

The 102 Landslide: human–slope interaction in SE Tibet over a 20-year period

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Abstract The evolution of large-scale landslides should be studied because, over long periods of time, primary remediation measures may suffer reduced efficiency or have to be adjusted many times. The 102 Landslide in southeast Tibet, which originally formed in 1991 with a volume of 5.1 million m³ and still exhibits post-failure activity, provides a distinctive case study. The landslide evolved from earthquake destruction and unloading, rain-fall-triggered sliding, and debris flow to sands sliding slopes. The NE ringed scarp receded by 38.96 m during a five-year period (2003–2008). The total recession was 160 m with a total area of 2500 m² during a 17-year period (1991–2008). Although several types of remediation measures were applied and were temporarily effective, the normal function of the Sichuan–Tibet Highway was affected by landslide reactivation from time to time. Actual effects of the engineering measures such as retaining walls, prestressed anchor cables, and drainage ditches confirm that hasty governance of this type of large-scale landslide is generally unfeasible over long time periods. Finally, an approach involving a tunnel running backward from the front face has been adopted as a permanent solution to

large-scale moraine slope failures: This engineering practice has been in progress since April 2012. This paper describes the evolution of the 102 Landslide, the engineering interventions to mitigate the effects of the landslide on the Sichuan–Tibet Highway, and the choice of tunneling as a final mitigation measure. The present study concludes that approaches that allow escape from developing geohazards should always be the initial choice.

Keywords Large-scale landslide · Moraine · Tibet · Debris flow · Sands sliding slope · Remediation

Introduction

Assessment of landslide hazards requires consideration of both the complex initial stages of failure and unpredictable post-failure behavior, which involve changes in the failure mechanism and movement procedure, substantial variations in volume, and alterations in the characteristics of the moving mass. Geology and topography are the main factors affecting the initial failure mechanism (Evans et al. 2006), although the post-failure mechanism of partial collapse is affected by human activity on the cut slope. To improve hazard assessment and understanding of landslide behavior, observations of typical landslides over a long period are necessary.

At mileage pile K4078—4081 km of the Sichuan–Tibet Highway (Chengdu–Lhasa, a section of No. 318 state highway), the 102 Landslide sits at No. 102 maintenance squad east of Tongmai Town, Bomi County, SE Tibet (Fig. 1). The squads, which are sited at 10-km intervals, were put in place to supply large trucks transporting construction supplies with water and oil during the initial construction of the highway in the 1950s.

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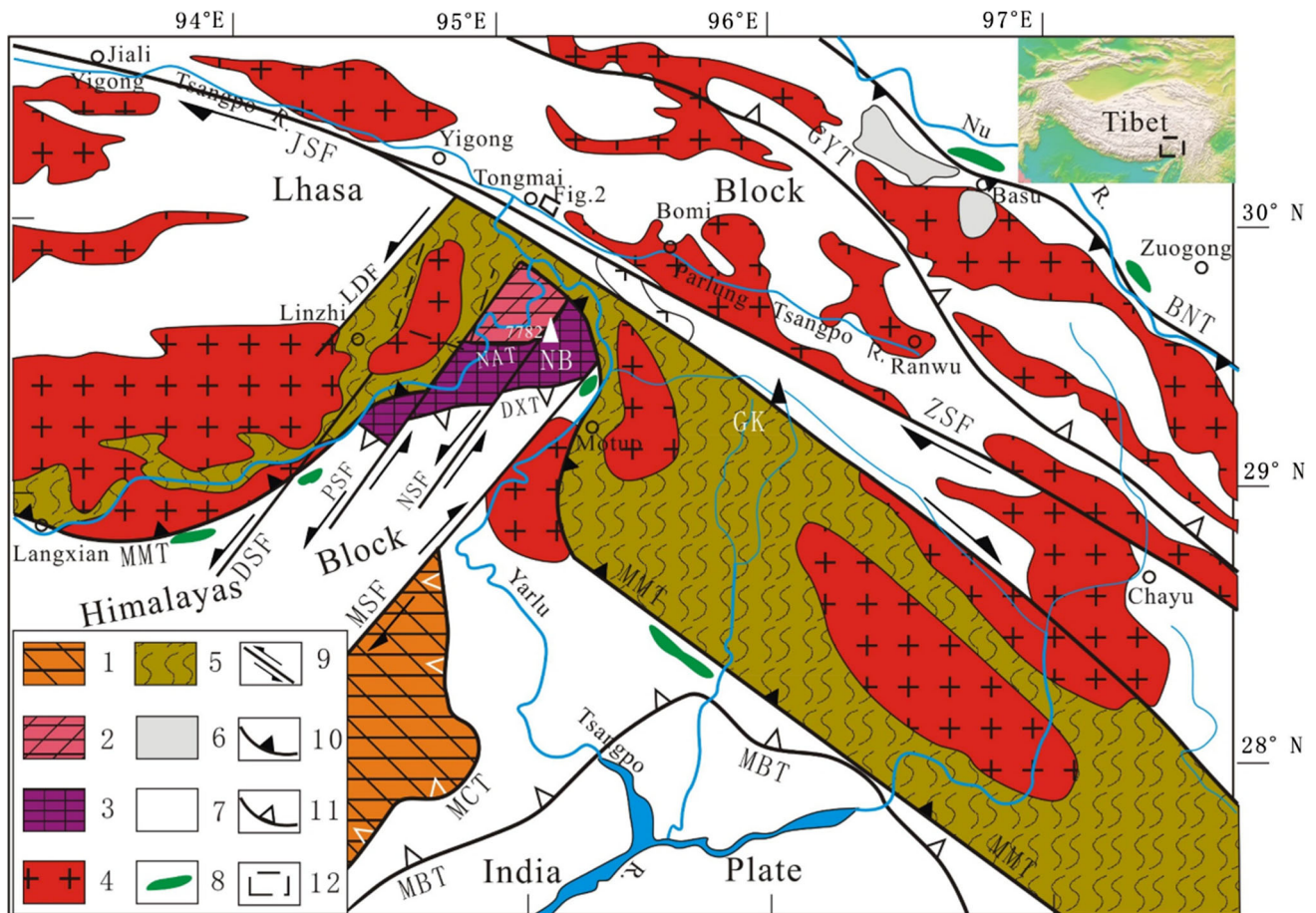


Fig. 1 Location of the 102 Landslide (from Zeng 2006): 1 High Himalayas crystalline rock system; 2 granulite facies metamorphic rocks; 3 gabbro, diorite rock body; 4 Gangdise island-arc granite; 5 metamorphic rocks of the Gangdise basement; 6 volcanic rocks of the Gangdise island-arc; 7 Paleozoic-Mesozoic group; 8 ophiolite; 9 large-scale strike-slip fault; 10 plate suture; 11 large-scale thrust

nappe structure. 12 Study area (MBT main boundary thrust, MCT main central thrust, MMT main Motuo thrust, MSF Motuo strike-slip fault, NAT Nan'ao thrust, NSF Nage strike-slip fault, DSF Dongjiu-Milin strike-slip fault, BNT Banggongcuo-Nujiang thrust, GYT Guyu thrust, JSF Jiali strike-slip fault, LDF Lulang-Dongjiu fault, NB Nanjiabawa peak, ZSF Zayu strike-slip fault)

The 102 Landslide is a landslide group containing a total of 22 landslides (6 large-scale, 16 small-scale). Of the 6 large-scale landslides, No. 2 (vol. $510 \times 10^4 \text{ m}^3$) is the largest (Wang and Zhang 1998). The total volume of the other five large-scale slides is approximately $59.7 \times 10^4 \text{ m}^3$. The present study addresses only No. 2 slide of the 102 Landslide (Table 1; Fig. 2). In the altitude zone

1500–3400 m, in the wider parts of the valleys moraines have been breached and reworked by fluvial processes, resulting in moraine-derived secondary accumulations (Iturrizaga 1999).

