5 m is 13.08 km long, and is a rainy area with a historical annual average rainfall of 1900 mm. The gully bed has a gradient of 25–208‰, which is 65.9‰ on average. The ravine is V-shaped. The debris flow gully bank slope is 30–60°, with dendritic branch gullies developed on both sides of the channel. This area is topographically steep and characterized by outcropping bedrocks. The outcropping strata are dominated by sandstone and mudstone. In this area, there are developed landslides and collapses, intensive human activities and serious water & soil loss. The vegetations are mixed evergreen deciduous broad-leaved forest composed of pine and fir trees, with a covering ratio of 65%. This area is the main water source and provenance supply area for ravine due to rich precipitation recharge, large longitudinal gradient of gully bed, strong scouring and carrying capacity of gully flow, and is beneficial to the drainage of surface water, and increases the kinetic energy of debris flow.

Fig. 3. Existing blocking measures

Table 2. Results of particle size analysis on sediments in provenance area

Sampling gully name		Sample No.	Volume weight of debris flow (KN/m^3)	Composition of soil particle (mm)									
				Stone					Gravel	Sand			Silt
				> 400	150 ~200	100 ~150	50 ~100	20 ~50	2 ~20	0.5 ~2	0.25 ~0.5	0.075 ~0.25	< 0.075
Shiwei river	Tianerjing section	d22	20.2	17.48	10.84	13.84	10.58	15.79	14.39	4.11	3.43	6.51	3.43
		d23	20.1	42.72	7.53	9.52	9.14	12.88	8.71	1.34	1.53	4.79	3.83
		d24	19.8	29.44	16.58	10.98	11.85	10.11	8.97	2.83	2.38	4.01	3.07
		d28	20.8	26.75	15.84	11.04	12.84	10.71	11.87	2.03	1.52	4.31	3.30
		d29	17.1	10.62	10.48	13.27	12.59	19.14	19.18	4.10	2.98	4.84	2.98
		d30	18.9	19.57	15.87	11.37	18.51	14.31	11.38	1.48	2.23	3.96	3.46
	Dajing-Chenjia village section	d4	23.0	32.90	16.67	8.36	8.62	10.22	14.10	3.30	1.51	2.27	2.02
		d5	23.2	21.03	19.15	12.04	14.20	11.48	8.16	2.16	2.64	5.04	4.08
		d6	22.9	21.81	15.44	11.92	14.73	12.95	9.67	1.53	1.78	5.10	5.10
		d7	22.3	21.19	14.55	12.91	11.46	12.92	11.20	3.40	2.30	5.46	4.80
		d8	22.9	16.04	7.59	11.41	13.98	20.30	16.90	3.45	2.41	4.48	3.45
		d9	21.9	21.57	13.05	10.51	10.11	13.02	12.15	4.73	3.03	7.09	4.73

The gully bed section with a ravine bottom elevation of 1,662–1,710 m is 1.37 km long, and the rainfall increases with the altitude. The gully bottom width is 8–10 m, the cutting depth is 300–400 m and the longitudinal slope of gully bed is 35‰. The gully is composed of two branch gullies, with a topographical slope of 25–30° and a ravine bank slope of 35–40°. The two banks are mostly sloping field, making possible quick precipitation afflux, together with many bends and river blocks, so this area is the main area of debris flow-caused flood peak.

The gully bed section with a ravine bottom elevation of less than 1,627.5 m is 1.24 km long. There are arable land or buildings on both banks of this gully section, with decentralized points of flow afflux, and the precipitation in this area has little effect on the formation of debris flow. With a longitudinal slope of 26.2‰, the river bed is a silting-up and hazardous place of debris flow.

4.2. Main characteristics of debris flow

According to the development of depositional fan of debris flow, sediment accumulation, survey and investigation, the debris flow occurs every year in the Shiwei river, with high frequency and large scale. The debris flow is currently active.

The channel in the debris flow formative region of the Shiwei river is mainly downcut, the slumped mass is formed after the foot of surface residual slope is scoured by water flow. The specific slumped masses include different degrees of water & soil erosion, collapse, landslide and local shallow soil sliding. The moving region suffers from scouring and silting, but is dominated by lateral erosion. The accumulation region is mainly silted up, and some sections suffer from lateral erosion and accumulation. As double V-shaped drainage channels have been built, the scouring and silting characteristics are mainly little silting and local scouring. After flowing out from the gully mouth, debris flows are discharged into the Bijiang River. Only a small amount of debris flows carried away by the Bijiang River are silted up in some sections with double V-shaped drainage channels at the gully mouth, with some traces of scouring.

