

Correlation between incompetent beds and slope deformation at Badong town in the Three Gorges reservoir, China

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Abstract Badong town is a new immigration area in the Three Gorges reservoir, China, which is built on many giant deep-seated landslides. In this region, the slope deformation is very severe and it is strongly correlated with the incompetent beds, which are distributed widely in the rock mass. In this paper, two giant deep-seated translational rock landslides used as study cases are Huangtupo landslide and Zhaoshuling landslide. Firstly, the composition materials, structures and deformation characteristics of the two landslides are analyzed. Then, the position, structure, mineral composition and the formation mechanism of the incompetent beds are studied in detail. Finally, based on the comparison of the position, mineral and structure between incompetent beds and sliding zones of the landslides, the correlations between incompetent beds and giant landslide are discussed. The results indicate that 13 large incompetent beds exist in the middle Triassic Badong Formation strata, which can be divided into three types as weak interlayers, crushed beds and groundwater corrosion

zones. The dominant minerals in the incompetent beds are illite, chlorite, quartz and calcite. The contents of the clay minerals in different positions are quite distinct, and the maximum difference of clay content exceeds 70 %. In addition, it is found that the contents of minerals in incompetent beds are similar to the slide zones of the landslides. The initial deformation of slopes normally developed along the incompetent beds, which induced subsequent shear displacement easily. Under the effect of gravity, the deep slip zones were generated mainly along the incompetent beds and the failure mode evolved from creep to integral slide gradually. The results can provide an important reference for the mechanism analysis and prevention of landslides in Badong town.

Keywords Incompetent beds · Slope deformation · Deep-seated translational rock landslides · Marl

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Introduction

Badong town is a new immigration residential area in the Three Gorges reservoir on the south side of the Yangtze River, and it is seriously affected by slope deformation. Many giant deep-seated translational rock landslides are located in this area, such as the Huangtupo, Zhaoshuling and Tongjiaping landslides. For preventing landslide disasters from destroying human beings and contractures in the area, it is mandatory to study the mechanisms of these slope failures.

Deep-seated slope deformation (generally with depths of >10 m) is very common in most mountain ranges (Crosta 1996; Agliardi et al. 2001; Tibaldi et al. 2004; Turconi et al. 2010), and the deformation is closely related to regional tectonics and lithology (Cadoppi et al. 2007; Bois et al. 2008; Chigira 2009). In general, special geological

conditions can be found in these areas, e.g., uniformly dipping beds, intersecting faults, clay-rich beds or steep terrain (Pellegrino and Prestininzi 2007; Hradecky and Panek 2008; Wang et al. 2008). For instance, Pellegrino and Prestininzi (2007) have indicated that numerous deep-seated gravitational slope failures occurred on the slopes of Mt. Granieri-Salincriti (Calabria, Italy), and they are related to deep geochemical processes, inducing intense chemical weathering along the thermal–metamorphic contact belt. In addition, Wang et al. (2008) has investigated the failure mechanisms of the Qianjiangping landslide in the Three Gorges reservoir, China. The landslide is reactivated along pre-existing sheared bedding planes, and the rapid movement is caused by a black silt layer within the sliding zone.

In Badong town, most of the bank slopes consist of uniform dipping beds that have alternating soft and hard lithology with multiple layers of incompetent beds. Those incompetent beds generate shear deformation easily, where the sliding surfaces have formed due to tectonic activity and induced giant landslides. The slope is bounded by the Badong fault and Yangtze River with the fan shape in Badong town. The slope has similar outline with some landslides, e.g., Vajont landslide, and has several giant deep-seated landslides. The generation of the fan-shaped slope and giant deep-seated landslides in this region is a research hotspot and various attempts have been made to study these. Many researchers proposed that joints, schistosity and bedding slip zones related to tectonic activity are the main factors that result in the slope failures. For instance, Chai and Yin (2009) noted that the slopes can be classified into different rock mass structures based on the density of bedding, joints and schistosity generated by tectonics, and the deformation of the rock mass is mainly generated on these discontinuities. Some researchers have studied the formation of the fan-shaped slope of Badong town and put forward a “argument of gravity formation”, which proposed that the giant deep-seated landslides are the results of slope gravity deformation when the Yangtze River valley is being cut and unloaded (Liu et al. 2006). Giant deep-seated landslides have been observed by Deng et al. (2000) and Tang et al. (2002). Tang et al. (2002) have proposed that the Zhaoshuling landslide is a translational rock landslide that slid along a bedding plane within the middle Triassic Badong Formation.

In this paper, it is proposed that incompetent beds are distributed widely in strata at Badong town. Two giant deep-seated translational rock landslides, Huangtupo landslide and Zhaoshuling landslide, are analyzed, including their structure and genesis. In addition, the characteristics of incompetent beds are presented, i.e., position, mineral composition, deformation structures and source. Finally, the correlation between incompetent beds and slope deformations is discussed.

Geological setting

Badong town, located on the south shore of the Yangtze River, is the transition area between the Xiling Gorge and Wu Gorge (Fig. 1a). The town is divided into five districts by several gullies: Xirangpo, Yuntuo, Baitupo, Daping and Huangtupo. The topography of study area is composed of gorge and moderate-low mountain. The Yangtze River valley bends from NE42° to SE136° (Fig. 1b).

The study area is affected by the folds striking E–W and several faults striking E–W, S–N, NW–SE and NE–SW. The Guandukou syncline and Badong fault striking E–W control the tectonic framework and geomorphologic character of Badong town. The Guandukou syncline contains multiple secondary folds that are mainly asymmetric and box folds. Badong fault is the back boundary of the fan-shaped slope in Badong town. Besides the Badong fault, the F2 fault and F3 fault are the main E–W striking faults. The E–W striking faults are formed at the same time with the E–W striking folds. The S–N striking faults form the boundary of landslides such as the Zhaoshuling landslide (Fig. 1c).

The slopes of study area are made up of middle Triassic Badong Formation (T2b). The strata can be divided into five sections. Microcrystalline dolomite with karst breccia, shale and thin layered marlite are the main lithologies of the first section (T2b¹). The second and fourth sections (T2b² and T2b⁴) consist mainly of argillaceous siltstone, calcareous or gray mudstone and silty mudstone. Argillaceous limestone and marlstone are the main lithologies of the third section (T2b³). Laminations of microcrystalline and argillaceous dolomite form the main lithology of the fifth section (T2b⁵). The T2b² and T2b³ strata are widely distributed in the bank slope from Xirangpo to Huangtupo. T2b³ is the major stratum affected by slope deformation and giant deep-seated landslides (Fig. 1c).