The 102 Landslide occurred on June 20, 1991. The landslide dam, which was 10–50 m in height, lasted for 40 min and destroyed 3.5 km of highway (Wang and

Table 1 Geometric features of six large-scale landslides within the 102 Landslide (from Zhang et al. 1998)

No.	Elevation a.s.l. (m)	Slope angle (°)	Length (S–N; m)	Width (E–W; m)	Mean thickness (m)	Volume ($\times 10^4 \text{ m}^3$)
1	2180–2276	37	110	67	12	8.8
2	2120–2525	32	550	380	35	510
3	2111–2329	35	240	100	14	33
4	2125–2327	38	150	110	7	12
5	2135–2240	36	80	33	5	1.3
6	2125–2215	36	150	62	5	4.6

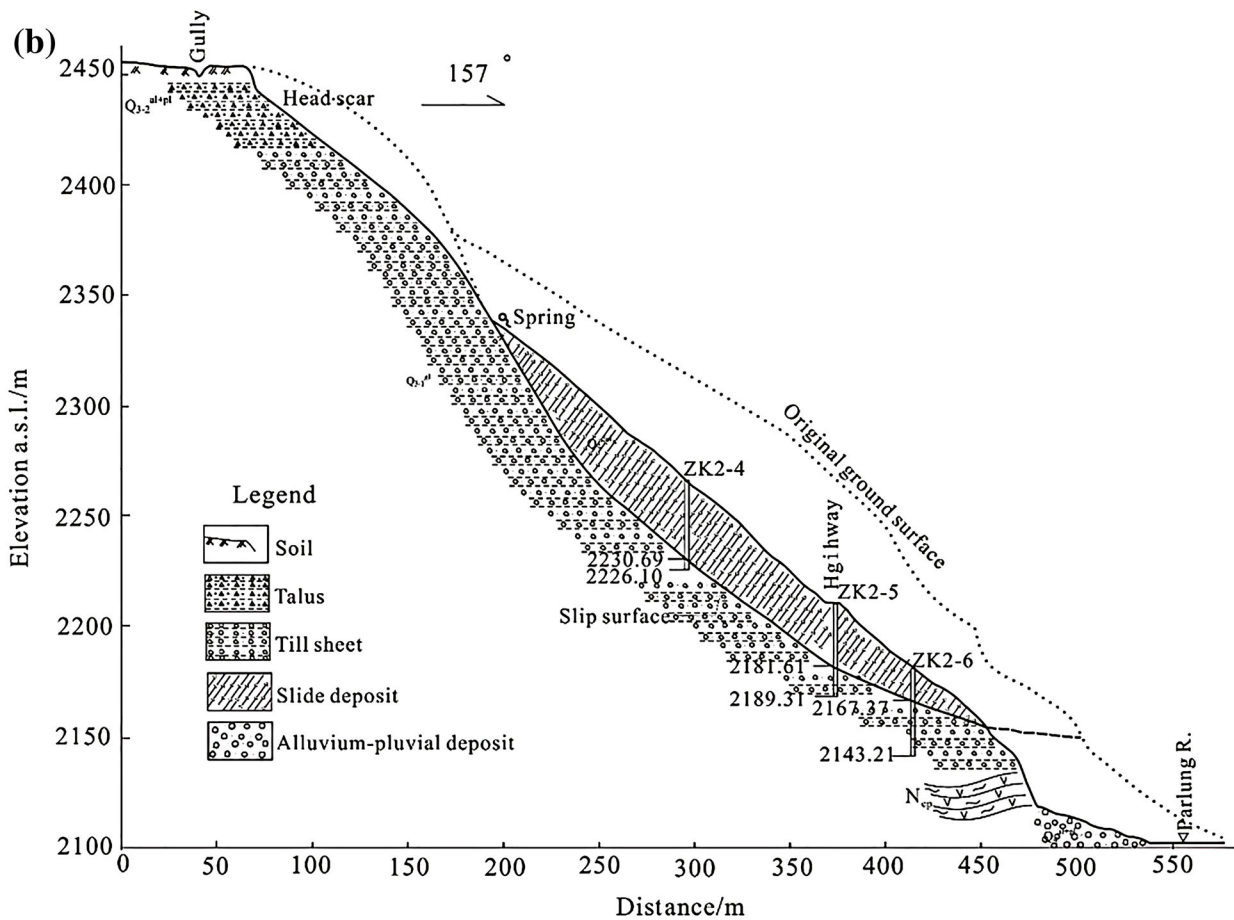
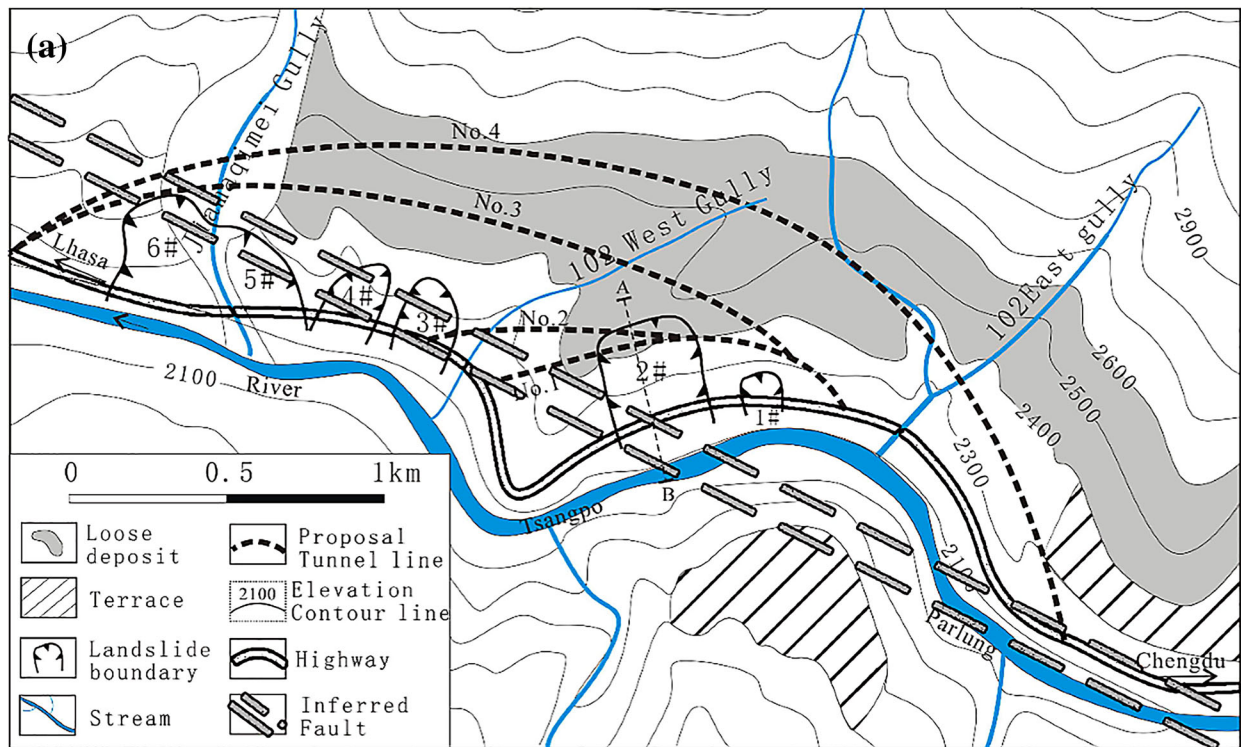


Fig. 2 Layout of the 102 Landslide (modified after IMHE and ITS 1999): **a** a plane map showing the locations of proposed tunnels as a permanent solution to slope failures; **b** longitudinal section

Zhang 1998). Traffic was blocked for 179 days in 1991, 116 days in 1992, 101 days in 1993, 97 days in 1994, and more than 50 days each year from 1995 to 2002. According to local news reports, there were 17 accidents between June 1991 and December 1996. By reinforcing the landslide, the whole situation was brought under control by the use of wood piles for consolidation; however, there are still debris flow in gullies and local loose weathered rocks. The soil on the slope has been stabilized with prestressed anchor cable frames, and cleaning works related to debris accumulations above the highway were carried out after 2001. In addition, monitoring has been strengthened.

Previous investigations of the landslide included geophysical exploration, core drilling, triaxial tests on undisturbed samples from the landslide shear outlet, and back-analysis of the shear strength of the slip zone (Zhu et al. 1998; Liao et al. 2004). Continuous observation of the landslide's evolution and operation status was carried out by the authors, particularly from 2001 to 2008. In addition, it is valuable to perform retrospective analyses of remediation measures and to assess human–slope interactions (Shang et al. 2003; Zhu et al. 2000).

Herein, the 102 Landslide is described and its failure mechanism is analyzed. From observations of the landslide variation over a long period, the 102 Landslide originated as a landslide was transformed to slope debris flows because of the formation of five gullies and is now sand sliding slopes as a result of construction of retaining walls and installation of prestressed anchor cables at cut slopes inside the highway, which was accomplished in 2002. Construction of one tunnel directed backward from the slope front face is currently being undertaken as a permanent landslide measure.

Physiographic and geological setting

The study area is located on the southern face of Nyainqentanglha Shan Mountain, SE Tibet, and is mainly a steep alpine canyon (Fig. 1). Over most of the area, the difference in elevation ranges from 4000 to 2000 m (Shang et al. 2005a). The interactions of exogenic and endogenic agents are intense. Exogenic agents include rainfall, groundwater saturation, stream scouring, and glacier erosion and are relatively intense in the Quaternary strata, which contain uniquely thick moraines and display mass movement, i.e., mud–rock flows and avalanches (TPSRT 1982, 1986; IMHE and ITS 1999). Endogenic agents include neotectonic movements (faulting and uplift) and earthquakes.

