Engineering measure and its effect for Shaofanggou landslide type debris flow

Bu Xiang hang, Tang Chuan
(State Key Laboratory of Geohazard Prevention and Geoenvironment Protection,
Chengdu University of Technology，Chengdu 610059)
E-mail:309351649@qq.com.

Abstract

By analyzing the motion process, the gully characteristics, landslides blocking point as well as the high depth of cutting, We noted that dealing with clogging and cutting are of most importance in a basin comprehensive management project. Building the check dams helps to weaken the kinetic energy of debris flow heading down from the upper reaches. A new type of drainage channel which is composed by anti-slide piles, sidewalls and ribbed slabs, will control the landslides blocking point and protect the "toe cap" in the middle reaches of the gully. A series of check dams with opening sizes and aqueduct will intercept the coarse particle and discharge debris flow smoothly. Finally, by comparing the figure of accumulated rainfall, solid matter participation of "2010.8.14" and "2013.7.10", the dynamic reserves and gully channel characteristics pre and post control measures. Specifically, comprehensive engineering measures have good effect to the Shaofanggou landslide type debris flow. Provide a reference for engineering measures for landslide type debris flows in the earthquake areas.

Key words: landslide type debris flows, drainage channel, check dam, Wenchuan earthquake, Effect evaluation

1. Introduction

Although mitigation measures were constructed in a few gullies such as the Wenjia and Bayi Gullies, disastrous debris flows still occurred because the mitigation measures installed in those areas proved to be inadequate (Wang et al. 2012; Wang et al. 2013b). Thus, developing new techniques based on the debris flow characteristics in the quake-stricken area is a critical task. In this paper, debris flow hazard mitigation measures are evaluated based on an analysis of the formation mechanism of Shaofang gully, which was blocked by a large-scale slope and characterized by a small catchment and a high gully slope. A new layout and designs of engineered structures were proposed to mitigate the potential debris flow hazard and were shown to be effective in protecting a highway located downslope. These new mitigation techniques can provide a reference design for landslide type debris flows hazard mitigation in similar locations.

2. The study area

Shaofang gully locates the northeast of Yingxiu and on left bank of Minjiang River, with the main stream of 1.58Km long and catchment area of 0.61Km2. The gully catchment elevation is 888m-1902m asl, representing an elevation difference of 1014m. Its basin is willow-leafed in shape, and the longitudinal gradient is 464.97‰. Most of the slopes are steep, varying from 30°to 80°(Fig.1). LS01 body is about 480 m long, 200 m wide and 18 m thick with a total volume of about 204.3×10^4 m^3. The slide direction tends to 196°, the altitude is 983─1544m. The channel was blocked completed by LS01 landslide.

Rainfall is the most important triggering factor for initiating debris flows (Tang.2011). On August 14, 2010, Shaofanggou debris flow was triggered by an intense rainfall. However, with the failure of the LS01 landslide dam, there would have an instant dramatic increase in the discharge. Ground investigations of the deposition area indicate the run-out of the debris flow was some 250,000 m^3 a relatively high volume from such a small catchment. The landscape changed radically, particularly in the outlet of the gully (Fig.1).

3. Present-day channel characteristics

3.1 Source materials characteristics

The huge amounts of landslide debris produced by the strong earthquake, that is the prerequisite of debris flow event in the Wenchuan earthquake area (Tang.2009). The Shaofang catchment had larger debris storage, with a total volume of about 251.9×10^4 m^3. On the 4th of August 2010 a debris flow volume of the solid materials that rushed out of the gully was estimated to be approximately $25 \times 10^4 m^3$, approximately 10% of the total volume. After debris flow event, types, number and volume of solid materials had some changes in Shaofang gully. The total volume reduced to approximately $223.9 \times 10^4 m^3$, still, it is huge, with its dynamic reserve about $54.7\times 10^4 m^3$. The key LS01 had about $46.9\times 10^4 m^3$, it was very easy to block channel again. Above all, present-day source material characteristics were similar to the formers, the LS01 materials occupied most part of them (Fig.2).