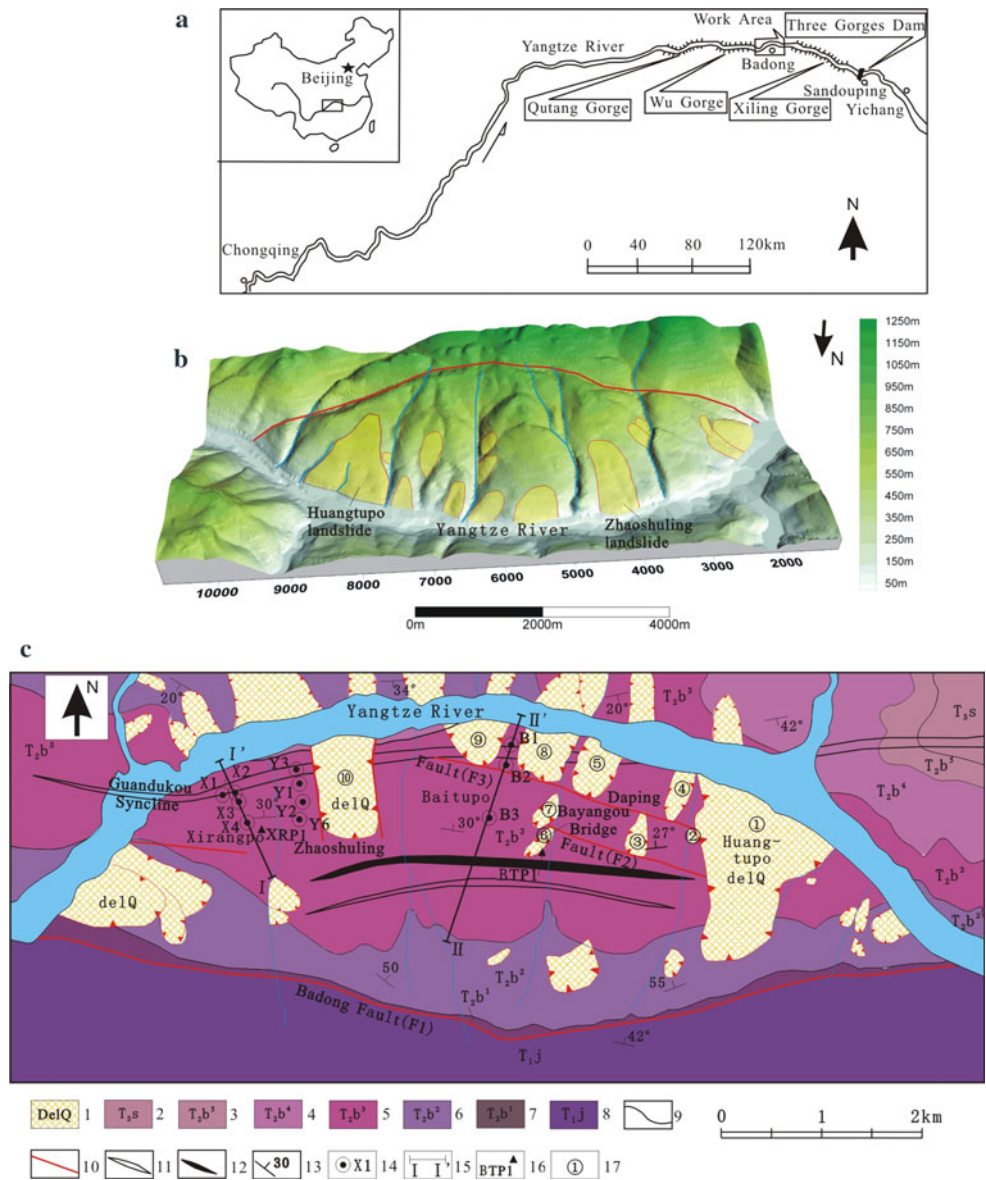
Methods

To analyze the relationship between the incompetent beds and slope deformation at Badong town, it is necessary to search out the rock mass structure, tectonic stress, and landslides deformation mechanisms. The study methods are listed as follows:

Firstly, the composition materials, structures and deformation characters of two giant deep-seated landslides (Huangtupo landslide and Zhaoshuling landslide) are analyzed with the available data obtained from ground survey and drilling (Fig. 1c). The schematic diagrams of the structure of the landslides are drawn, and the main deformational position and sliding surface are analyzed as well.

Secondly, the position of incompetent beds in the strata and deformation structures are analyzed based on the surface surveying and the drilling of monitoring profiles. The mineral

Fig. 1 **a** Location of study area in Three Gorges reservoir, China. **b** Topography and landslides location in Badong town. **c** Engineering geological graph of Badong town: 1, debris of landslide; 2, upper Triassic Shazhenxi Formation; 3, fifth segment of middle Triassic Badong Formation; 4, fourth segment of middle Triassic Badong Formation; 5, Third segment of middle Triassic Badong Formation; 6, second segment of middle Triassic Badong Formation; 7, first segment of middle Triassic Badong Formation; 8, lower Triassic Jialingjiang Formation; 9, stratigraphic boundary; 10, fault; 11, syncline; 12, anticline; 13, attitude of strata; 14, borehole and number; 15, geological profile; 16, observation point of incompetent beds; 17, number of landslide: ① Huangtupo landslide, ② Yanwanqiao landslide, ③ Liangshuixi landslide, ④ Dongjialiangzi landslide, ⑤ Hongshibao landslide, ⑥ Baiyangou qiaoxi I landslide, ⑦ Huaping landslide, ⑧ Tanjiaping landslide, ⑨ Zhafangping landslide, ⑩ Zhaoshuling landslide



composition of the incompetent beds is determined by X-ray diffraction (XRD). Formation mechanism of incompetent beds is discussed by analyzing the tectonic history.

Finally, the correlation between incompetent beds and slope deformations is studied by comparing the position, mineral and structures of incompetent beds and slip surfaces. Then, the failure processes of two study cases in Badong town are discussed.