The study region sits in the northern margin of the northern subtropical region, where warm and humid air from southeastern Bay of Bengal in the Indian Ocean blows along the Brahmaputra and moves into the Yarlu Tsangpo Canyon as a wet tongue (Sun 1996) to the drainage area of the Parlung Tsangpo River. The study area almost faces the tip of the tongue. There are two seasons in the year: the rainy season (May to October) and the drought season (November to April). The mean annual precipitation is 1086.1 mm, and the mean annual temperature is 11.9 °C (Fig. 3). In general, the highest monthly precipitation is in June, accounting for 21.2% of the total annual amount (Fig. 4a).

The Parlung Tsangpo River, a branch of the Yarlu Tsangpo River, has an average discharge value of 420.8 m³/s (1953–1996), with a maximum value of 529.2 m³/s in 1988 (Fig. 4b) and a minimum of 296.5 m³/s in 1971 (IMHE and ITS 1999). The hydrological station of the river is located in the lower reach of the 102 Landslide in the outlet from Jiamaqimei Gully (Fig. 2a).

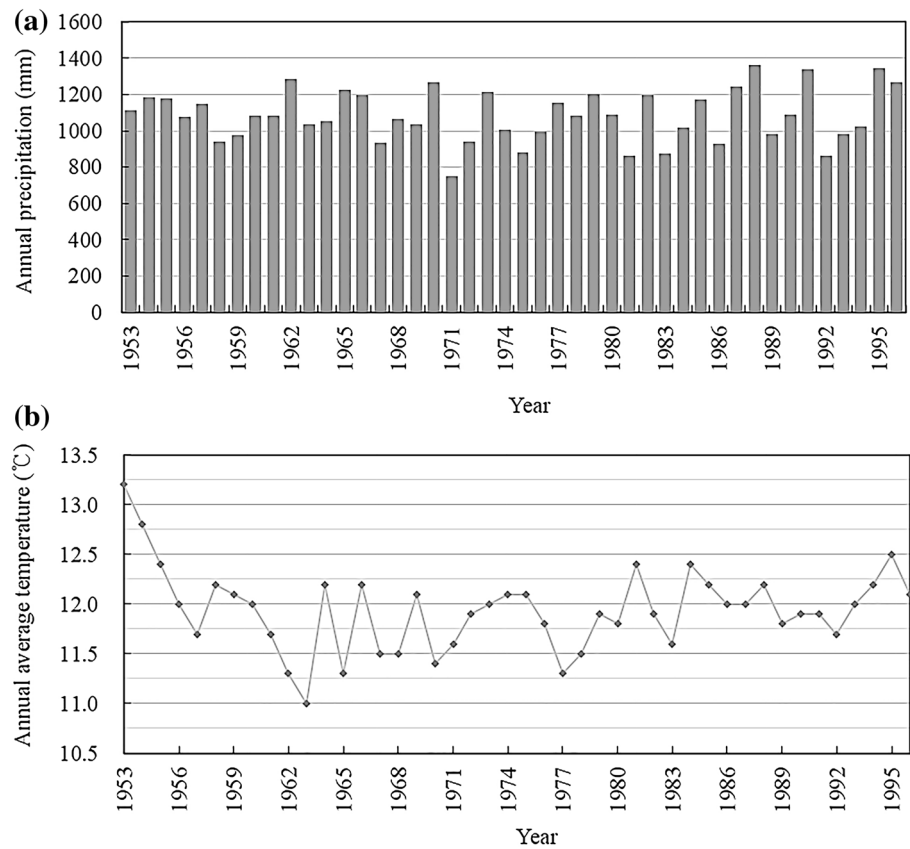
Active major geological structures and strong neotectonic movements regulate the origin and evolution of geological hazards (Parise et al. 1997; Schenk and Bulmer 1998; Philip and Ritz 1999; Strecker and Marrett 1999). The study area in the Parlung Tsangpo drainage area is part of the Gangdise island-arc terrane, i.e., the Lhasa block, in the region between the Bangong Nujiang suture (thrust) and the Yarlu Tsangpo suture (thrust). Many deep faults, including the left-lateral strike-slip Linzhi-Dongjiu fault, the large-scale right-lateral strike-slip Jiali fault, and the right-lateral strike-slip Zayu fault, are still active (Shang et al. 2005a; Fig. 1).

The Motuo (previously called the Zayu) earthquake occurred on August 15, 1950, and was the largest earthquake in China ($M_s = 8.6$). Small-scale earthquakes often occur in the region (Fig. 5). The geological setting is exceptionally active and complex. These active geological factors, together with exogenic agents such as precipitation, stream scouring, weathering, and erosion, contribute to the occurrence of landslides. The Sichuan–Tibet Highway was originally constructed in 1950–1969. Human activity such as cutting and reinforcing disturbs the normal balance of natural slopes. The highway must be able to cope with the challenges of large-scale slope failure. Highway restorations and modifications reflect human–slope interactions to a certain extent.

Layout of the 102 Landslide

In terms of the engineering geological zonation of the highway section along the Parlung Tsangpo River, the 102 Landslide is located in sub-zone VI₂, which has been

Fig. 3 Meteorological features of the 102 Landslide area over a long period: **a** mean annual precipitation; **b** mean annual temperature



qualitatively evaluated as the worst class (Shang et al. 2005b). The 102 (2#) Landslide occupies an area 360 m long, 420 m wide, and 35 m thick in the original slope, with the main slip direction being toward the Parlung Tsangpo River (Shang et al. 2005a). The thickest part of the sliding body is more than 35 m thick (Fig. 2b).

The difference in elevation is more than 400 m [2120–2525 m above sea level (a.s.l.)]. The landslide body has a stepped shape with a mean slope angle of more than 37° and steeply dipping (>70°) scarps. The scarp height is 80–90 m in the eastern section, 40–50 m in the middle section, and 60–70 m in the western section. The underlying sliding surface has a dip of 15°–20° in its front section, altering to a dip of 30°–45° in its back section.

The 102 Landslide is a Type II (tractive) landslide. This type of landslide occurs next to streams, and different ranks of mass movement in the sliding layers of moraines typically occur in the area (Table 2). This classification can be characterized by considering volume, thickness of slides, composition, and action time (Shang et al. 2005a).

Investigation of the lateroglacial sediment landscape of the Karakoram glaciers demonstrated that secondary debris supplied by reworking of older glaciogenic deposits (Late Glacial slope moraines) represents a major debris source (Iturrizaga 2001). At the 102 Landslide site, the Late

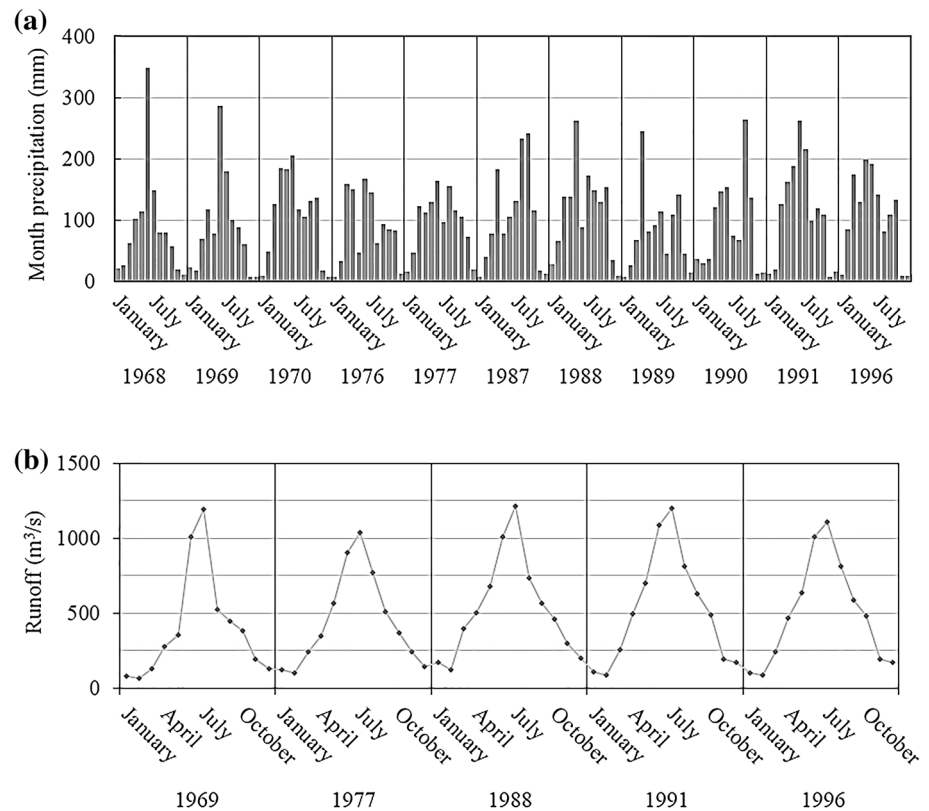
Pleistocene moraines, which occupy a large thickness of 256.4 m, formed during the penultimate glaciation (Fig. 2b).