3.2 Geomorphological characteristics

Catchment longitudinal gradient was still steep, after debris flow event. By comparing gradients of six channel segments before and after debris flow, the average longitudinal gradient increased from 427.72‰ to 464.97‰. There is one exception: the sixth segmentation (F-G) decreased slightly, the others increased (Table.1). As a result, the vertical and middle erosion were mainly in upper and middle parts of the gully, and the loose accumulation were mainly in lower part. On the whole, longitudinal gradient increased in upper and middle parts of the gully, it is beneficial to initiate of debris flow. Longitudinal gradient decreased in lower part, it is of no beneficial to initiate of debris flow, but it helps to for accumulation of rainfall and loose materials. After debris flow event, there were two steep tributaries formed, especially in the middle part of the No.2 tributary was deposited by an abundance of loose accumulation, with about 1-2 m above the ground in height.

After debris flow event, there were still an abundance of loose accumulations remaining the gully, with dynamic reserve about 54.7× $10^4 m^3$. And the key LS01 had about 46.9× $10^4 m^3$. The gradient of each segmentation channel ranged between 277.3 and 682.2‰, the average gradient of main channel increased from 427.72‰ to 464.97‰. Above-mentioned reasons, the present-day channel characteristics are similar to before, and still highly prone to debris flow hazard under a certain rainfall intensity.

4. Debris flow mitigation engineering in the Shaofang gully

The maximum sediment load of main river may be exceeded due to the over loaded confluence of debris flow, which causes main channel blockage and results in a disaster chain (Cui.2013). The main river can be either partially or completely blocked by a debris flow. Therefore, the capacity of sediment load of main river should be considered in planning a debris-flow mitigation. Tang (2005) proposed an equation for estimating the degree of blockage:

$$Z = \frac{2KQ_n\gamma_n\beta}{BQ_z}$$

When Z is the discrimination value of blockage ($Z \geqslant 1.0$, the river is completely blocked. Z=1.0~0.5, the river is partially blocked. $Z \leqslant 0.5$, the river is not blocked), B is the width of the main river, Q_n is the peak discharge of bebris flow, Q_Z is the discharge of the main river, K is the correction coefficient (K=1.0~1.5), γ_n is the density of the debris flow, β is the direction angle between gully and main river.

Huang (2012) combined with actual situation of debris flows along Minjiang river, and calculated the K by inverse calculation. When K=1, analysis result is mostly approach to reality. Tang (2010) discussed the estimation method of the sediment yields from debris flows with various return period rainfall in Wenchuan earthquake area, the equation is flowing:

$$W_s = \frac{\gamma_n - \gamma_w}{\gamma_h - \gamma_w}(19 \cdot T \cdot Q_n/72)$$

When W_s is the outflow volume of debris flow, γ_h is the density of materials, γ_w is the density of water, T is the. duration of debris flow.

So, an equation for calculating the outflow volume is proposed when the Minjiang river at the critical state of being partially and not blocked by Shaofanggou debris flow (Z=0.5), the following result derived from the debris-flow data set of Table 2:

$$W_s = \frac{19TZBQ_Z(\gamma_n - \gamma_w)}{144K\gamma_n\beta(\gamma_h - \gamma_w)} = 3.2 \times 10^4 \text{ m}^3$$

In order to protect the safety of the hingway and the lives and property of locals, a debris flow mitigation project was found in the Shaofang Gully in October 2010. The design standard of the debris flow mitigation measure was to resist rainstorm-induced debris flows with a 50-year return period, and ensure the outflow volume must be less than 3.2× $10^4 m^3$

4.1 Engineering layout

In practice, as seen in Fig.2 and Fig.3, the engineering layout of debris flow prevention was applied in Shaofang gully with integrated methods including slope toe protection and stabilization, sediment trap works in gully, aqueduct over the open tunnel.