The structures of giant deep-seated landslides

Huangtupo landslide

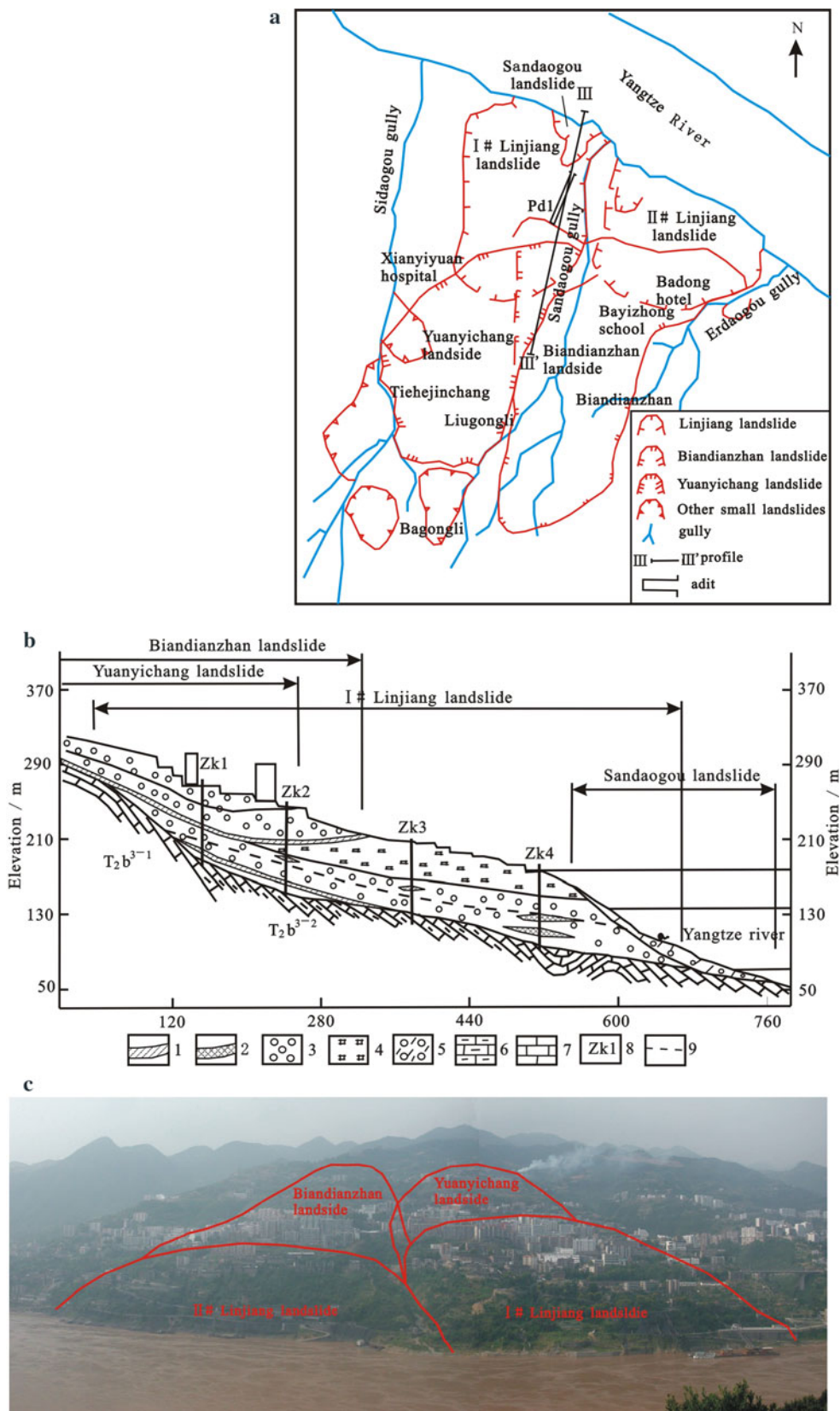
Huangtupo landslide is the largest landslide in Badong town. The landslide is bounded by Sidaogou gully and

Erdaogou gully, extending between 80 and 640 masl in elevation with the volume of $6,934 \times 10^4 \text{ m}^3$. The landslide can be divided into four parts: Yuanyichang landslide, Biandianzhan landslide, and I# and II# Linjiang landslides (Fig. 2a).

Yuanyichang landslide lies between Sandaogou gully and Sidaogou gully. The elevation of its toe ranges from 220 to 240 m and the top elevation is 640 m (Fig. 2a). The sliding mass is composed of gravel soil and blocks, which are the debris of T_{2b}² and T_{2b}³ strata. Basically, this landslide is a translational rock landslide; however, the deformation mode and speed of different parts are quite different, which cause the complexity of the sliding mass material.

Biandianzhan landslide extends between 180 and 600 m in elevation, whose bottom and top are located near the

Fig. 2 **a** Distribution graph of Huangtupo landslide.
b Geological profile of I# Linjiang landslide: 1, slip zone; 2, weak layer; 3, blocky rock; 4, disintegrated rock; 5, gravel soil; 6, marl; 7, limestone; 8, borehole; 9, groundwater level.
c Panoramic view of Huangtupo landslide



Badong Hotel and Bagongli separately (Fig. 2a). It has a width of approximately 0.65–1.00 km, from the western edge nearby Liugongli to the eastern edge along Erdaogou. The upper sliding mass is made up of debris from T2b² strata and the lower part is the debris from T2b³ strata. This landslide has two sliding zones: the upper sliding zone is composed of brown red silty clay and gravel soil, while the lower one is composed of weathered rock or residual deposits of T2b³.

The I# and II# Linjiang landslides are located between Erdaogou gully and Sidaogou gully, the top elevation is between 250 and 260 m and the front edge is lower than 80 m, under the water level of the Yangtze River (Fig. 2a). Both landslides are made up of gravel soil, silty clay, blocky rock and disintegrated rock derived from T2b³ strata (Fig. 2b). The #I and #II Linjiang landslides are located in the lower part of entire Huangtupo landslide area, covered by the front edge of Biandianzhan and Yuanyichang landslides (Fig. 2c). Based on the material of sliding mass, superposition relationship and characteristics of the slide zones, it is observed that the Huangtupo landslide has experienced complicated deformation processes (Deng and Wang 2005). The failure can be divided into two stages. In the earlier stage, the Linjiang landslides were formed under gravity when the bank slope of the Yangtze River was being cut and unloaded. The failure mode is rotating and creeping, and the process is slow. Their rock mass becomes disturbed mass and the shear strength decays before failure. In the later stage, the upper slope slid along a soft interlayer and formed the Yuanyichang and Biandianzhan landslides. Because of the sufficient earlier failure and the lost of basal resistance, the sliding process is relatively rapid (Wu et al. 2006).

The Linjiang landslides play a key role for the stability of Huangtupo landslide and have a complicated structure (Fig. 2b). The sliding mass is almost completely remolded and consists of gravel soil, silty clay, and disintegrated rock. Gravel and rock block are mostly marlite and argillaceous limestone. Based on the statistical data, there are about 114 layers of discontinuous weak layers distributed in Linjiang landslides. The sliding surface of landslide is developed along a relative continuous weak layer consisting of clay and gravel soil.

Zhaoshuling landslide

Zhaoshuling landslide has an area of 1,500 m × 600 m with the volume of 5,000 × 10⁴ m³. The top of landslide located at the elevation of 596 m and the toe formed at the elevation of 65–100 m. Both of the lateral boundaries are controlled by S–N striking faults with different topographies, the eastern one is a small gully and is difficult to identify as Fig. 3a shows (Li et al. 1996).

Zhaoshuling landslide is a planar slide along the interface of T2b² and T2b³ strata (Tang et al. 2002). The material of the sliding mass is mainly derived from T2b³ with a small part from T2b², which can be divided into three types: the sliding rock mass, the block–stone mixture of clay and gravel soil. This landslide has multi-sliding surfaces that can reflect different deformation periods of the T2b³ rock mass. These sliding surfaces are composed of khaki disintegrated rock and clay. The main and lowest one is composed of gravelly clay with a thickness of 0.3–0.5 m, located close to the interface of T2b² and T2b³, which is undulating and controlled by topography and stratum. The bedrock of landslide is unaltered and intact rock mass, except for several tens of centimeters of crushed rock mass just under the main slip zone (Fig. 3b).

Slope composed T2b³ is easy to deform due to the valley cutting and softening process by groundwater. These deformations are usually developed with multi-stage and are generated slow like Huangtupo landslide and Zhaoshuling landslide, whose deformations are closely correlated with incompetent beds.