According to the investigation, visit and observed test data from the Institute of Mountain Hazards and Environment (IMHE), Chinese Academy of Sciences, Chengdu, the debris flows in the town of Yunlong County have large flow velocity and bear down menacingly, and blocking occurs occasionally. All debris flows are thin or sand-containing to be slurry with a fluid density of 1.56 t/m^3. With complex composition, the debris flow is composed of mainly coarse sand – cobble and gravel. The mountains in the river basin are broken, with very abundant loose matters. Therefore, the debris flow here is classified as thin type developed in the mountain front ravine, and is currently active.

The velocity, discharge, one-time volume and overall impact force of debris flow as well as the impact force of large boulder are fully demonstrated and calculated through the calculation and analysis of moving characteristics of debris flow. The calculation results are shown in Table 3.

Table 3. Moving characteristics of debris flow in the Shiwei river

Design frequency P	Year	10 years	20 years	50 years	100 years
	(%)	10	5	2	1
Design velocity V_s (m/s)		6.57	7.24	7.69	7.96
Maximum flood discharge Q_P (m^3/s)		70.7	87.3	110.5	128.8
Peak discharge Q_C (m^3/s)		73.8	100.3	147.5	177.0
Overall impact force (tf/m)		8.83	10.59	12.00	12.93
Single impact force (tf)		87.89	96.24	102.47	106.34
Maximum height of surge (m)		2.21	2.65	3.01	3.24
Bend superelevation (m)		0.65	0.77	0.88	0.95
Total volume of one-time debris flow Q ($\times 10^4$ m^3)		59.93	74.70	94.71	110.17
Sediment discharge of one-time debris flow Q_H ($\times 10^4$ m^3)		9.31	12.66	18.61	22.34

4.3. Formation mechanism of debris flow

The formation mechanism of debris flow mainly includes such factors as geology, topography, adverse geological action, rainfall and human activities.

1. Geology
   The work area is located in the fault zone of the Shiwei river, where the geological structure is complex, the lithology mainly shows sandstone and mudstone, the rock masses are broken, the joints and fracture are developed, the weathering is intensive, and the surface is sandy, earthy and easy to suffer water & soil loss. Besides, intensive rise and fall of earth's crust, continuous undercutting of the Shiwei river, as well as easily-caused collapse, landslide and retrogressive erosion provide a large number of loose solid provenances for the formation of debris flow.
2. Topography
   The debris flow gully in the town of Yunlong County is steep in the water source region, formative region and moving region. Rainwater will easily influx into the gully, and the side slope is of poor stability, which may easily cause landslide and collapse and is detrimental to water & soil conservation. The gully bed gradient is 25–208‰ and the average gradient is 65.9‰ , making it difficult for gravel & sand to accumulate and easily causing discharge due to the action of the flood. Such steep topography provides the conditions for the formation of debris flow. Besides, the steep topography on both banks of the riverway, especially many bends, water falls and river blocks in the Shiwei river, makes a barrier lake easily formed in case of landslide and collapse of branches. Lake water bursting will enable the increased scale and hazards of debris flow.

3. Adverse geological action
   Such geological disasters as debris flow, landslide, collapse, slope sliding & collapse, potentially unstable slope, gully, artificial side slope and artificial spoil are developed due to the loose structure and poor stability of soil on the gully bank in this area. In this area, there are 3 debris flows, 8 landslides, 2 collapses, 46 slope slidings & collapses and 12 potentially unstable slopes, 32 gullies, 68 artificial side slopes and 16 artificial spoils. Upon unstability-caused sliding and collapse, these poor geological bodies and accumulation bodies accumulate in gully bed, providing a lot of provenances for debris flow.
4. Rainfall
   Influenced by the warm and humid climate in southwest China, this area is rich in concentrated rainfall, with many high-intensity rainstorms. According to the record, the maximum precipitation in the upper reach of the Shiwei river was 94.7 mm in 24 hours, 15 mm in 10 min and 67.4 mm in 60 min. Such rainfall provides strong hydrodynamic conditions for the formation of debris flow.
5. Human activities
   As the population density in the river basin is high, and the arable land per capita is small, a large number of land reclamation and timber cutting cannot be controlled in order to survive. Such phenomena as artificially changing the direction of water flow, blocking, changing the riverway exist. In addition, due to the gradual expansion of urban construction scale, the wide and straight channel becomes narrower and curved, and the large accumulation region of debris flow is occupied. Meanwhile, a large amount of household garbage is dumped in the gully, so the channel blockage is also the reason for the formation and increase of debris flow.