4.2 Check dams

Three check dams were adopted for controlling the initiation of remaining loose accumulations, and weakening the kinetic energy of surge in the upper part (the No.2 and No.3 segmentations) of Shaofang Gully, as shown in Fig. 4. They were all constructed using concrete, the sequence of the dams is as follows : the first dam is 5.0m high and 28.5m wide; the second dam is 5.0m high and 19.7m wide; the third dam is 5m high and 22.6m wide.

The average gradient of the upper part was larger than before about 27.25‰（Table.1）, and there were still a lot of loose accumulations remaining in gully, the structure of bank slopes were loose, with 35-55°in gradient. Steep slopes and gully bed provided terrain conditions for loose debris potential energy transformed into kinetic energy, and forming high-speed debris flow head (Tang.2009). Vertical and lateral erosion of debris flow is much larger than clear water. So block-silting method can prevent erosion of fluid, reduce the average gradient of main channel, lower impact force of debris flow head, and weaken the pressure of engineering in the middle and down parts.

4.3 A new type of drainage channel

Drainage channels are important. They are widely used in engineering owing to their structure are consisted of local materials. The styles of drainage channels are limited in debris flow gully for limited space (Okubo et al. 1997; You et al. 2011; Takahisa 2008; Chen 2014). A neo-drainage channel that will control the landslides blocking point and protect the "toe cap" in the middle reaches of Shaofang gully. It will prevent unstable source from being eroded by debris flow, reduce the volume of materials which maybe taken part in fluid.

The neo-drainage channels are made of reinforced concrete with anti-slide piles ,step-ribbed slabs and sidewalls on both sides of them (Fig.5). and connecting the ribbed slabs and sidewalls with anti-slide piles through the embedded rebar so that the sidewalls would close with soil and stone ,prevent the rainfall from eroding foundation and stabilize the overall structure. In the paper, a total 465m long channel was constructed in the No.2 tributary and the middle part of Shaofang gully, with 146 anti-slide piles (Fig.3).

Loose composition materials of LS01 front are very poor to concrete, which will be failure to block the channel while a heavy rain poured. One possible source supply model of LS01 blocking channel is supplied (Fig.6). Source supply order as follows: First of all, fluid scour loose materials of LS01 foot; Then, fluid carry material at the bottom of the slope to flow, causing the upper part of the slope to participate in the activities of debris flow; After that, sliding resistance get dramatically plunged ,causing an unbalance the upper body of slope and finally a blockage.

Let us analysis the mode from the perspective of prevention and control to analysis the model, if the LS01 foot is steadied by the neo-drainage channel, it will prevent the occurrence of step 2 and 3. As well, the No.2 tributary and "shoe toe" can be controlled by that. A lot of active source could be steadily stopped, the scale and probability of debris flow can be significantly reduced.

4.4 Check dams with opening sizes

Three check dams were constructed with opening sizes in downstream are mainly for intercepting the coarse particle and smoothing the drain fluid. The fluid which passed dams was harmless and discharged smooth into Minjiang River by aqueduct. They were all constructed with concrete, the sequence of the dams is listed as follows : the first dam is 17 m high with a maximum opening of 1.0 × 1.2 m (width × height); the second dam is 13 m high with a maximum opening of 1.0 × 1.2 m (width × height); the third dam is 17 m high with a maximum opening of 1.0 × 1.2 m (width × height).

The average gradient of the downstream was gentler than before about 23.7‰（Table.1）. Bedrock are common on both sides, that provide better conditions to dam abutment. When debris flow transit the three check dams, water and stone can be separated. The mean particle size of debris flow becomes smaller, thereby decreasing the impact forces of the large stones to the open tunnel and highway, and draining the fluid into designated area of Minjiang River. This method thus makes use of both the siltation and hazard mitigation functions of check dams. The function of engineering measures and variation of sources were illustrated in table3.

5. Effect of the debris flow mitigation engineering in the Shaofang gully

The mitigation engineering was accomplished in May 2012. On July 2013, Mozigou and Huaxigou extra large-scale debris flows were triggered by a rainstorm near Shaofanggou.