In the upper part of the slope (from 2220 m a.s.l. in the western part of the slope to 2380 m a.s.l. in the east), there are 13 springs above the moraines that are active all year (Fig. 6). The spring water temperature varies between 10 and 20 °C, and the artesian discharge is 0.1–2.6 l/s (IMHE and ITS 1999). These springs flow out from the contact zone between underlying ancient moraines formed during the penultimate glaciation and overlying pluvial–alluvial deposits formed during the later interglacial stage. The latter, which are 182.61 m thick, can be divided into two sections. The upper part (127.86 m thick) consists of light yellow to brown-yellow moderate–coarse sandy gravels, interbedded with dark gray coarse sandy gravels. The lower part (54.75 m thick) consists of gray to dark gray sandy gravels.

There are five gullies in the slope surface (Fig. 7), which divide the sliding body into several parts with different movement styles. The gullies are 220–455 m long, 5–65 m wide, and 5–30 m deep, with a normal gradient of 586–622‰. Slope debris flows often emerge and rush out along these gullies in rainy seasons.

The particle-size distribution of the loose slope material was measured using the sieving method (Fig. 8). The loose

Fig. 4 **a** Precipitation and **b** runoff in the 102 Landslide region (data from IMHE and ITS 1999)



material consists of gravel-bearing sands, with little clay and a few cobbles (Fig. 8). The shape of the curve is very similar in samples obtained from different parts of the slope, with only one peak in the particle-size distribution curves (Fig. 8).

The shear strength of these moraines is mostly characterized by inner friction angles (ϕ) of 30° – 35° , consistent with the angular particle friction in gravelly sand. The cohesive force (c) is as small as 100 kPa because of the small amount of clay (Fig. 9). The scatter in the c values of total and effective shear strength reflects the influence of pore water pressure and magnifies the sensitivity of the sediment to unloading, i.e., a decrease in c .

To understand the characteristics of surface water flow around the landslide zone and in the surrounding area, hydrological modeling techniques based on geographic information system (GIS) were applied. A digital elevation model (DEM) of the study area was extracted from the six Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model version 2 (GDEM V2) tiles squared off every one degree of latitude and longitude (Fig. 10a). The spatial resolution of the DEM was 1 arc-second (Tachikawa et al. 2011). Catchment areas in the study area and the relative amounts of flowing water in streams were determined from the DEM using ArcGIS 10.3 software and Arc Hydro Tools

(Djokic et al. 2011) using the following process: pit removal in the DEM; determination of flow directions; calculation of cumulative flow; extraction of streams from the cumulative flow values using a threshold of 100,000 cumulative cells threshold; and delineation of catchments.

The calculation of cumulative stream flow reflects relatively higher discharge volume in the stream adjacent to the 102 Landslide (i.e., the Parlung Tsangpo River) because of its location close to the outlet of a downstream branch (Fig. 10b). The catchment area encompassing the 102 Landslide is relatively larger than is usual for a catchment area (Fig. 10c): a larger catchment basin can lead to greater flooding potential.

Formation and evolution of the 102 Landslide

During the 1950s, when the Sichuan–Tibet highway was under construction, signs of slope deformation appeared in the No. 2 section (landslide) along the highway. Unstable sliding masses slowly developed by creeping deformation between 1960 and 1980 at the site.

An earthquake of Ms 5.3 (Richter magnitude) in 1982 triggered eastward enlargement of the unstable sliding land (Zhu et al. 1998). During 1988–1990, several extreme floods intensively scoured the front margin of the slope in

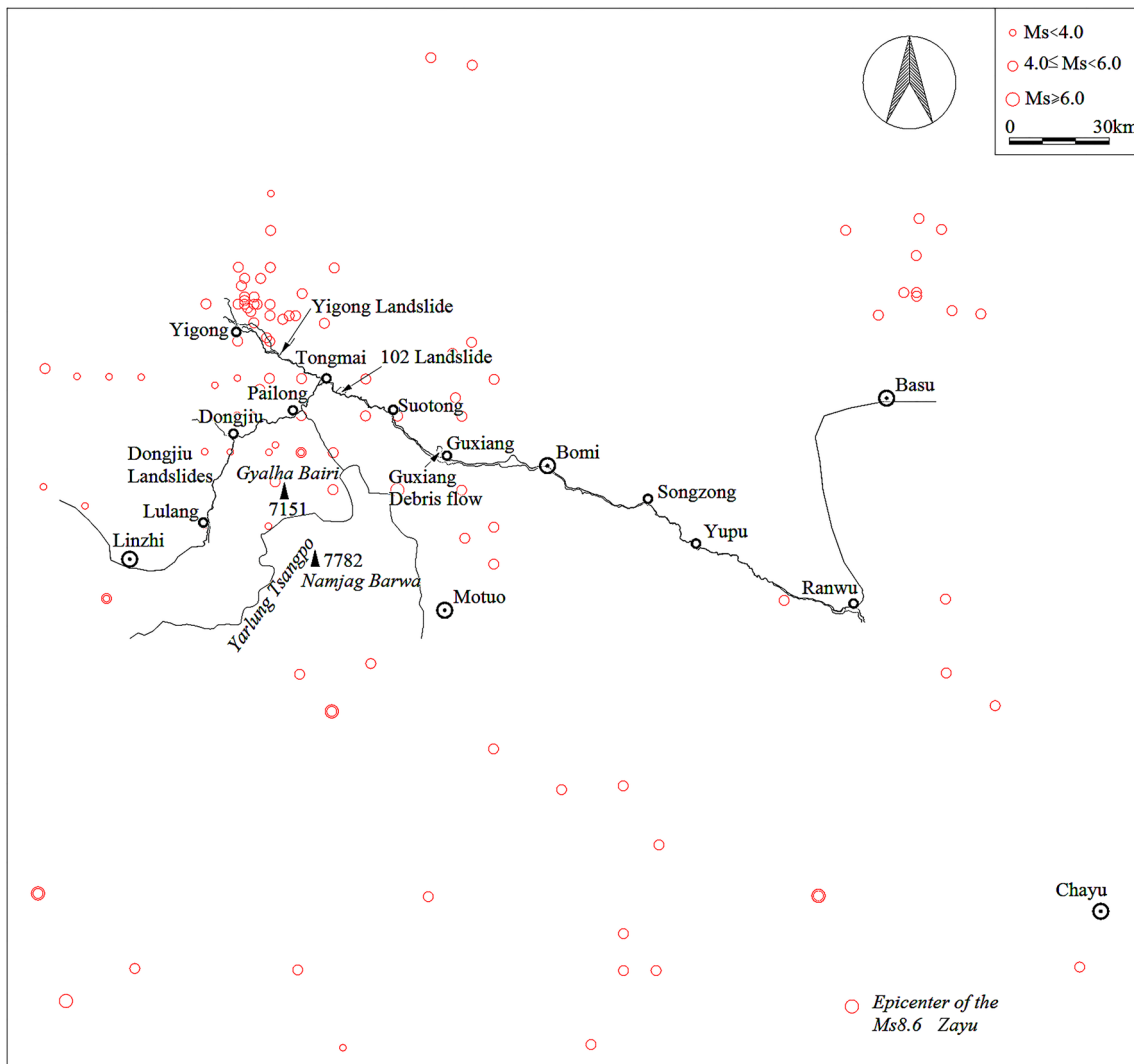


Fig. 5 Historical earthquakes in the area around the 102 Landslide

the convex bank of the Parlung Tsangpo River; as a result, several slope failures occurred in the form of basement subsidence along the highway at a rate of 0.5–1.0 m annually. On June 16, 1991, the basement suddenly subsided by 2 m in this section, subsidence of 1 m occurred on 17 June, and local collapse took place. On 20 June, the whole slope rapidly moved downward to the river, and a landslide dam was formed over the bed.

From historical records, the landslide was initiated as a result of earthquake influence between 1980 and 1996, with heavy rainfall and flooding erosion directly acting as trigger factors. The pluvial–alluvial and colluvial deposits were saturated and moved slowly along their boundary with the Late Pleistocene (Q_3) moraines (Shang et al. 2005a).

The failed volume of about $510 \times 10^4 \text{ m}^3$, which ruined 550 m of highway (Wang and Zhang 1998), mainly slipped to the Parlung Tsangpo River. The front of the landslide

moved directly to the other side of the Parlung Tsangpo River, causing 3 km of backflooding. The landslide dam was about 20 m high and blocked the river in 40 min. The subsequent dam burst led to formation and expansion of the Nos. 3–6 landslides in the lower reaches (Zhang et al. 1998), and the field geological investigations being carried out by the No. 7 group of the Gangsu Regional Geology Survey Team on the 1:200,000 Tongmai and Bomi sheets had to be stopped (Zhang et al. 2004). In 1998, large-scale sliding occurred again.