4.4. Evaluation of debris flow activities

Dynamic changes in the debris flow environment of the Shiwei river can be divided into the following stages:

1. Before 1956, the debris flow environment of the Shiwei river is also very fragile, and the debris flow formative region is topographically steep. There are complex geological structures, broken faults, broken rocks, developed unfavorable phenomena of landslide and collapse, and abundant Quaternary sediment. The large rainfall capacity will easily cause debris flow.
2. In 1994–1996, China conducted scientific research experiments and comprehensive control over debris flow in the Shiwei river basin. According to the actual project operation, various works play their own due roles, which improves the environment of river basin with debris flow to a certain extent and reduces the debris flow hazards.
3. The existing debris flow prevention and control works (e.g. silt arrester and check dam) for the Shiwei river basin have been silted up or partially silted up, some diversion dikes, drainage channels and check dams have been destroyed, some grilled dikes and dams fail to fully play their roles, and the drainage channels are seriously silted up. Existing works cannot continue playing their roles in controlling debris flow activities and such phenomena as landslide, collapse and debris flow occur frequently and are increasingly serious in the Shiwei river basin, so that the environment trends to further deteriorate.

The medium- or small-scale debris flow in the Shiwei river (if any) will afflux into the Bijiang River after flowing out along the existing gully. However, in case of large-scale debris flow, due to the limited cross section of flow of existing gully in the formative region like Xianglu Village and Heping Village, the debris flow will inevitably overflow out of the gully and accumulate on both side the gully, inevitably posing a threat to the safety of residential areas.

According to the topographical and geomorphic characteristics, the influence range of debris flow under different design frequencies shall be predicted. It is considered that the debris flow with a frequency of less than once in 100 years follows the direction of the gully, and the overflowing debris flow flows to the low-lying places on both sides with the gully as the center. The large-scale debris flow with a frequency of once in 100 years will not be limited by the gully, but will flow to the straight place instead of the curved one from the higher place to the lower place. The debris flow will flow directly into the slope diluvial fan on both sides of the gully, posing a threat.

According to the study, the debris flow in the Shiwei river basin is active, possibly causing large-scale debris flow in the future. As the check dam clusters, silt arresters and bed fixing works in the formative region are approaching their design service life and they have been silted up with debris flows, protective measures cannot achieve the desired objectives of protection. If once again the debris flow occurs, debris flow or flood in the formative region is easy to overflow the gully to the residential areas on both sides of the gully to form accumulation, which will directly threaten the safety of life and property of residents in the forest area and Yunlong County. In order to eliminate any threat of the Shiwei river to life and property, proper engineering measures must be taken for the debris flow gully for treatment, so the design frequency of prevention and control works for debris flow in the Shiwei river basin is set as: $P = 3\%$ (once in 30 years).

4.5. Landslide stability evaluation

Guanzhuangdian landslide is large-scale middle-traction partial-displacement soil type. The landslide has a clear boundary and is of large scale. With a slope direction of 258°, a longitudinal length of about 970 m and a transversal width of 780 m, the landslide is overall high in the northeast and low in the southwest from the topographical perspective. The elevation of its front edge close to the bed of Qingshiyan Gully is about 1940–1880 m, and the elevation of its rear edge is 2195–2208 m, with a relative elevation difference of 268–328 m. With an overall direction of 258°, the potential slip mass is mainly composed of loose crushed stones. The total area of the landslide is about 502,000 m^2, the thickness is about 10–25 m, and the volume of slip mass is about 7.53 million m^3, belonging to large-scale middle-traction partial-displacement soil type.

According to the landslide type and slip surface shape, the formulas in reference [13] are used for quantitative evaluation and calculation.