The "2013.7.10" duration rainfall was larger than "2010.8.14", but the "2013.7.10" outflow volume of debris flow was about 33 times less than "2010.8.14" (Table.4). That reflected comprehensive control project had a certain effect. The outflow volume of debris flow ($0.72\times10^4m^3$) was less than Minjiang river carrying capacity (3.2×10^4 m^3). So the "7.10" debris flow did not cause a disaster to Minjiang River. Field investigation, Three check dams were constructed in upstream, two dams were fully deposited, the other one was deposited about two thirds, and they stopped source all about $2.07\times10^4m^3$. The neo-drainage channel stopped source about $44.28\times 10^4m^3$ in midstream. Three check dams with opening sizes were stopped source about $0.5\times 10^4m^3$.

The fig.7 shows the change of upstream channel after constructing check dams. Longitudinal grade of gully reduced from 346.87‰ to 251.8‰, making fluid run slowly and dissipate the energy of debris flow. So debris flow materials were under control, the erosion rate greatly reduced, and vegetation restored. Vegetation would be served as botanical check dams (Cui.2013). Not only control gully erosion，but also protect structural check dams by load share. Looking into the vegetation which are rooted on LS01 accumulations with new-built neo-drainage channel, the restoration of vegetation grows to 70% which result directly from the gully erosion control and the protection of slope toes (Fig.8).Here is the contrast analysis on the sediment from upstream and downstream areas in table 5.

In this manner, the particle size of the sediments is smaller downstream than upstream. And the closer the distance from gully mouth, the smaller the mean particle size of specimen. This outcome indicates that check dams with opening sizes are rational.

6. Conclusions

(1)A rainstorm induced large-scale landslide type debris flow hazard occurred in Shaofang Gully on 14 august, 2010. The outflow volume of debris flow was estimated to be 250,000 m^3.The disaster destroyed highways, and blocked the part of Minjiang River. Eighty percent of outflow volume was created from the LS01.

(2) Shaofang Gully is a typical landslide type debris flow gully, abundant source materials were induced by earthquake. LS01 blocked the channel with landslide dam under "2008.5.12" earthquake action, with the failure of the landslide dam, an instant dramatic increase took place in the discharge by the "8.14" intense rainfall.

(3) After debris flow event, the total volume of source materials was approximately $223.9 \times 10^4 m^3$, dynamic reserve was about $54.7\times 10^4 m^3$. LS01 has the volume of dynamic reserve was about $48.72\times 10^4 m^3$, with an potential blocking. The average longitudinal gradient increased to 464.97‰. It is still highly prone to debris flow hazard under a certain rainfall intensity.

(4) Three check dams were adopted for controlling the initiation of remaining loose accumulations, and weakening the kinetic energy of surge in the upper part of Shaofang Gully. The neo-drainage channel using prefabricated reinforced concrete includes anti-slide piles, step-ribbed slabs and sidewalls on both sides of the channel in the middle reaches of Shaofang gully. They developed based on the characteristics of debris flow. A series of check dams with opening sizes were used to settle out debris flow particles of various sizes and separate water from stone along the gully channel. The impact forces of a debris flow can be reduced using this method.

(5) These mitigation measures in the Shaofang Gully effectively resisted a debris flow triggered by rainfall on July 10, 2013. Moreover, it effectively protected the highway and minimized losses. Field study, longitudinal grade of gully reduced from 346.87‰ to 251.8‰, vegetation restoration rate of LS01 was at about 70%, the closer the distance from gully mouth, the smaller the mean particle size of specimen. Those outcomes indicate that mitigation measures are rational for Shaofanggou landslide type debris flow.

References

Vallance JW, Scott K M, 1997. The Osceola Mudflow from Mount Rainier sedimentology and hazard implications of a huge clay-rich debris flow, GeolSoc Am. Bull 109. 143-163.

Wang, Z.Y., Qi, L.J., Wang, X.Z., (2012). A prototype experiment of debris flow control with energy dissipation structures. Nat Hazards 60:971-989 (in Chinese).