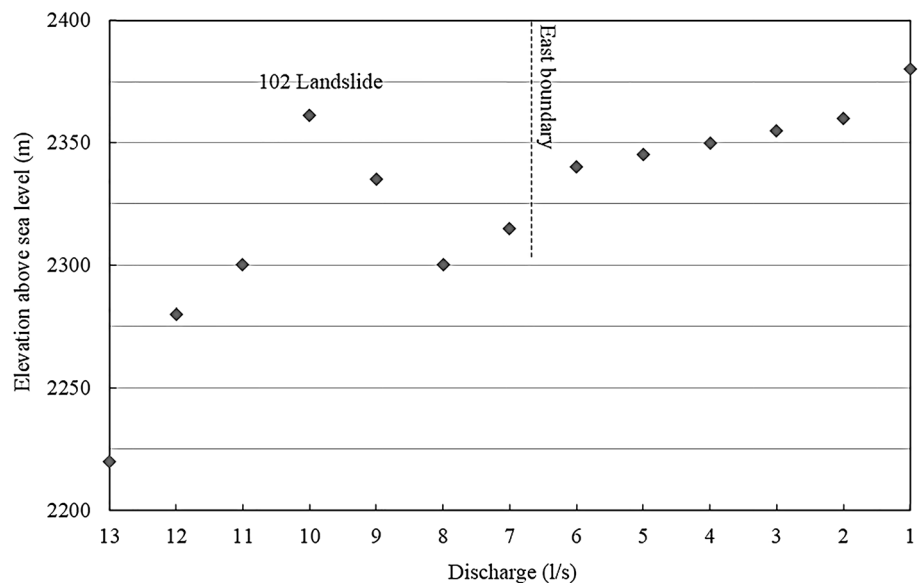
From the 1950 Zayu Earthquake until 1986, the 102 Landslide underwent creeping deformation. Between 1987 and June 1991, the slide moved faster than before, and then the slide completely slipped with showing slightly accelerating behavior of slippage. On June 20, 1991, complete slippage occurred, after previous basement subsidence and local collapse between June 16 and June 18, 1991. After the complete landslide on 20 June, almost fully saturated

Table 2 Landslide classification and the categories of the 102 Landslide

Items	Class	Subclass	102 Landslide features	102 Landslide category	
Materials	Soil	Clayey soil	Moraine, fluvial, alluvial	✓	
		Soil with rock			
		Weathered soil			
Magnitude	Rock	Bedding	5.10 × 10 ⁶ m ³	✓	
		Dissecting			
	Small	<3 × 10 ⁴ m ³			
		Middle			3 × 10 ⁴ to 50 × 10 ⁴ m ³
	Large	50 × 10 ⁴ to 3 × 10 ⁶ m ³			
	Super-large	>3 × 10 ⁶ m ³			
Occurrence	Ancient	Inactive	Initial creep before 1986, accelerated deformation during 1986–1991, and sliding on June 20, 1991. Sliding triggered by rainfall and stream scouring	✓	
		Reactive			
	New	Initiated			
		Secondary			
Thickness of sliding plane	Shallow	<3 m	25–35	✓	
		Middle			3–15 m
		Thick			15–30 m
		Super-thick			>30 m

✓ The subclass to which the 102 Landslide belongs

Fig. 6 Discharge and elevation of the 13 springs that flow out from slopes near or in the 102 Landslide



sliding mass was seen by someone walking through the adjacent area, but the saturated condition disappeared soon.

After the stepped slope had been divided into several small landslides by five deeply scoured gullies (Fig. 7), the highway passed through the slide as a snake curve with a wooden retaining wall to reinforce the basement (Fig. 11).

After its formation, the 102 Landslide became a debris flow and subsequently a sands sliding slope. The scarp retreated to 38.95 m in its NE area during a five-year period (2003–2008; Fig. 12a, b): The amount of retreat was 160 m, and the area was 2500 m² over a 17-year period (1991–2008; Fig. 12c).

Fig. 7 Lengths and depths of gullies in the 102 Landslide. The gullies are nearly *parallel*

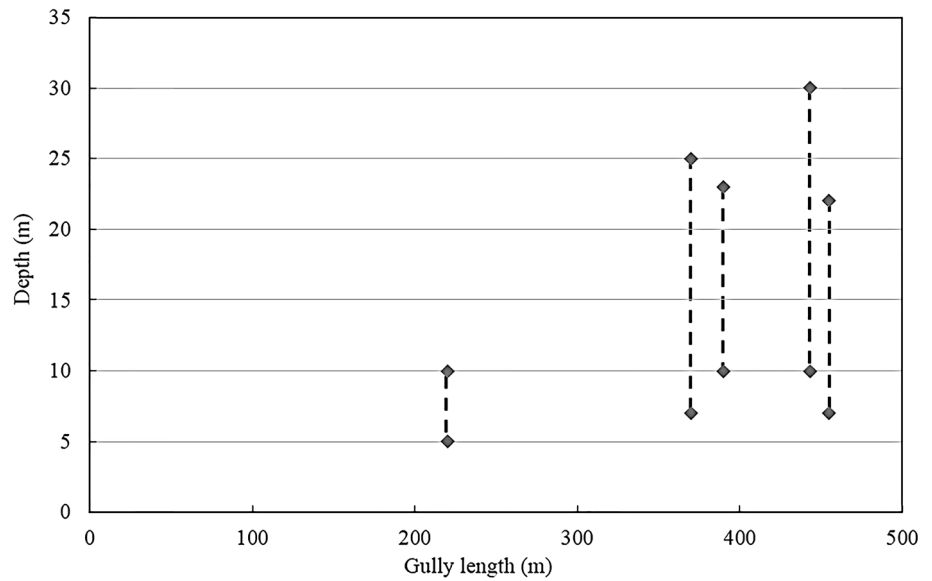
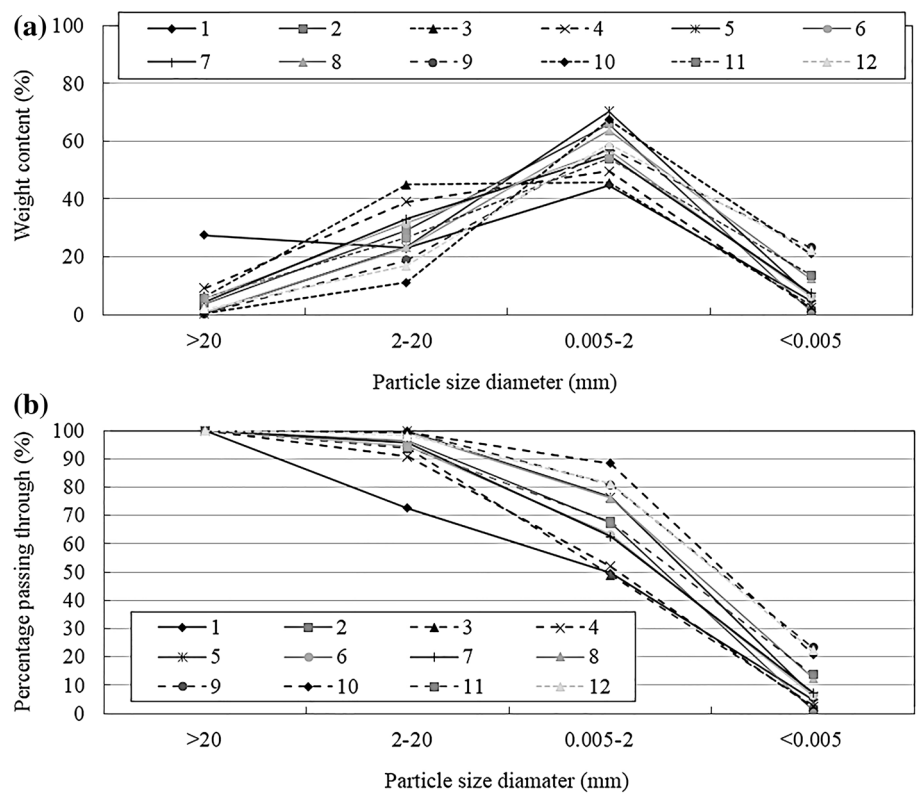


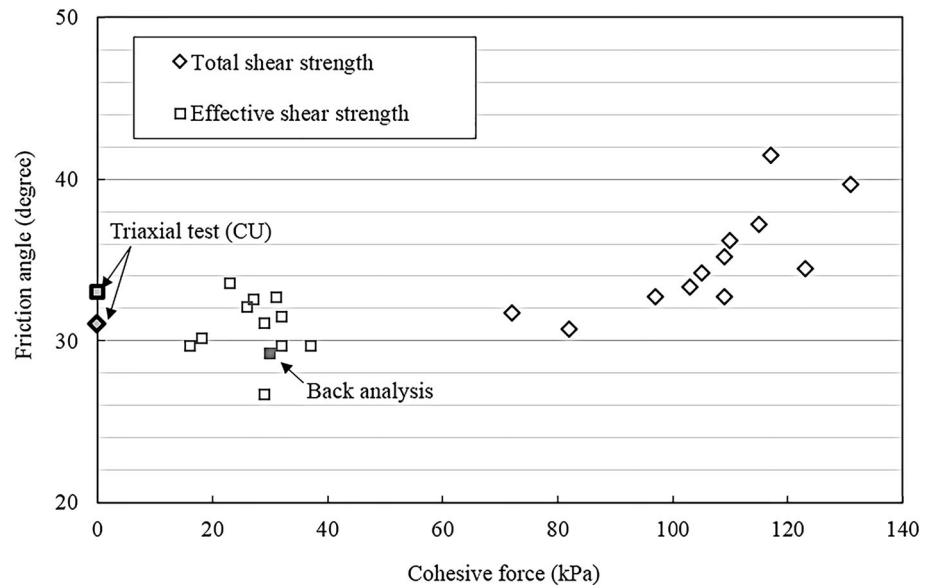
Fig. 8 Particle-size distributions of different samples from different areas of the 102 Landslide: **a** distribution curves; **b** cumulative curves