Fig. 4. Partial collapse of front edge of Guanzhuangdian landslide

The stability coefficient shall be calculated according to the following calculation formula:

$$K_f = \frac{\sum_{i=1}^{n-1}\left(((W_i((1-r_U)\cos\alpha_i - A\sin\alpha_i) - R_{Di})\tan\varphi_i + c_i L_i)\prod_{j=i}^{n-1}\psi_j\right) + Rn}{\sum_{i=1}^{n-1}\left((W_i(\sin\alpha_i + A\cos\alpha_i) + T_{Di})\prod_{j=i}^{n-1}\psi_j\right) + Tn} \tag{4.1}$$

where: $Rn = (Wn((1-r_U)\cos\alpha_n - A\sin\alpha_n) - R_{Di})\tan\varphi_n + c_n L_n$; $Tn = Wn(\sin\alpha_n + A\cos\alpha_n) - T_{Dn}$; $\prod_{j=i}^{n-1}\psi_j = \psi_i \cdot \psi_{i+1} \cdot \psi_{i+2} \ldots \cdot \psi_{n-1}$; Ψ_j is transfer coefficient ($j = i$) when the surplus sliding force of the i^{th} block transfers to the $i+1^{\text{th}}$ block, that is $\Psi_j = \cos(\alpha_i - \alpha_{i+1}) - \sin(\alpha_i - \alpha_{i+1})\tan\phi_{i+1}$; T_{Di} is a component of osmotic pressure parallel to the slip surface, that is $T_{Di} = N_{Wi}\sin\beta_i\cos(\alpha_i - \beta_i)$; R_{Di} is a component of osmotic pressure perpendicular to the slip surface, that is $R_{Di} = N_{Wi}\sin\beta_i\sin(\alpha_i - \beta_i)$; N_{Wi} is pore water pressure, that is $N_{Wi} = \gamma_W h_{iW} L_i \cos\alpha_i$; r_U is pore pressure ratio; A is the seismic acceleration (g is the gravitational acceleration); α is the inclination angle of slip surface; β is the groundwater flow direction; L is the length of slip surface; c is the cohesion of slip surface; φ is the internal friction angle of slip surface; ψ is the transfer coefficient; F is the seismic force; hw is the height of groundwater level above the slip surface; γ_w is the volume weight of groundwater. K_f is the landslide stability coefficient.

Landslide thrust shall be calculated by transfer coefficient method, and the formula is as follows:

$$P_i = P_{i-1} \times \psi + K_s \times T_i - R_i \tag{4.2}$$

where: P_i is the thrust of the i^{th} block (kN/m); P_{i-1} is the surplus sliding force of the i^{th} block (kN/m); R_i is the anti-sliding force, that is $R_i = (W_i((1-r_U)\cos\alpha_i - A\sin\alpha_i) - R_{Di})\tan\varphi_i + c_i L_i$; T_i is the sliding force, that is $T_i = W_i(\sin\alpha_i + A\cos\alpha_i) + T_{Di}$; $\Psi = \cos(\alpha_{i-1} - \alpha_i) - \sin(\alpha_{i-1} - \alpha_i)\tan\phi_i$.

Values of anti-sliding safety coefficient in various working conditions: Working condition I: Dead weight, anti-sliding safety coefficient is 1.25; Working condition II: Dead weight + groundwater, anti-sliding safety coefficient is 1.15; Working condition III: Dead weight + rainstorm + groundwater, anti-sliding safety coefficient is 1.10; Working condition IV: Dead weight + earthquake + groundwater, anti-sliding safety coefficient is 1.10;

The natural unit weight is the statistical average of natural unit weight of slip mass in laboratory geotechnical test, equaling to 21.2 kN/m^3; The saturated unit weight is the maximum saturated unit weight of slip mass in laboratory geotechnical test, equaling to 22.5 kN/m^3; They are determined in a combination of empirical data analogy and inversion by the remolded soil shear test of slip zone. $\varphi = 8.5°$ is obtained by reverse calculation in case of $C = 30.5$ kPa. The seismic fortification intensity of the area is Magnitude 7, the design basic earthquake acceleration is 0.10 g and the seismic influence coefficient is 0.05.

