

Article

Abrasion Behavior and Anti-Wear Measures of Debris Flow Drainage Channel with Large Gradient

Dongxu Yang ^{1,2,3}, Yong You ^{1,*}, Wanyu Zhao ¹, Hai Huang ², Hao Sun ^{1,3} and Yang Liu ^{1,3}

¹ Key Laboratory of Mountain Hazards and Earth Surface Processes, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China; dxyang@imde.ac.cn (D.Y.); wyzhao@imde.ac.cn (W.Z.); sunhao@imde.ac.cn (H.S.); liuyang@imde.ac.cn (Y.L.)

² Institute of Exploration Technology, Chinese Academy of Geological Sciences, Chengdu 611734, China; huangh@mail.cgs.gov.cn

³ University of Chinese Academy Sciences, Beijing 100049, China

* Correspondence: yyong@imde.ac.cn; Tel.: +86-028-8523-2541

Received: 25 May 2020; Accepted: 25 June 2020; Published: 29 June 2020



Abstract: Debris flow gullies have high potential energy and geomorphic characteristics including a steep longitudinal slope and abundant loose material sources. They often experience debris flow with a strong impact force and a large instantaneous flow. Drainage engineering measures are most commonly used for mitigation in these gullies. However, the abrasion of drainage channels with large gradients (DCLG) is complex and strong because of the high-speed flushing of debris. In this study, the abrasion behavior of debris flow in DCLG is analyzed based on the kinematic characteristics and the theory of composite abrasive wear. Energy dissipation and anti-wear measures are suggested, and their effects are summarized with reference to a case study and in situ observation. The results show that there are four main types of wear morphology in drainage channels. The abrasion system of drainage channels shows the characteristics of system dependency, time dependency and multidisciplinary coupling. Energy dissipation and anti-wear measures include prefabricated reinforced concrete boxes as substrate, transverse roughening belts, adding a wear-resistant admixture, etc. The flow velocity of the debris flow is reduced by 5.7–37.1% after passing through the energy dissipation section. The distribution of abrasion and the mud depth show that the variation trend of the flow velocity in the channel is “acceleration → deceleration → reacceleration”. According to tracking observations during two flood seasons, the energy dissipation and anti-wear measures are the most effective.

Keywords: debris flow; drainage channel; large gradient; energy dissipation; scour and abrasion

1. Introduction

Debris flow gullies in earthquake-affected areas and mountain areas vary, with differences in the micro-geomorphic conditions, loose material conditions and hydrological conditions [1]. High potential energy debris flow is a type of debris flow which has a steep topography in the longitudinal direction and a narrow topography in the transverse direction, and its activity characteristics and mitigation measures are distinct from others [2]. According to relevant research [3], there was a considerable amount of debris flow in the area affected by the Wenchuan MS 8.0 earthquake which occurred on 12 May 2008, which was observed in a large gradient gully with a watershed area of $F \leq 5 \text{ km}^2$, a gully bed with an average longitudinal slope of $I \geq 300\%$ and a basin integrity coefficient of $\delta \leq 0.4$ (a parameter representing the shape of a basin, which can be calculated by dividing the watershed area by the square of the length of the gully [4]). Such debris flows are defined as “narrow-steep” debris flows. Compared with ordinary debris flow gullies, such debris flow gullies feature a higher

longitudinal gradient, a larger amount of material source per square kilometer, a reduced critical rainfall for triggering debris flow and a high frequency and group occurrence of debris flow events. Typical cases are the mass debris flows which occurred on 13 August 2010 in Northwest Sichuan, China [5], the mass debris flows which occurred on 17 August 2012 in Mianzhu City, and the debris flows which occurred on 20 August 2019 in Wenchuan County, resulting in greater damage, loss and environmental impacts than those which occurred before the earthquake [6].

In terms of the mitigation strategies for debris flows with a high potential energy, the engineering measures are also different from those of common debris flows [7]. A reasonable drainage gradient of a conventional debris flow is generally 30‰ to 100‰ (dilute debris flow) or 50‰ to 180‰ (viscous debris flow) [8], while the average longitudinal slope of a high potential debris flow is generally more than 300‰. Large altitude differences in the catchment area have two consequences: one is the high flow velocity of the debris flow, some of which can be as high as 8.0 m/s; and the other is the strong carrying capacity, by which it can carry a large quantity of large-sized boulders (generally with a grain size ≥ 1.0 m). For example, the largest boulder found in the Sanyanyu debris flow gully was 12.9 m $\times$ 8.6 m $\times$ 7.2 m [7]. Therefore, the debris flow's ability to abrade is significant for the movement process. In projects for debris flow prevention and control, the limit velocity of the abrasion resistance of masonry material is 8–10 m/s and that of concrete material is 10–12 m/s [8]. If the velocity of the debris flow exceeds this limit, the structure will suffer serious abrasion, which will affect its normal operation, even reducing its service life.

The need to effectively reduce the abrasion damage of the debris flow to the bottom plate and side wall of the drainage channel and to ensure the set service life of the drainage channel are important issues in the design of drainage channels with large gradients (DCLG) [3,9]. From the perspective of engineering applications, the possible solutions can be summarized as follows [10]: (1) the approach of optimizing the structural design so as to dissipate energy at the channel bottom; (2) the measure of improving the construction material's performance, such as improving the concrete grade and adding admixtures; (3) the measure of adding auxiliary structures, such as laying formed steel structures on the channel bottom. A series of experimental studies were carried out using a new type of drainage channel with an energy dissipation structure [11–14], as well as different types and energy dissipation characteristics of debris flow deceleration baffles [15]. Chen [16] proposed a debris flow drainage channel with a step-pool configuration. Zhou [17] analyzed the erosion mechanism and stress of a debris flow slurry on the drainage channel, but this study was insufficiently supported by quantitative data. In terms of the use of auxiliary materials to improve the wear resistance of concrete, the current research mainly focuses on the wear resistance of the structural concrete of hydraulic structures, such as spillways, discharge holes and ship locks. Steel fibers, epoxy resin, steel rail and steel plate are added to the concrete as auxiliary measures [18–21]. For example, silicon powder with high hardness is suitable for micro-cutting wear, while polypropylene fibers and steel fibers with high flexibility and integrity are suitable for mitigating the impact of deformation wear [22].