According to the 102 Landslide topographic map surveyed in April 2003 by the No. 1 Institute of Design and Survey, China Transportation Inc., one drainage ditch was constructed as designed 15–30 m northward of the scarp. The southern margin of the ditch was 25 m north of the scarp. However, when the drainage ditch was checked in 2004, it was found that the scarp had receded to the

northern margin of that ditch and the middle section of the ditch had fallen down and disappeared, together with the slipped scarps. At that time, the scarp had receded by 25 m. On March 20, 2006, one total station (TCA2003) was set up to survey the landslide. At that time, the scarp was 13.96 m north of the left-hand section of the ditch. On April 4, 2008, the data from the total station revealed that

Fig. 9 Cohesive force versus friction angle (representing shear strength). *Hollow rhombuses* denote data from laboratory direct shearing tests, *hollow squares* denote data from multiple shearing tests (IMHE and ITS 1999), a *solid square with thick line* denotes data from total consolidated and undrained (CU) triaxial test, a *solid rhombus with thick line* denotes data from effective triaxial test, and a *solid square* denotes data from back-analysis (Liao et al. 2004). The *solid symbols* indicate results of the sample or back-analysis results of samples obtained at the shear outlet of the landslide



there was no obvious change in the scarp relative to the ditch, and scarp recession had slowed. On average, the recession speed was 7.79 m/a over 5 years (2003–2008; Fig. 12c).

Even in the drought season, debris flows occurred in gullies with banks containing more than two sliding platforms and steps (Fig. 13a). One of the platforms was situated immediately above the road surface. The top of a drill hole in the platform was observed to be approximately 0.5 m higher than the neighboring ground level. In addition, an abandoned road surface is exposed in the gully and below the current road surface. From this information, the slope is calculated to have experienced approximately 10 m of horizontal displacement and 4 m of subsidence between 1997 and 2000. On the upper slope side of the highway, a layer of carbonated vegetation and tree roots buried by landslide debris was examined. A secondary sliding plane between the overlaying gray-brown Holocene silty sands from sliding deposits (Q_4) and the buried gray-black Late Pleistocene moraines (Q_3) was observed during the site survey, during which an undisturbed block sample was obtained at the shear outlet of a secondary landslide for triaxial testing in the laboratory (Shang et al. 2005a; Fig. 14).

From the site investigation, the landslide was controlled by the active right-lateral strike-slip Zayu fault in the north and the Jiali fault in the south (Fig. 1). Heavy rainfall and flood scouring triggered landslide occurrence on June 20, 1991, during the rainy season.

In terms of the mechanism of the 102 Landslide, earthquake vibration, precipitation saturation, stream, and groundwater erosion were significant in its toe and scarp

sections. During the whole procedure with different deformation and failure features, precipitation and stream scouring played major roles in triggering land slippage: The peaks in precipitation in 1997, 1998, and 1992 and the corresponding peaks in discharge were correlated with the occurrence of deformation (Shang et al. 2005a; Fig. 15).

Engineering remediation and stability

As described above, the 102 Landslide occurred on the northern bank of the Parlung Tsangpo River and blocked the river with landslide dams. The stream scouring the concave bank plays a dominant role in triggering slippage of the underlying slope. Accordingly, effective engineering measures include prevention of slope toe scouring, reinforcement of the sliding body, and diversion of runoff (Shang et al. 2005a). A cheap and easy engineering measure, mud-proof corridors, were erected for temporary traffic safety, but were frequently destroyed during the 1960s.

Figures 11 and 13 display examples of engineering remediation measures. These measures include flood-diversion walls on the gully banks, such as wooden retaining walls at the foundation of the highway, to prevent erosion. A widely adopted measure is timber retaining walls built in the foundation of the highway in the middle portion of the 102 Landslide. A timber retaining wall bounded with reinforced bars was installed using local pine timber. The walls act to retain soil without loosening and prevent mass movement of slopes. The walls are generally constructed

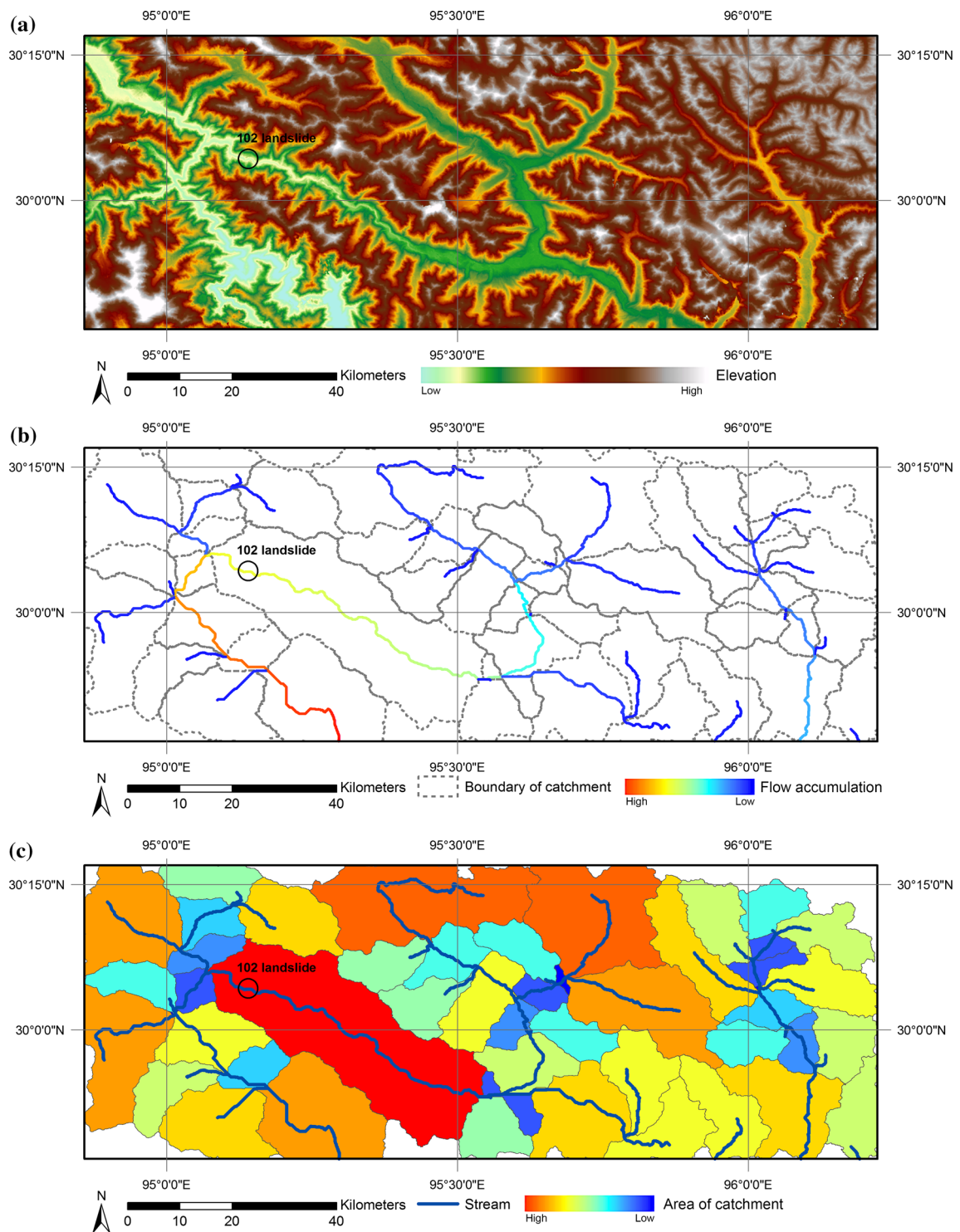


Fig. 10 Characteristics of surface water flow around the landslide zone and the surrounding areas: **a** digital elevation model of the study area used as input data for hydrological modeling; **b** streams extracted

from the cumulative flow values using a threshold of 100,000 cumulative cells; **c** catchment areas for each stream section

on both sides of the highway at the 102 Landslide (Fig. 13) to reinforce the highway foundations by supporting the lower slope and to protect the highway from the failing rock blocks and loose soil (Shang et al. 2005a). After a

significant length of time, the timbers will lose their strength as a result of decay (Shang et al. 2003). The plentiful use of pine does not result in durability and is not feasible in ecological terms, because the work requires a



Fig. 11 Evolution of the 102 Landslide to form gully divisions between 2001 and 2006: **a** wood retaining wall for basement reinforcement (February 2001); **b** reinforcement of the highway surface to ensure traffic safety at a cost of 53 million yuan (December

2002); **c** slope debris flow covering the highway surface (April 2005); **d** workers moving and cleaning the accumulated debris (February 2006)

large number of pine trees and consequent forest destruction. The remediation measures did not work very effectively (Fig. 13). Hence, improving the stability of the slope is necessary to prevent additional sliding at this site. Measures also include erosion-protection and flood-diversion walls on the gully banks. These were constructed along the river bank at a larger width as a retaining wall against the landslide front and to decrease the scouring force in the concave bank.