Wang, Z.Y., Qi, L.J., Wang, X.Z., (2013b). Debris flow control with energy dissipation structures-experiences from Wenjiagou. Journal of Hydraulic Engineering, 43(3):253-263 (in Chinese).

Tang,C.,2010. Activity tendency prediction of rainfall induced landslides and debris flows in theWenchuan Earthquake Areas.Journal Of Mountain Science.2010 ,28(3) :341~349(in Chinese).

Wang, T. Shi, J. S.，Wu, S. R.，2010. Formation mechanism of Wenjiagou high-speed and long-runout debris flow avalanche triggeredby Wenchuan earthquake. Journal of Engineering Geolo-gy18(5): 631-644 (in Chinese).

Luo, G., 2010. Nalysis of blocking mechanism of tangjiashan high-speed short-run landslide and dam-breaking mode of TangJia Shan barrier dam. Southwest Jiaotong University (in Chinese).

Hu, X.W., Huang, R.Q.,2009. Analysis of blocking river mechanism of TangJiaShan landslide and dam-breaking mode of its barrier dam. Chinese Journal of Rock Mechanics and Engineering 28 (1):181-189 (in Chinese).

Tang, C., T.W.J. van Asch., 2011. Catastrophic debris flows on 13 August 2010 in the Qingping area, southweatern China: The combined effects of a strong earthquake and subsequent rainstorms. Geomorphology 139-140 (2012) 559-576.

Liu, C. Z., 2012. Anaysis on Genetic Model of Wenjiagou Debris Flows in Wenchuan Earthquake Area，Sichuan. Geological Review58(4):709-716 (in Chinese).

Tang, C., Tie, Y.B., 2009. Reconnaissance and Analysis on the Rainstorm Induced Debris Flow in Weijiagou Valley of Beichuan City after the Wenchuan Earthquake. Journal of Mountain Science 27 (5): 625-630 (in Chinese).

Cui, P., Lin, Y. M.,2013. Debris-flow treatment：the integration of botanical and geotechnical methods. Journal of Resources and Ecology 4(2):97-104.

Tang, C., Huang, R.Q.,2006. Impacts of debris flow s on the reservoir of a hydropower station in the meigu river of JinShaJiang. Journal of Engineering Geology 14(2): 145-151.

Huang, X, C., 2012. The possibility of blocking river of typical debris flow in Wen ChuanEarthquake zone. Chengdu University of Technology.

Okubo,S., Ikeya, H.,Ishikawa, Y., Yamada, T., 1997. Development of new methods for countermeasures against debris flows. Recent Developments on Debris Flows, 64: 166-185.

You, Y., Pan, H.L., Liu, J.F. et al., (2011). The optimal cross-section design of the “Trapezoid-V” shaped drainage channel of viscous debris flow. J. Mt. Sci. 8:103-107.

Takahisa M., (2008). Structural countermeasures for debris flow disasters. International Journal of Erosion Control Engineering 1(2): 38-43.

Chen,X.Q., Cui, P, 2014.Engineering measures for debris flow hazard mitigation in the Wenchuan earthquake area. Engineering Geology.

Table.1 Comparison of longitudinal gradient before and after bebris flow event

Seq. No.		Before debris flow（‰）		After debris flow（‰）	
Tributary	1	/		577.4	
	2	/		726.5	
Main gully Segmentation	1 (A-B)	623.9	Average longitudinal gradient 427.72‰	682.2	Average longitudinal gradient 464.97‰
	2 (B-C)	443.3		462.1	
	3 (C-D)	211.2		277.3	
	4 (D-E)	355.4		395.9	
	5 (E-F)	526.9		579.7	
	6 (F-G)	405.6		381.9	

Table.2 Date set of Shaofanggou debris flow used for calculating the outflow volume

Gully name	T (s)	Q_z (m^3/s)	Z	B (m)	γ_n (t/m^3)	γ_h（t/m^3）	γ_w（t/m^3）	β（°）
Shaofang	3600	400	0.5	80	1.95	2.27	1.0	90

Table.3 Engineering measures and its effect (Unit: × 10^4 m^3)