The typical section is selected for calculation, results of which are shown in Table 4. According to the stability calculation results, in working condition I, the landslide stability coefficient Fs is 1.04–1.26, indicating that the landslide is stable – basically stable. In working condition III (dead weight + groundwater + rainstorm), the landslide stability coefficient Fs is 0.82–1.04, indicating that the landslide is less stable – unstable. In working condition IV (dead weight + groundwater + earthquake), the landslide stability coefficient Fs is 0.87–1.04, indicating that the landslide is less stable – unstable.

Table 4. Summary of stability calculation results of Guanzhuangdian landslide

Reference section		Working condition	Stability coefficient
1-1′	(H1-1 slip surface)	Working condition I (dead weight)	1.19
		Working condition III (dead weight + rainstorm)	1.01
		Working condition IV (dead weight + earthquake)	1.03
	(H1-2 slip surface)	Working condition I (dead weight)	1.20
		Working condition III (dead weight + rainstorm)	1.01
		Working condition IV (dead weight + earthquake)	1.04
3-3′		Working condition I (dead weight)	1.26
		Working condition III (dead weight + rainstorm)	1.04
		Working condition IV (dead weight + earthquake)	1.02
6-6′		Working condition I (dead weight)	1.05
		Working condition III (dead weight + rainstorm)	0.86
		Working condition IV (dead weight + earthquake)	0.89
7-7′	(H7-1 slip surface)	Working condition I (dead weight)	1.07
		Working condition III (dead weight + rainstorm)	0.82
		Working condition IV (dead weight + earthquake)	0.90
	(H7-2 slip surface)	Working condition I (dead weight)	1.04
		Working condition III (dead weight + rainstorm)	0.86
		Working condition IV (dead weight + earthquake)	0.87

Note: A sliding zone is formed along the contact surface of rock and soil layer, allowing broken line-type sliding.

4.6. Control scheme

The technical scheme for prevention and control is realized by the following three measures:

1. Monitoring measure
   The monitoring and early warning system shall be established and perfected, and special monitoring and early warning personnel shall be provided according to the actual conditions of debris flow in the county planning area. In weather and periods when debris flows are likely to occur, the debris flows in the county planning area shall be subject to all-weather monitoring on duty. Corresponding emergency prevention and control schemes, avoidance and evacuation measures shall be adopted in the early stage for possible debris flow to avoid casualties and property losses. Once the debris flow disaster occurs, remedial measures and schemes for disasters shall be timely implemented, and relevant personnel shall be organized for rescue and disaster relief to prevent the recurrence of debris flow disaster.
2. Vegetation measure
   According to the actual conditions of debris flow gully, the biological measures taken for debris flow include restoration and cultivation of vegetations and maintenance of relatively optimal ecological balance. The biological measures can protect the slopes in the river basin, reduce the slope scouring & erosion and prevent water & soil erosion.
   For the upper middle and upper reaches of debris flow, the scheme of banning grazing and returning farmlands to forests shall be implemented. In the lower middle and lower reaches, the forest and grass species that are suitable for local growing conditions and have developed roots, as well as proper planting methods shall be selected. The afforestation is required for ravine slopes on both sides of the debris flow gully, and it is prohibited to destroy trees and vegetations in the area with debris flow.
3. Engineering measure
   The county town is located on the depositional fan of debris flow accumulation fan at the gully mouth. The loose solid matters of debris flow gully mainly come from the collapse and landslide area above the source. According to such characteristics as high mountain and steep slope in the solid provenance area, wide distribution of provenance and large longitudinal gradient of river beds in moving region and accumulation region, it is advisable to take engineering measures that focus on blocking, supplemented by discharging, in order to prevent and control debris flow.

The blocking works mainly include these two types, i.e. silt arrester and check dam. The silt arrester is arranged in the ravine in the moving region in the upper middle and upper reaches of debris flow gully. Meanwhile, such ravine is characterized by gentle river bed slope, wide cross section landslide and collapse developed and intensive lateral erosion to the gully bank. The check dam is arranged in the section with intensive erosion and downcutting to the debris flow gully. The drainage works adopted are mainly drainage channel and diversion dikes, which are arranged in the urban debris flow gully section to play their roles in supporting and retaining the bank slopes while discharging debris flow.