Properties and distribution of incompetent beds

Distribution and types of incompetent beds

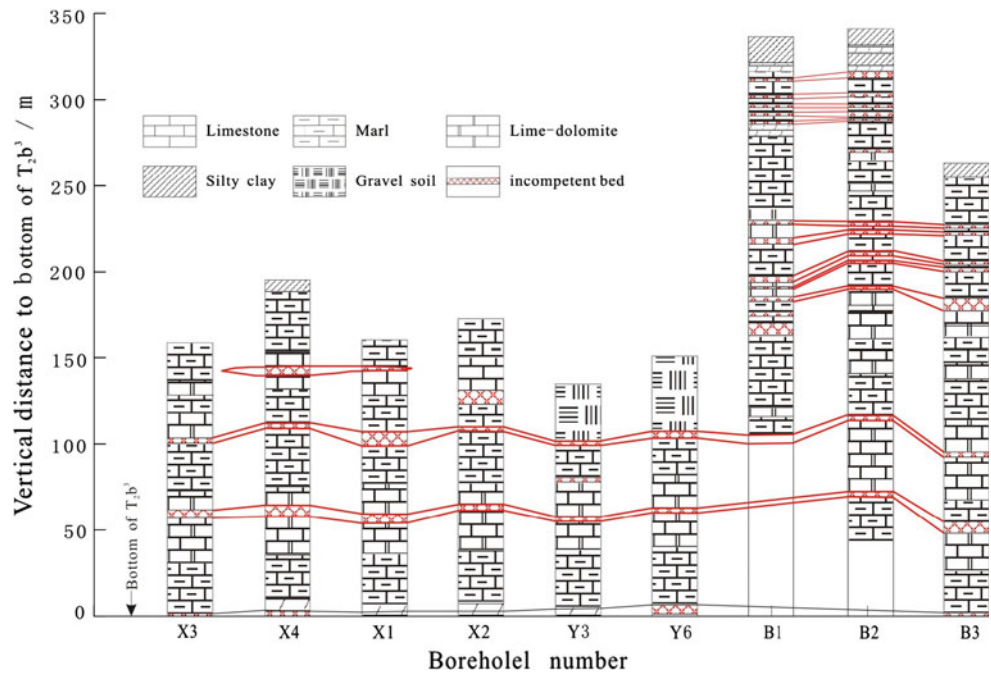
Based on borehole data, the stratum histograms of T2b³ are drawn to analyze the distribution of incompetent beds (Fig. 4). As Fig. 4 shows, there are 13 layer incompetent beds in T2b³ at Badong town, if the interface of T2b² and T2b³ is regarded as a datum-plane. Most of the incompetent beds are distributed at the interface between different lithology or in soft interlayers of marlite stratum. According to content and structure characteristics, they can be classified into three types (Chai et al. 2009). The details are presented as follows.

Type1: clay interlayer

The main mineral composition is clay with the proportion of more than 50 %, i.e., illite and chlorite. The clay interlayer has low strength and weak expansibility. It is easily to be weathered and eroded, which would form a groove or cavity if it is exposed above the ground surface, or present as a muddy interlayer if it is underground (Fig. 5a).

The clay interlayer is usually softer than the surrounding rocks, which is easy to cause interformational sliding under tectonic stress. Due to this kind of sliding, the stratum in clay interlayer presents dislocation deformation from the interface between the interlayer and the surrounding rock. There are two kinds of dislocation deformation: the first mode represents bedding schistosity caused by sliding

Fig. 4 Combined borehole histogram and incompetent beds distribution



gully. The gravel soil situated on both sides of the crushed bed presents orientation arrange ③. The stria caused by shear deformation can be found on the surface of crushed bed (Fig. 5e). The layer beneath the gravel soil is thick silty marl ①, the above layer ④ is disintegrated rock, which is loosely arranged and has lost the original structure. Layer ⑤ is thin marl and ⑥ is microcrystalline argillaceous limestone, with stria caused by interformational sliding. Layer ⑦ is thin microcrystalline argillaceous limestone, which developed a set of joints with high density as ⑤ and the rock is fractured. Layer ⑧ shows dense fracture plane with the shape of “S”. Layer ⑨ is thick microcrystalline argillaceous limestone incised by two groups of joints and presents blocky structure. Many bedding shear sliding zones developed in this section and the combined effects cause the formation of fracture zone.

Type3: groundwater corrosion zone

Groundwater corrosion zones are often discontinuous. The main lithology is marlite with both characteristics of corrosion and weathering. The corrosion generated in the surfaces of layers, joints and fractures causes the formation of discontinuous argillaceous bands.

Mineral of incompetent beds and slip zones

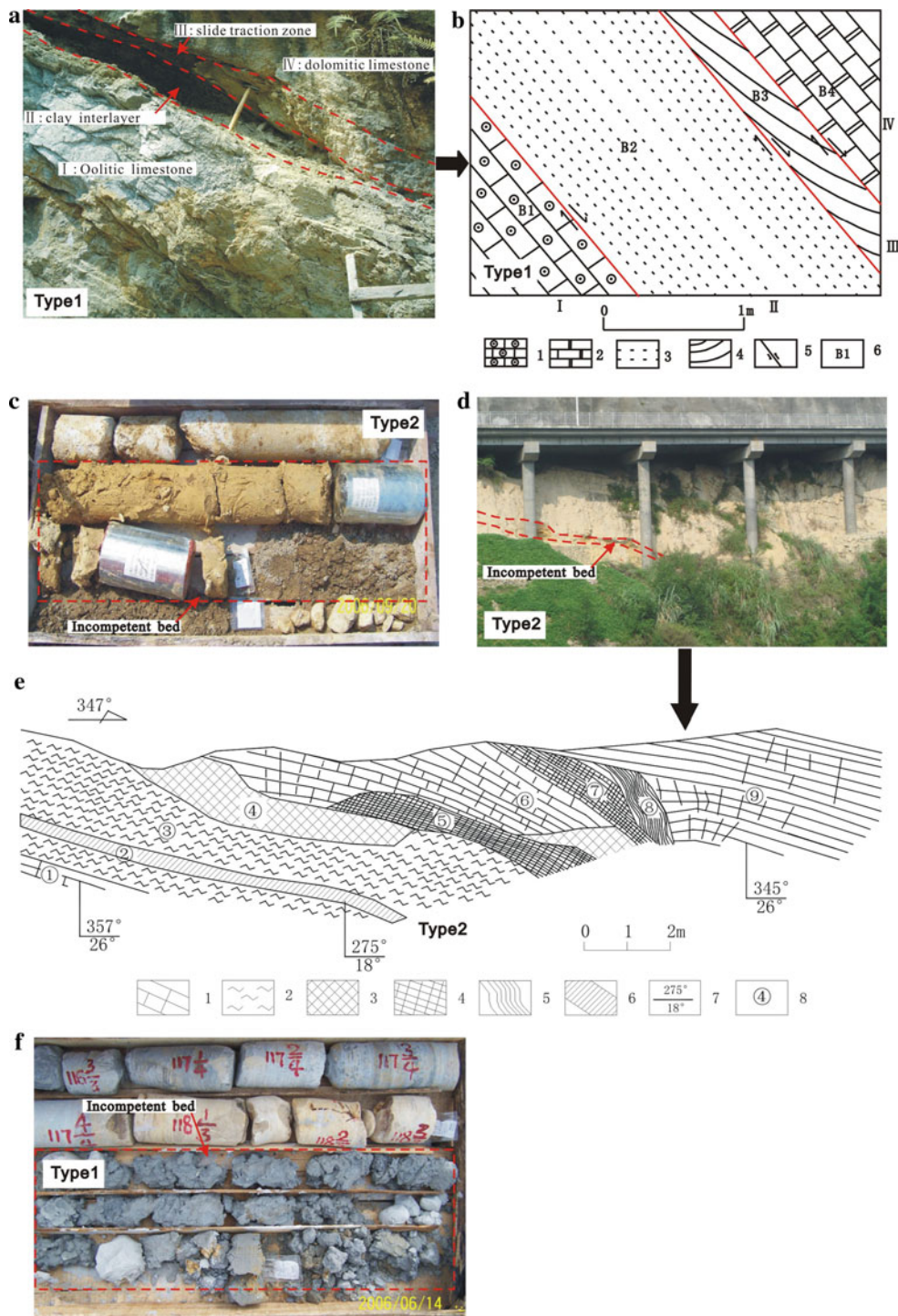
The mineral composition of incompetent beds is tested by XRD. The experiment used the diffractometer of X’Pert PRO DY2198, in the testing center of China University of Geosciences.