Channel	Engineering measures	Main function	Designed volume of blocked source	Now volume of blocked source	Dynamic reserve before engineering	Dynamic reserve after engineering
Upstream（C-D）	Check dams	Weaken the kinetic energy of surge	2.73	2.07	2.58	1.51
Midstream（D-F）	Neo-drainage channel	Control the LS01 blocking point + protect the “ shoes toe ”	53.11	44.28	49.10	4.83
Downstream（F-G）	Check dams with opening sizes + aqueduct	Separate water and stone + discharge smooth	3.35	0.50	2.98	2.48

Table.4 Rainfall and outflow volume

Rain time	Duration rainfall (mm)	Outflow volume （$\times 10^4 m^3$）
2010.8.14	162.1	25
2013.7.10	169.6	0.72

Table.5 Specimen particle size analysis

Number of specimen	1	2	3	4	5	6
Distance from gully mouth(m)	10	30	50	70	90	980
Particle size (mm)	10.28	24.23	52.97	91.85	112.65	402.9

Specimen were taken from sediment surface; The first to fifth and the sixth specimen were taken from deposition basins of check dams in downstream and upstream areas respectively.

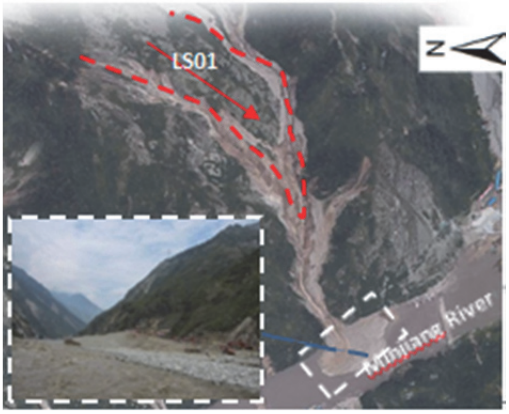
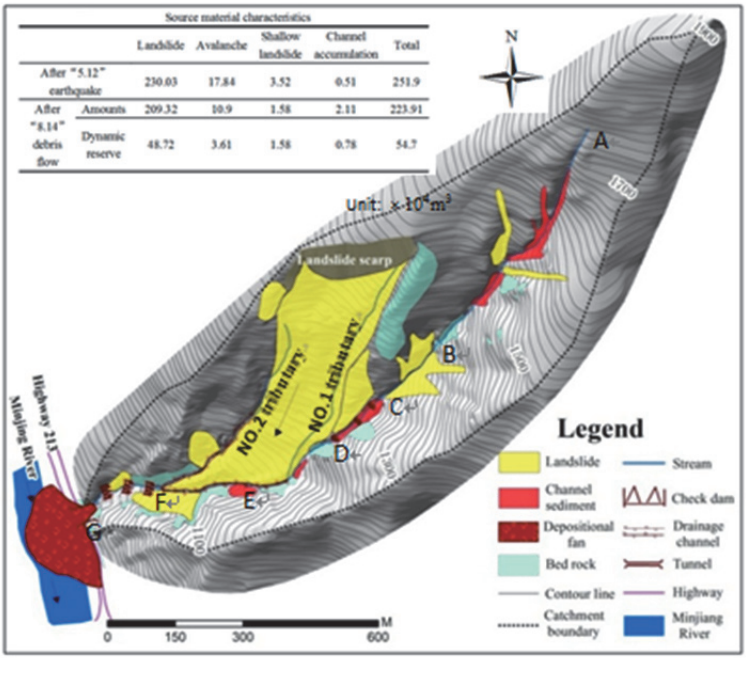


Fig.1. Aerial photograph, taken on August, 2010 showing the LS01 and depositional zone after “8.14” debris flow event


Source material characteristics

		Landslide	Avalanche	Shallow landslide	Channel accumulation	Total
After “5.12” earthquake		230.03	17.84	3.52	0.51	251.9
After “8.14” debris flow	Amounts	209.32	10.9	1.58	2.11	223.91
	Dynamic reserve	48.72	3.61	1.58	0.78	54.7