At significant cost, temporary consolidation for normal traffic passing the 102 Landslide was completed in 2002 (Fig. 16). Erosion-protection and flood-diversion walls were installed to protect the highway slope toes from direct erosion by the stream. One such wall 400 m in length was built in front of the 102 Landslide and on the banks of the river at the slope toes to prevent further erosion of the slope, which was regarded as an economic way to reduce stream incision (Shang et al. 2005a). From field inspection, it was found that the walls were cracked, and there were large fissures in some rock blocks that have fallen to the ground (Fig. 16). It is important to ensure that construction work is resistant to weathering to avoid slope failures near or under important buildings.

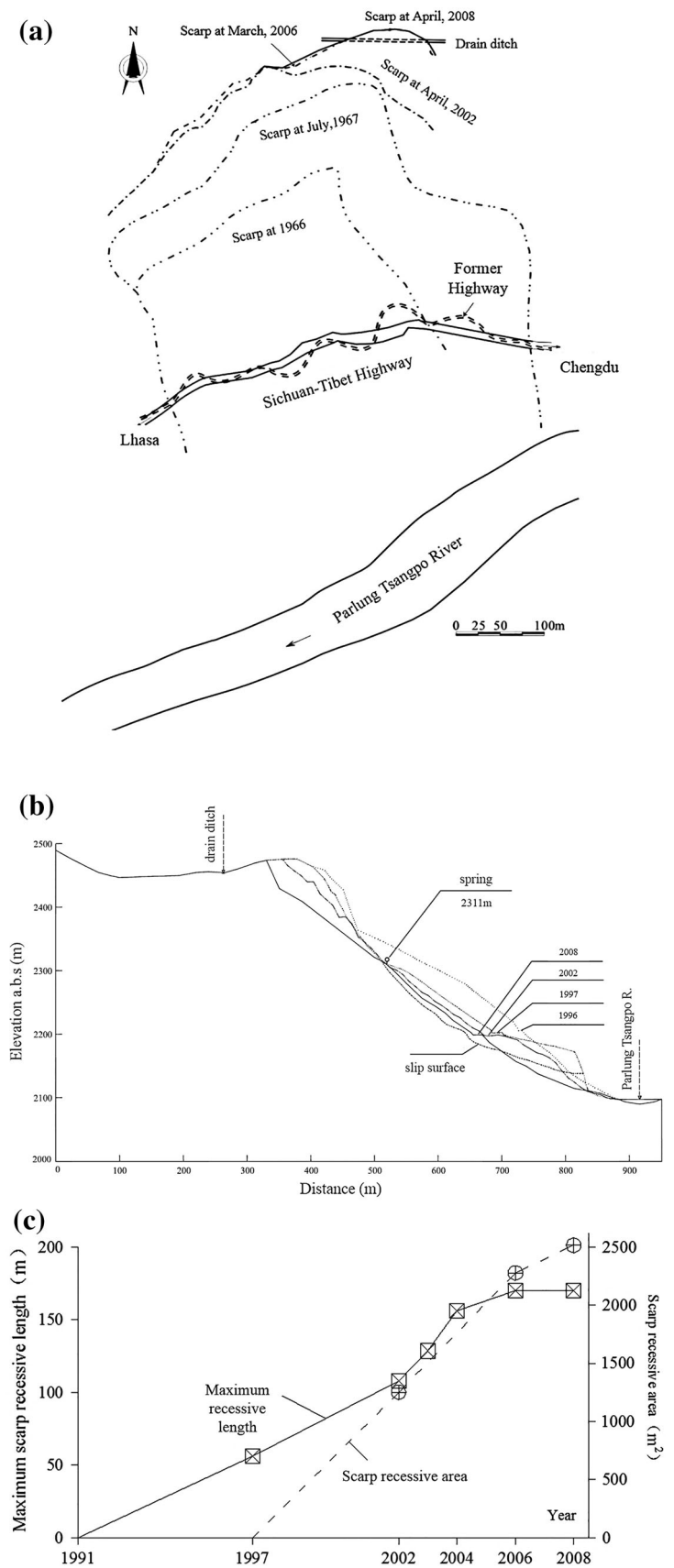
As the highway region is in a remote area, any construction work will encounter many tremendous difficulties. Therefore, quality control and assurance of construction work along the highway are extremely important; in addition, it is extremely difficult to ensure that the work will last for a long time.

Different slope failure mechanisms operated at different times (Fig. 16); thus, appropriate engineering measures were adopted and adjusted to cope with these changes.

Existing problems and proposed measures

The evolution of the 102 Landslide has been continuous, resulting in development of sand sliding slopes. Reinforcement of the landslide is difficult because of springs and leakage in the loose material, and it is not possible to avoid the landform because of its position as a concave bank beside the stream route. Therefore, cessation of slope deformation or failure to ensure normal operation of the highway is impossible. Thus, it is better to avoid direct contact with or significant disturbance of this large-scale slope slippage.

Fig. 12 Changes in the scarp in the NE section of the 102 Landslide in 1991–2008: **a** relict drainage ditch and receding scarps; **b** variation of slope surface and highway surface; **c** recession in the NE scarp area



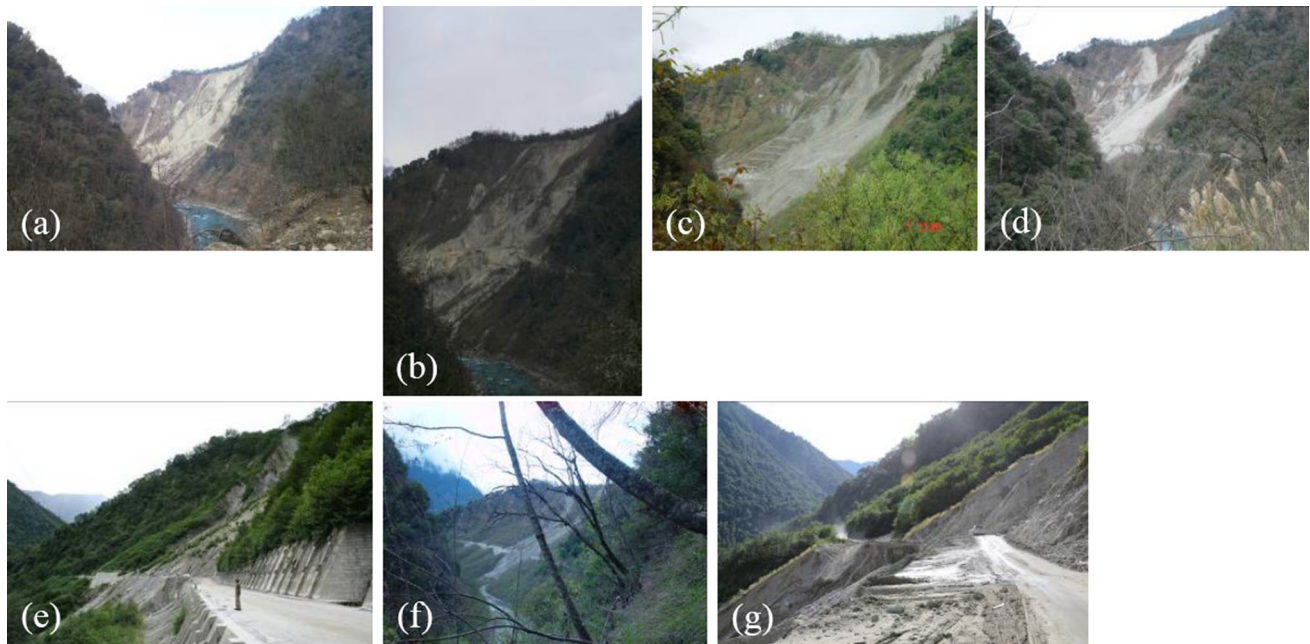


Fig. 13 General view of the 102 Landslide showing its slope failure status with wooden piles and the snake-curved highway in different years. The scarp is visible in the *upper parts* of the photographs (the viewpoint is east of the 102 Landslide and beside the highway, viewing direction is NW): **a** February 9, 2001. Deeply scoured gullies with debris flows; **b** 11 March 2002. The newly cut highway surface is lower in elevation; **c** April 1, 2005. Well-preserved retaining wall

and prestressed anchor cables. The reinforcement had a better effect in the western section than in the eastern section; **d** February 26, 2006. Scarp recession brought more debris to the highway surface; **e** July 17, 2007. Sand sliding slopes appeared; **f** April 4, 2008. Sand sliding slopes are still active and bare; **g** July 25, 2011. Sand sliding slopes still experience scouring