The mineral composition and relative content of incompetent beds are shown in Table 1. The results indicated that two kinds of mineral compositions typically are found in the incompetent beds; the details are presented as follows:

- (i) Clay mineral is the main component with the content of more than 50 %. At the observation point of BTP1, mineral compositions of incompetent beds are chlorite (50 %), illite (20 %), quartz (15 %) and calcite (15 %). This kind of mineral composition often indicates the clay interlayer of calcareous mudstone (Fig. 1a, ESM only).
- (ii) Carbonate mineral is another kind of main mineral. Those incompetent beds have similar mineral composition with marlite of T2b³, but it suffers tectonic fracture. Mineral compositions of incompetent beds are montmorillonite (15 %), illite (5 %), quartz (10 %) and calcite (70 %), at observation point of BTP2 (at the south of Baiyangou bridge 50 m; Fig. 1b, ESM only). Chlorite and illite are the main clay mineral of original T2b³. The difference of clay minerals between incompetent beds and original stratum indicated that illite transits to montmorillonite gradually under long-term action of groundwater (Chai et al. 2010).

The data of XRD analysis of rock samples in I# Linjiang landslide is shown in Table 2. It is observed that materials of both the slide zones and the host materials are mainly composed of quartz, calcite and clay minerals. The slide zone has the greatest abundance of clay minerals, the least abundance of calcite, and relatively lower quartz content compared with the host materials (Wen and Chen 2007). In

Fig. 5 **a** clay interlayer at the south of Baiyangou bridge 100 m (number: BTP1) **b** structure sketch map of BTP: 1, Oolitic limestone; 2, dolomitic limestone; 3, bedding cleavage; 4, cutting bed cleavage; 5, slip surface; 6, sampling point. **c** cataclasite in borehole with long-term groundwater corrosion. **d** catalasite soft-weak zone and its effect area at Huangjiadagou (number: XRP-1). **e** structure sketch map of XRP-1: 1, layered and block rock mass; 2, gravel soil with directional arrangement; 3, cataclasite; 4, cataclasite with thin layer; 5, rumple; 6, soft-weak zone; 7, attitude of rocks; 8, number of rock mass structure. **f** clay-rich marlite in borehole



addition, it is found that the mineral contents of slide zones are similar with clay interlayer.

Mechanical properties of incompetent beds

The gradation test and direct shear tests are used to analyze the mechanical properties of the incompetent beds. All of the test samples come from the rock core of boreholes. The

incompetent beds of the clay interlayer and crushed beds usually have different characteristics, and the test results are discussed as follows:

Mechanical properties of clay interlayers

A test sample of weak interlayer material is obtained at the depth of 47.44–47.74 m in borehole B2. The particle-size

Table 1 Major mineral and contents of incompetent beds

Numbering of incompetent beds	Borehole or observation point	Depth (m)	Mineral relative content (%)						
			Chlorite	Illite/mica	Montmorillonite	Quartz	Feldspar	Calcite	Dolomite
1#	B1	29.87–30.07	15	25		15	3	42	
2#	B1	38.25–38.45	7	3		5		70	15
3#	B2	47.44–47.64	30	30		10		20	10
5#	B2	58.54–58.74	13	15		8	2	62	
8#	B2	143.65–143.91	5	10		10	3	72	0
9#	B2	147.87–148.07	2	10		5	3	80	
	BTP2			5	15		10	70	
	BTP1			50	20		15	15	
	X4			2	8		15	75	
11#	X3	55.6–55.8	Little	15		10		75	

Table 2 Major mineral and contents within slide zones of I# Linjiang landslide and their host materials (Wen and Chen 2007)

Sample No.	Sampling location	Type of sample	Whole rock mineral and their relative content (%)			Clay minerals and their relative content (%)		
			Quartz	Calcite	Clay mineral	Illite	Kaolinite	Interlayered illite–smectite
1	110	Main body	10	58	31	79	8	13
2	133	Main body	7	66	26	77	6	17
3	140	Main body	14	50	35	74	12	14
4	143	Main body	28	34	37	72	15	13
5	143	Main body	29	16	54	70	19	11
6	144	Slide zone	25	12	62	67	12	21
7	143	Bedrock	35	20	44	70	11	9
8	144	Bedrock	31	35	33	–	–	–

and direct shear tests are done in the testing center of China University of Geosciences. The grain-size curve is shown in Fig. 2a (ESM only); the average grain size is 4.99 mm and the coefficient of uniformity C_u is 9.93.

The shear test results show that the clay interlayer has the cohesion of 20.4 kPa and internal friction angle of 29.7°. The residual shear strength of clay interlayer is tested by repeated slow shear test. The relationship curve of shear strength and shear times is shown in Fig. 3 (ESM only), which indicates that the shear strength descends and closes to residual strength at fourth shear. The residual strength is very low and its internal friction angle is 10.2° (Fig. 3, ESM only). This test proposes that clay interlayer have low strength. Its shear strength descends when rock strata are affected by tectonic deformation or gravitation creep.

Mechanical properties of crushed beds

The samples for grain-size analysis are obtained from boreholes B2 and X2, with grain-size curves shown in

Fig. 2b, c (ESM only). The average grain size is similar with 2.43 and 3.85 mm, but the size of D60 is different, bigger than 50.1 mm and less than 5.45 mm. The crushed bed usually consists of gravel and sand, which has fewer angular grains and large gravel due to the effect of groundwater over a long period. In contrast, it has more fine sand.

For crushed bed, its gravel content and cementation material have a significant effect on the strength. Eight samples from the boreholes are used to direct shear testing. Because the soil sample contained a lot of gravel, a direct shear test cannot be performed with soil shear apparatus. Therefore, the rock rheometer is used to finish this test. The curves of the shear tests have different shapes and the peak strength is dispersed because of various grain sizes. The test samples have three shear failure modes depending on the differences of gravel content. The first mode is sand interface shear failure for material with low gravel content and the shear surface is smooth (see Fig. 4a, ESM only). The second mode is gravel interface shear failure for materials with high gravel content and the shear surface is

Table 3 Calculation data of crushed beds shear test

Sample No.	1	2	3	4	5	6	8
Water content	11.23	12.2	11.9	14.4	16.4	12.3	8.5
Shear area (mm ²)	1,0935	1,0936	1,0930	1,0936	5541.8	7535.6	7697.7
Gravel area (mm ²)	1,619	836	993.8	241.8	316.9	608.2	1726.1
Sand area (mm ²)	9,316	1,0100	9936.2	10694.2	5224.9	6927.4	5971.6
Roughness profile linear length (mm)	105.3	106.7	117.1	99.6	70.2	86.2	85.9
Roughness profile absolute length (mm)	107.8	109.9	110.8	101.5	73.9	89.3	89.3
Average climbing angle (°)	18.8	16.7	16.5	13	26.2	26.5	22.8
Normal force (KN)	2.25	3.25	3.25	1	2.25	0.75	5
Shear stress (KN)	3.05	3.5	2	1.85	4	1.65	6.5

smooth (see Fig. 4b, ESM only). The third mode is gravel and sand interface shear failure for samples with middle gravel content and the shear surface is rough (see Fig. 4c, ESM only).