Unit: $\times 10^4 m^3$

Fig. 2 The distribution of landslide-debris in Shaofang gully catchment

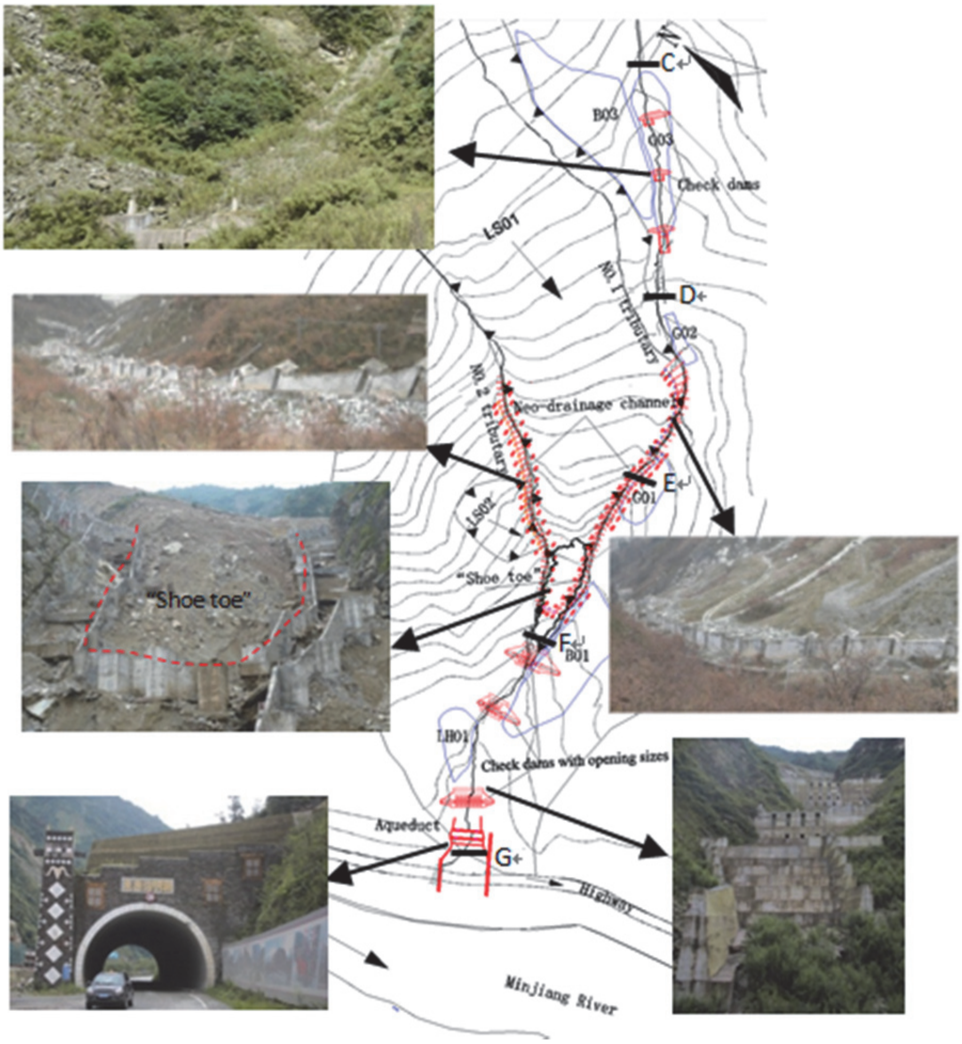


Fig. 3 Site plan and photographs of the mitigation measures in the Shaofang Gully