At present, common methods adopted for debris flow prevention and control works mainly include: (1) Stabilization: Use drainage, blocking and slope protection measures etc. to stabilize loose materials, slide & collapse bodies and slope residual materials; (2) Blockage: Provide check dams or retaining dams in the upper middle and upper reaches to block solid matters carried by debris flow. (3) Drainage: Provide drainage channels in the moving section of debris flow to smoothly discharge debris flows. (4) Stoppage: Provide silt storage yards at the debris flow outlet if possible to avoid blocking the riverway. (5) Closing: Close hillsides to facilitate afforestation and return farmland to forests. Increase the vegetation coverage by afforestation

According to the actual conditions of debris flow in the Shiwei river basin, if the method of stabilization is adopted to control the slumped masses in the formative region. The control methods adopted firstly shall be mainly anti-slide piles. As the slumped masses in the provenance area are located in the section with an altitude of 1710–2490 m in the middle and upper parts of the gully and of large-scale, their control costs are also quite high, and it is possible to completely eliminate the potential risks of debris flow if anti-slide piles are used. Therefore, it is very difficult and hardly feasible to adopt the method of stabilization. As the provenances for debris flow in the Shiwei river basin are mainly sediments formed by slumped masses and the vegetations on both sides of the gully are well developed, the method of "closing" has little effect. In addition, the front edge of accumulation region is the bed & floodplain of the Bijiang River with a width of 100–120 m, and the Bijiang River is capable of carrying away the sediments formed by debris flows of the Shiwei river. Therefore, the debris flows in the Shiwei river basin are controlled by the “blocking + discharging” method.

According to the results of survey on debris flows in the Shiwei river basin, the debris flow prevention and control scheme is proposed based on a further analysis on the ravine characteristics of debris flow gully, activity, hazards, development trends, influencing factors, hazard characteristics and sediment discharge of debris flow gully.

1. Check dam, silt arrester and bed fixing dam: According to the landform of the area with debris flow and provenance distribution, 20 gravity retaining dams shall be built over the debris flow gully and its branch gully, including 1 silt arrester, 6 check dams and 3 bed fixing dams for the Shiwei river, 5 check dams for Gangouchang Valley, namely a branch gully of the Shiwei river, 2 check dams respectively for Qingshiyan Valley and Zhuangshang Valley, and 1 check dam for Donghuage Valley, in order to block large bounders in the debris flow downstream of the gravity retaining dam and protect engineering measures downstream of the gravity retaining dam from being impacted by such large boulders. In addition, the purposes are to reduce hydrodynamic conditions of debris flow and the fluid density of debris flow is reduced, adjust the peak discharging capacity of debris flow and the total volume of solid matters, and weaken & adjust the debris flow.
2. Dike dam: An about 3861m long dike shall be reinforced or built in the section of the Shiwei river from Gangouchang Village to Shanjing Village. The debris flows will be discharged into the floodplain and river bed upstream of the Bijiang River, and straight wing walls shall be provided at the inlet and outlet of dike dam.

5. Conclusions

This paper studies the control of geological disasters of debris flow in the Shiwei river basin and draws the following conclusions:

1. In the Shiwei river basin, there are totally 71 geological disasters, including 3 debris flows, 8 landslides, 2 collapses, 46 slope slidings & collapses and 12 potentially unstable slopes. In addition, there are 32 gullies developed, 68 artificial side slopes and 16 artificial spoils. Landslide, collapse, slope sliding & collapse, potentially unstable slope and artificial spoil provide material sources for debris flow in the Shiwei river basin. The scouring of heavy rain, flood and debris flow provides a lot of material sources for debris flow, and it is possible to suddenly slide into the Shiwei river, forming blocking debris flow. The debris flows in the Shiwei river basin will directly damage and threaten the county town, while other geological disasters such as landslide, collapse, slope sliding & collapse and potentially unstable slopes will indirectly damage and threaten the county town.
2. The landslide form is clear, and the landslide stability calculation shows that the landslide body is generally stable – basically stable, but partially unstable – less stable. Especially, there is large deformation at the front edge of landslide and many water points in the rainy season, causing free faces to some extent. Several cracks are developed in residential buildings at the rear edge. The loose soil structure causes sliding at the front edge in the rainy season, while the rear edge suffers from creep deformation. The landslide body is partially less stable – unstable.
3. As the provenances for debris flow in the Shiwei river basin are mainly sediments formed by slumped masses and the vegetations on both sides of the gully are well developed, the method of "closing" has little effect. Based on the analysis, the "blocking + discharging" method is proposed for comprehensive control of the debris flows in the Shiwei river basin.

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