When the shear strength is calculated, shear surface could be divided into two parts: gravel part and sand part. The paper proposes that the gravels have a climbing effect like rock joint shear, as Fig. 4 (ESM only) shows. The calculation data and results are shown in Tables 3 and 4, which indicates that the shear strength of the sand interface is relatively low (internal friction angle, 28.5° and cohesion, 120 kPa), but shear strength of sand/gravel interface is relatively high (internal friction angle, 49.5° and cohesion, 72 kPa). The test samples of crushed beds have high shear strength, because it is cemented by calcite with low moisture content.

Disturbed sample that made by the sand (grain size <2.0 mm) of crushed beds is used to direct shear testing. The shear strength is very low (internal friction angle, 21.6° and cohesion, 10.0 kPa). It is proposed that crushed beds can easily deform and fail when they are affected by groundwater and have lost their calcite cementation.

Formation mechanisms of incompetent beds

From the above classification of soft incompetent beds, type1 of incompetent beds formed during sediment stage, type2 developed under the tectonic effect and type3 formed due to groundwater corrosion. However, they usually have multiple attributes. For example, type2 crushed beds usually developed in the contact surface of hard and soft rock, which is related to the sediment and can be transformed by groundwater later.

According to the profile of Baitupo and Xirangpo, the formation mechanisms of incompetent beds are analyzed based on the comprehensive features of the location, lithology and groundwater activities. From Baitupo profile, it can be speculated that these incompetent beds are continuously distributed and are displaced by fault F3. They

are formed earlier than the fault and are mainly controlled by the sediment process. The formation mechanisms are sediment and tectonic-associated incompetent beds. The distributions of incompetent beds 1#–5#, 6#–10# are very concentrated, while the 11#–13# are relatively disperse, which is related to the sedimentary and tectonic activity (Fig. 6a).

According to mineral analysis of samples from B2 borehole, clay minerals of lower strata in T2b³ are much less than those of the upper strata. The sedimentary environment of the upper strata is relatively volatile. According of the surface survey, the strata of T2b³ is mainly compose of marl and limestone which are interbed sedimentary structure and easy to generate crushed beds under the tectonic stress.

From the profile of Xirangpo, 11#–13# incompetent beds are located at the lower strata where the clay content is relatively low. However, the rock blocks have different strengths at different depths. The incompetent beds are located at the strata where the strength changed. Therefore, those rock strata still have the conditions to generate the tectonic crushed beds (Fig. 6b).

Drill core revealed that the incompetent beds are mainly yellowish brown and apricot gravel soil or disintegrated rock with shale or calcareous cementations, which indicated the effect of groundwater. Compared with the terrace elevations of the Yangtze River in Badong area, the elevations of most incompetent beds are equivalent to that of terraces. Crushed beds caused by tectonic effect have strong infiltration capacity. When they are located at the long-term table of groundwater, the calcareous minerals are easy to lose and the relative content of clay minerals will increase.

Under the effect of river incision and erosion, the crushed beds will be rebuilt by groundwater and will be located above the groundwater table. The crushed beds re-cemented and formed the current incompetent beds. Some boreholes have exposed corrosion caves or crushed beds, Crushed beds and corrosion caves usually locate at the nearby of terraces, such as the crushed bed in the depth

Table 4 Calculation result of crushed beds shear test

Fitting scheme	Calculation sample no.	Sand interface		Sand/gravel interface		Deviation
		ϕ_1 (°)	C_1 (kPa)	ϕ_2 (°)	C_2 (kPa)	
1	1\2\3\4\5\6\8	29	95	50	150	4.802
2	1\2\4\5\6\8	40	100	44.5	30	2.078
3	1\2\4\6\8	28.5	120	49.5	72	0.028