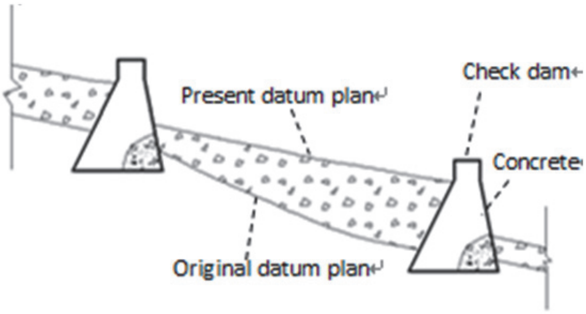


Fig. 4 Sedimentation schematic of check dams

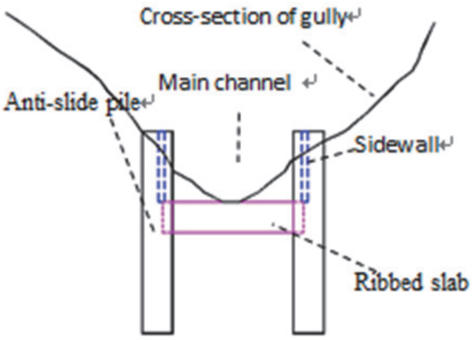
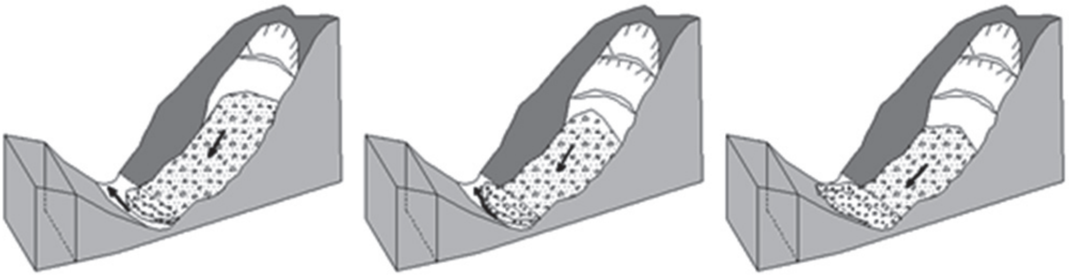


Fig. 5 Sedimentation schematic of a drainage channel



Step 1 erosion Step 2 materials participate in the activities of fluid Step 3 blocking channel

Fig. 6 One possible source supply model

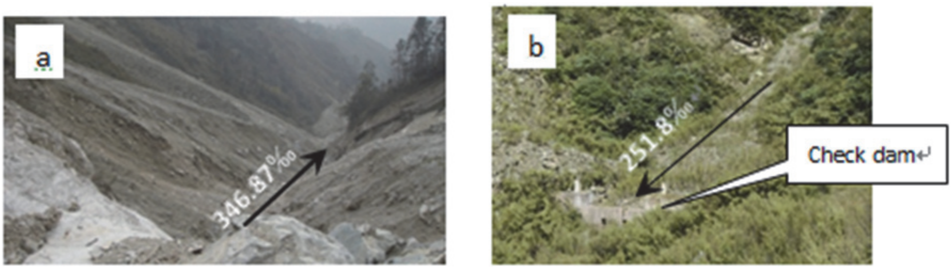


Fig. 7 The change of upstream channel prior to (a) and after (b) constructed check dams

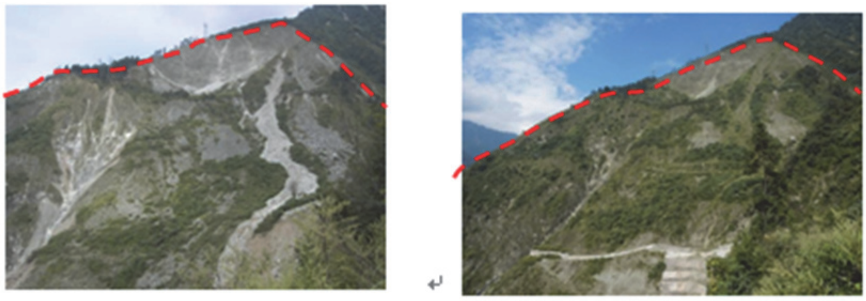


Fig. 8 Contrast of LS01 prior to (a) and after (b) constructed neo- drainage channel. Photographs are taken on September 2010 and on September 2014 respectively. Red dashed line is the top boundary of LS01.