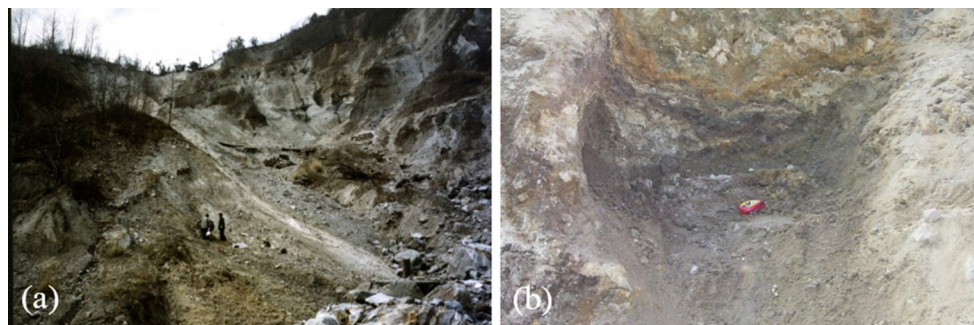


Fig. 14 Undisturbed sampling at the secondary slip outlet: **a** sampling at the outlet of a secondary slip surface (northward, February 2001); **b** trial pit for the undisturbed sample representing the slip surface

Slow deformation Mud proof corridors	Accelerating deformation	Timber retaining wall Scour prevention wall	Pre-stressed anchor cable
	Landslip	Debris flow slope	Sand sliding slope
Ms 8.6 Zayu Earthquake 1950-8-15	Heavy rainfall 1988	Prompt sliding landslide damming 1991-6-20	2002

Fig. 15 Changes in the failure mechanism and adjustments to the engineering measures

Tunnels immediately north of and behind the landslide have been proposed, as illustrated in Fig. 2. There are four tunnels to be considered. Tunnels 1 and 2 cross the

landslide and escape the zones affected by unloading adjacent to the deep gorges. These tunnels do not pass perpendicularly under gullies or creeks and are shorter

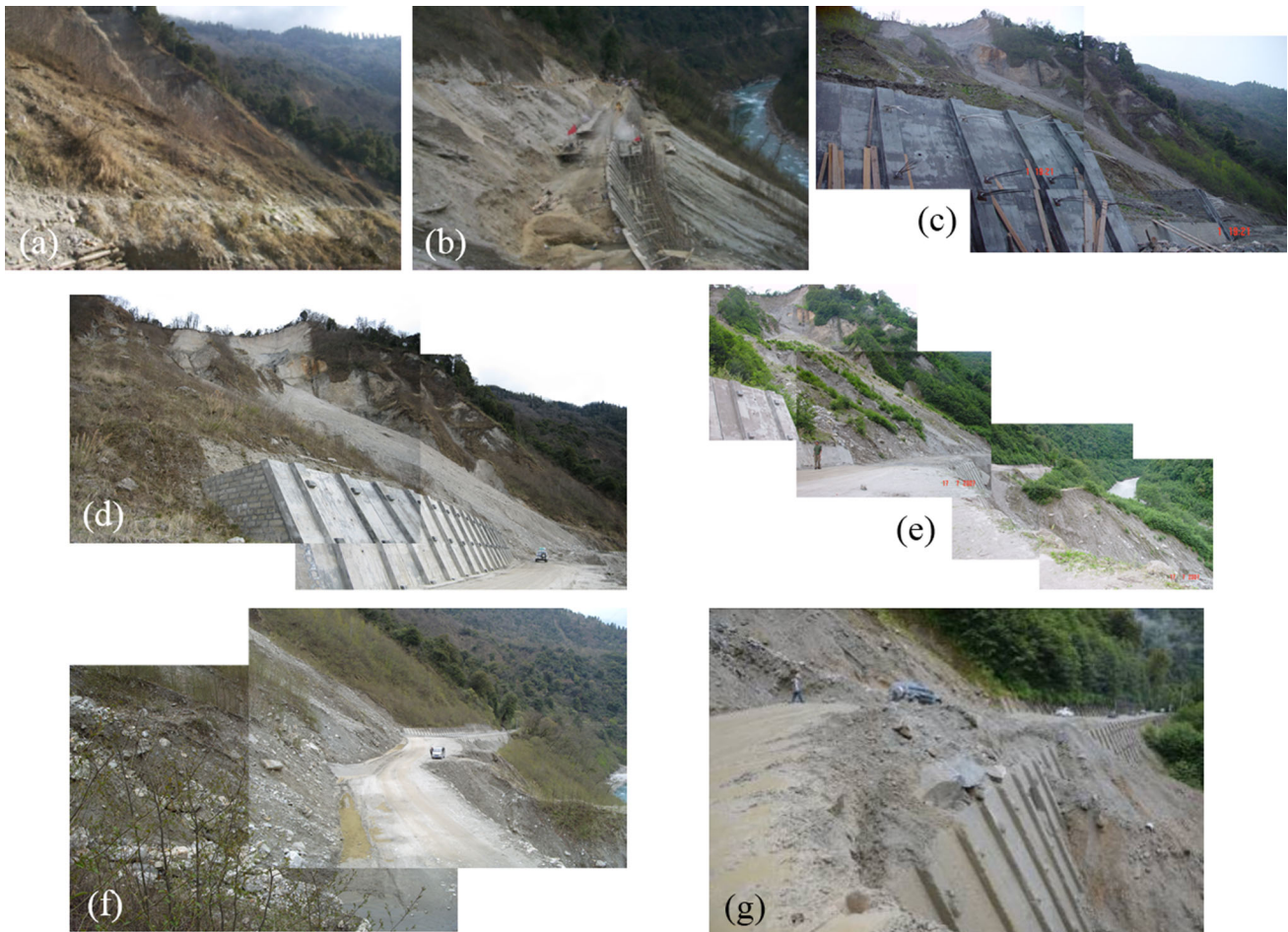


Fig. 16 Engineering measures adopted at different stages for mitigation of the 102 Landslide: **a** February 6, 2001. Timber retaining walls around the landslide; **b** March 11, 2002. Ribbed slab under construction as a retaining wall; **c** April 1, 2005. Prestressed anchor cable with retaining walls. Viewing direction SW to NE; **d** March 8, 2006. The central section of retaining wall was destroyed, and the highway was buried by flowing sand. Viewing direction NW to SE;

e July 21, 2007. Two gullies at the middle and east part are present, the anchor cable and retaining wall were destroyed and buried, and the highway surface was scoured; **f** April 5, 2008. The steps and drainage ditches were destroyed at the western side, and the retaining walls were destroyed and disappeared; **g** July 25, 2011. The retaining wall outside the highway with the highway surface covered with debris

than tunnels 3 and 4. In contrast, tunnels 3 and 4 are at least twice as long and pass through some gullies and streams. Shallow tunnels aligned close to steep valley walls should be avoided in case of potential geo-hazards. Thus, the geological risks of tunnels 1 and 2 are higher than those of tunnels 3 and 4; however, if the economic cost and construction period are taken into account, tunnels 3 and 4 have some disadvantages. Thus, the four tunnels should be compared in terms of feasibility, potential secondary geo-hazards, and economics. After comparison, tunnel 3 was deemed to be a better one with a short length that efficiently escapes from the unloading free wall of the gorge. By the end of 2012, the proposal for tunnel 3 was adopted; construction of the tunnel has begun.

Conclusions

The evolution of the 102 Landslide and efficiency of engineering measures reveal that the landslide was transformed to a debris flow and subsequently to sand sliding slopes. This pattern reflects that the natural occurrence of the landslide was initiated by an earthquake after a long period of 40 years of creeping deformation, with total slippage triggered by precipitation, leakage, and stream scouring in 1991. The landslide activities over the subsequent 20 years were affected by slope cutting and reinforcing to a certain extent; thus, human–slope interactions have an effect on the interior evolution of large-scale moraine slopes. Currently used engineering measures such as prestressed anchor cables constrained these slopes to adjust locally and be transformed into small-scale debris movements.

A practically feasible approach for permanent avoidance of this type of large-scale slope failures in concave banks in high-relief gorge areas is tunneling. The tunnel should be far from unloading steep walls and deep enough to escape the influence of slip planes, and the excavation method and advanced rate should be controlled to diminish disturbance of weak moraines. At the time of writing, the proposal for construction of one tunnel has been accepted and that tunnel is currently under construction.

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