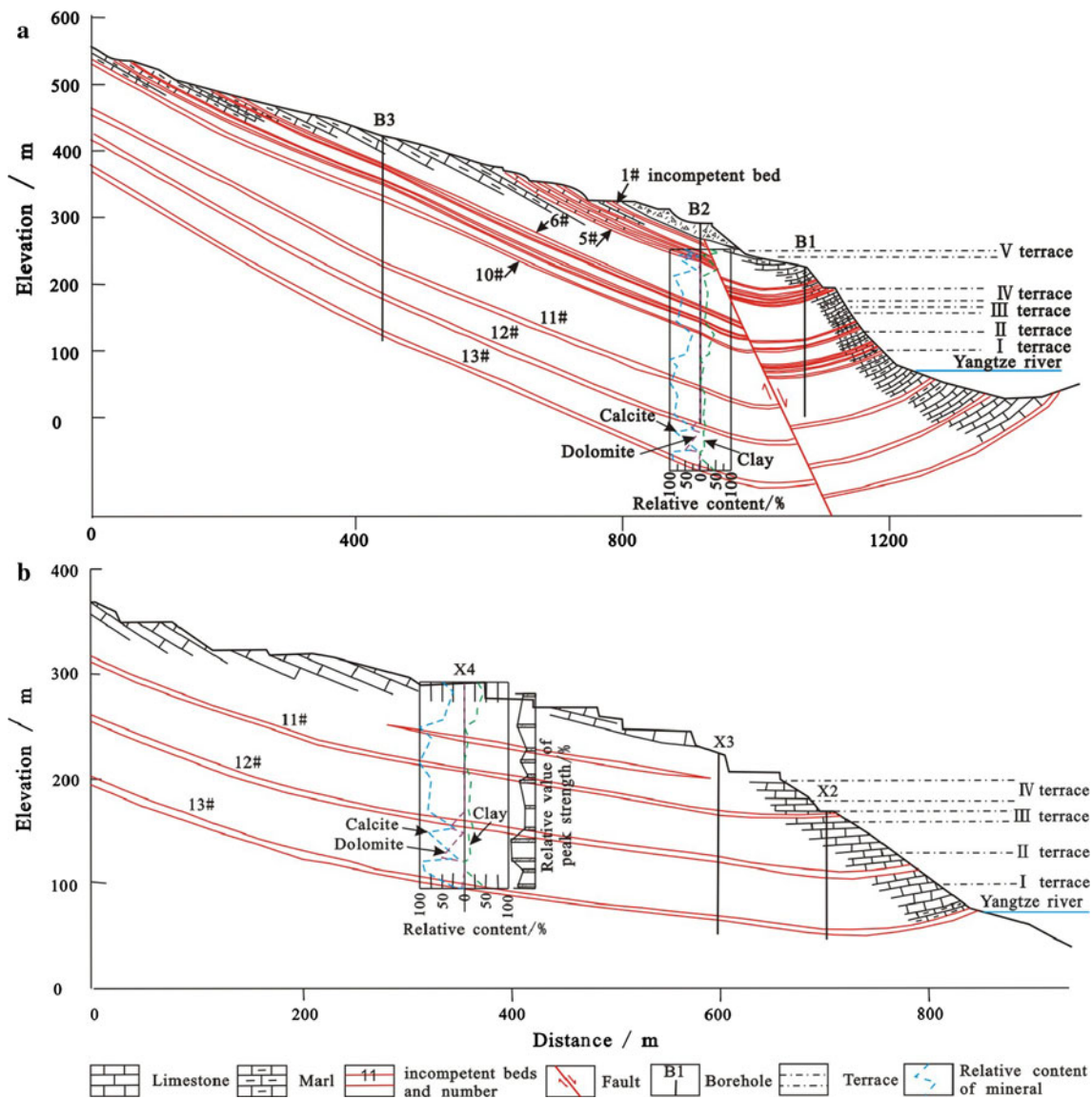


Fig. 6 **a** Incompetent beds distribution of Baitupo profiles (geological profile II–II' in Fig. 1). **b** Incompetent beds distribution of Xirangpo profiles (geological profile I–II' in Fig. 1)

of 76.7–78.5 m in borehole B2 and the corrosion cave in borehole X3 are equivalent to IV terraces.

In summary, those incompetent beds developed following the geo-evolutions process in Badong town are mainly controlled by sedimentary and tectonic activity. Because of the unstable sediment environment of T2b³, the

strata have different mineral contents and strengths, and generate clay interlayers easily. In the interbred of soft and hard rock, those crushed beds are developed with the Guandukou syncline deformation. They usually experience groundwater rebuilding when the river cuts to the corresponding elevation. The calcareous minerals are dissolved

partly and the content of clay is relatively increased. The river continued to cut and the incompetent beds are formed subsequently.

Discussion

According to the distribution of incompetent beds, the rock mass structure before the formation of Huangtupo landslide is rebuilt in the paper. The primary strata of Linjiang landslides is the upper strata of T2b³, which has relatively abundant clay minerals and alternate hard and soft rocks, under the unstable sedimentary environment. The incompetent beds in the landslide body are equivalent to the 6#–10# incompetent beds in Baitupo profiles. The secondary folds of Guandukou syncline are generated widely in the lower part of Huangtupo landslide. The rock mass in the fold core is usually broken and prone to collapse, creep and fail along the incompetent beds. According to the geological profile of Huangtupo landslide, the landslide has more than 100 discontinuous weak layers that plays a very important role on the failure of slopes. Those weak layers have similar component and structure with the incompetent beds in Badong town; therefore, it is concluded that the incompetent beds have dominant effect on the stable status of deep-seated translational landslide.

According to the order of strata and tectonic condition of the nearby area, by inferring the original structure before the landslide formed, the development process of the Huangtupo landslide is discussed here (see Fig. 7).

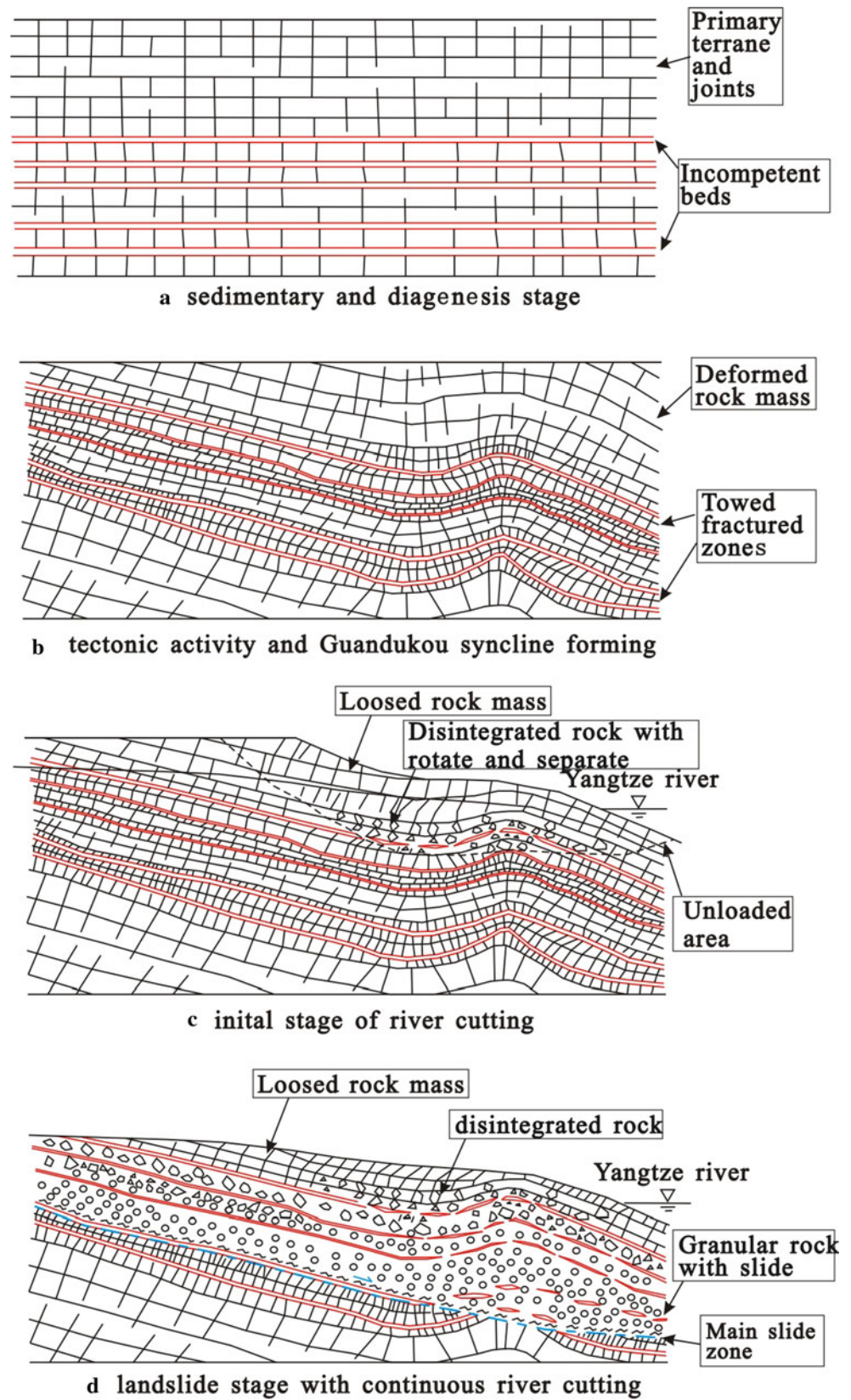
1. There are five incompetent beds in the bank slope, which is close to the lower part of Huangtupo landslide. They could be clay interlayer or the interface of hard and soft rock, which are easy to deform during tectonic activity (Fig. 7a).
2. The incompetent beds are the main deformed part when Guandukou syncline is developed. In the beginning, the shear deformation occurs and causes uncoordinated deformation along the incompetent beds. Then the dragged fractures zones are generated in the hard rock layer near the incompetent beds, and the rock mass broke into block, just like the crushed bed structure or the fractured zone of clay interlayer (Fig. 7b).
3. Under the effect of river incision, the slope unloads and the plastic deformation occurs in the incompetent beds along the valley. Consequently, the rock mass between the incompetent beds is rotated and destroyed by the dragged deform from incompetent beds. The connecting segments between incompetent beds impede the failure of landslide. In this process, the rock mass deforms and becomes loose continually (see Fig. 7c).
4. When the connecting segments are fractured and the continuous sliding zones are formed, the slope begins to deform as shown in Fig. 7d. The Linjiang landslides are the first sliding part, Biandianzhan landslide is the second part and Yuanyichang landslide is the last part.

Zhaoshuling landslide is a deep-seated planar landslide with multiple slide zones that coincide with incompetent beds. The main slide zone is close to the interface of T2b² and T2b³ strata. This landslide has a similar development process to the Huangtupo landslide. However, it took less time to form the sliding zone with a faster speed. The developing processes of this landslide are as follows:

1. Zhaoshuling landslide is affected by two folds, the bottom of landslide is near the Guandukou syncline and the back boundary locates along a secondary anticline, which is formed in the same period. These two folds have different characteristics: Guandukou syncline is a broad fold whereas the secondary anticline is a close fold. Thus, the rock mass has a different deformation model. The lower part of the landslide is close to the core of Guandukou syncline where a shear zone had generated, and the upper part of landslide is the core of a secondary anticline with broken rock mass.
2. The rock mass deformed along the bed slide face when the river cut and slope are unloaded. The landslide creeps along incompetent beds with gravity, then was transformed to catastrophic failure when the slope gained a giant disturbance, like an earthquake or storm.

The deformation of the slope is mainly developed along the incompetent beds. In addition, they are transfixion rock layer and low strength so that these incompetent beds are easy damaged to become the slip zones by the tectonic effect; then the entire slope will be unstable. There are other giant landslides except Huangtupo and Zhaoshuling landslide and Fig. 8 shows the relationship between positions of incompetent beds and main slip surface of landslides in Badong town. This figure shows the strata distributions of three districts (Baitupo, Daping and Huangtupo) on the main topography profile; the horizontal axis is the horizontal distance of main profile and the interface of T2b³/T2b²; the vertical coordinates are the vertical distance to the bottom T2b³, which also indicate the thickness of T2b³ strata. The parallel lines in the figure are the position of incompetent beds, each arrow indicating the location of each landslide in the main profile, and the ground average elevation and the positions of main slip surfaces (arrow position) were marked. The slip surfaces are widely distributed in the shallow incompetent beds; for example, slip surface is mainly distributed in 1#–5# incompetent beds at Baitupo, in 10# and 11# incompetent beds at Daping, and slip surface is distributed in 6#–10#

Fig. 7 Sketch map of Linjiang landslide in Huangtupo landslide



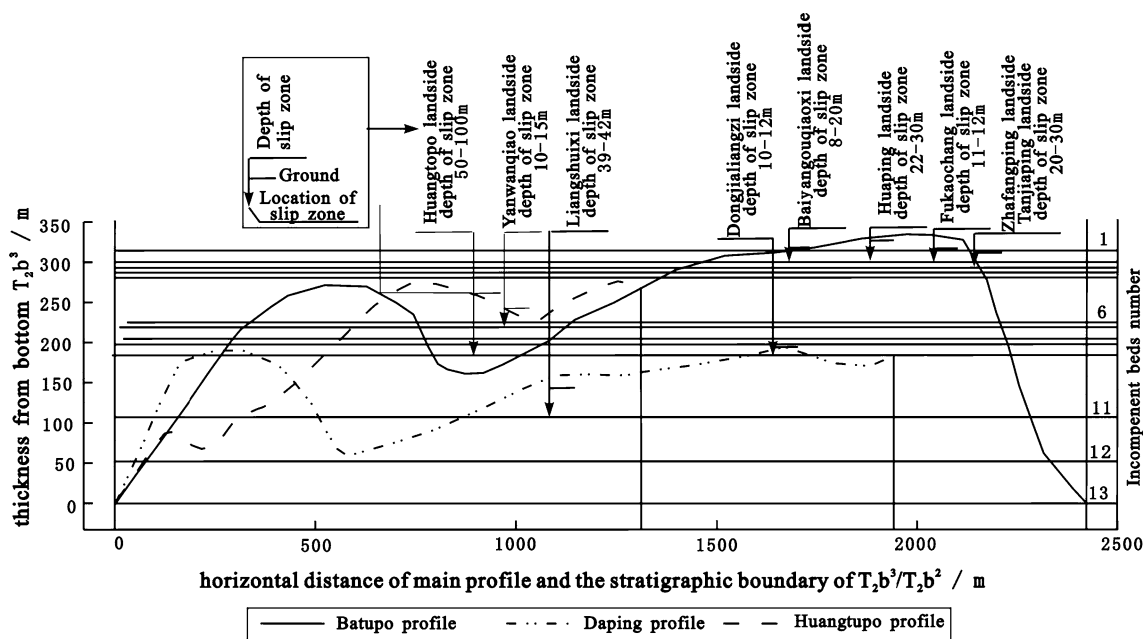


Fig. 8 Position relation of incompetent beds and slip zones

incompetent beds at Huangtupo. It is proposed that the incompetent beds play the main role for the deformation and failure of the slope and easily become slip surfaces.

By comparing the landslides susceptibility of Xirangpo and Baitupo district, it is indicated that the number of landslides in Xirangpo district are less than that in Baitupo district. It is proved that rock mass of Baitupo is prone to landslides, because the strata of nearby ground are mainly the upper strata of T_2b^3 , and the incompetent beds are relatively concentrated.

Based on these results, it is concluded that the incompetent bed is the main factor to generate deep-seated landslide. The lithologies of T_2b^2 and T_2b^3 have different mechanical strength and distribute multi-layer incompetent beds. When Guandukou syncline developed, rock strata are extruded by the S–N extrusion stress and form wide symmetric syncline fold. The incompetent beds begin to deform and develop shear zones. Deep sliding faces of slope are built along incompetent beds by gravitation slowly, and failure processes are generally developed from creep to slide.

Conclusions

By analyzing the correlation between incompetent beds and slope deformation, several conclusions can be obtained from this study:

1. Thirteen large incompetent beds exist in the T_2b^3 strata, which can be divided into three types: clay interlayer, crushed bed and groundwater corrosion zone.

2. The incompetent beds are composed of illite, chlorite, quartz and calcite, etc., which can be classified into two different categories according to the relative content of main mineral. The first one is the clay mineral with the content of more than 50 %, which often indicates clay interlayer of calcareous mudstone. The second one is the carbonate mineral, which has similar mineral composition with marlite of T_2b^3 and often suffers tectonic fracture. The mineral contents of incompetent beds are similar with landslide slide zones.
3. The positions of incompetent beds correspond to the slip surface of deep-seated landslides. In the beginning, these incompetent beds deform and generate shear zones, then slip zones of landslides are developed slowly along them due to gravity, and failure processes are generally developed from creep to slide.

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