However, most of the current research is focused upon model experimentation and numerical simulation, which have not been applied and efficiency-tested in engineering practice. It is necessary to further study the abrasion characteristics, energy dissipation and anti-wear technical measures of the DCLG for steep gullies. The influencing factors of debris flow abrasion capacity, the composition of the abrasion system and features of abrasion morphology, the regulating effects of energy dissipation and anti-wear measures of the drainage channel and the design and construction methods should be included so as to expand the applicable range of the use of drainage channels as a mitigation measure and improve the service life and operational uses of drainage channels.

2. Materials and Methods

2.1. Study Site Description

This study takes the Wenchuan earthquake zone, a representative area in the high mountain region of Southwest China, as the research area, and focuses on the Xiaogangjian debris flow drainage channel as an example in order to analyze the characteristics of abrasion and anti-wear measures. The Xiaogangjian gully is located in the town of Qingping, Mianzhu City, Sichuan Province. It is on the right side of the road from Mianzhu to Maoxian and on the left bank of the Mianyuan River. The coordinates of the gully fan are N 31°30'14.75" and E 104°07'44.55". The horizontal form of the watershed is shaped like a salix leaf (Figure 1), and the area of land sloping by more than 25° in the gully accounts for 85.29% of the total basin area. Moreover, the free face has become formed of loose deposits, which provides favorable conditions for the rapid collection of rainfall runoff and the development of adverse geological phenomena such as collapse, landslide and unstable slopes, as well as the transportation of a loose solid source of debris flow.

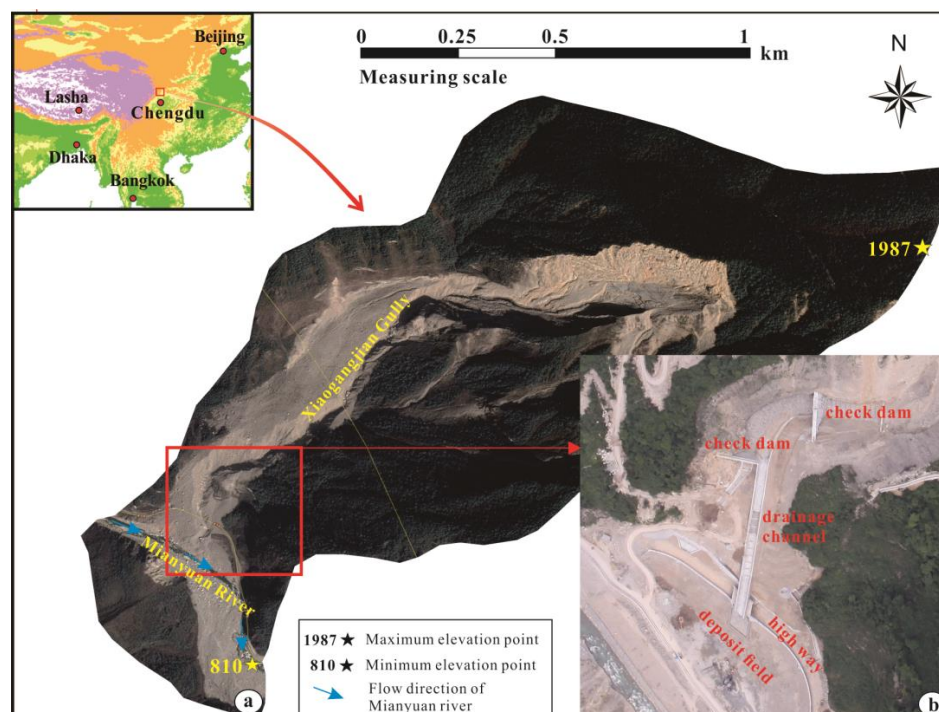


Figure 1. Location of Xiaogangjian gully and its full view. (a) Remote sensing image of Xiaogangjian's watershed in 2010 and (b) layout of the downstream mitigation works in 2011.

The Xiaogangjian gully is a typical debris flow with a high potential energy, due to a longitudinal slope of 506‰ in the formation area. The cross-section of the gully is of a deep "V" shape. The longitudinal gradient of the outlet section of the gully is 337.8‰, and on the left bank, there is a loose accumulation with a volume of $2.26 \times 10^5 \text{ m}^3$ and a slope of $42^\circ \sim 70^\circ$. There was no ditch developed before the "5.12" earthquake. After the earthquake, the topographic and hydrodynamic conditions of the gully were facilitated, and it was eroded intensely. Then, the gully developed a high susceptibility and high frequency of occurrence. From 12 May 2008 to 5 September 2011, 10 debris flows with a total volume of more than $5 \times 10^4 \text{ m}^3$ occurred, resulting in the gully being cut into a deep trench with a depth of 30–45 m and a width of 48–65 m. The debris flow burst out of the gully and rushed into the Mianyuan River. It not only buried the highway several times but also blocked the river, forming a barrier lake upstream of the accumulation fan. The geomorphological parameters of the gully are listed in Table 1.

Table 1. Geomorphological parameters of Xiaogangjian gully.

Basin Area (km ²)	Ditch Length (km)	Mean Gradient (‰)	Minimum Elevation (m)	Maximum Elevation (m)
1.36	2.59	412	810	1987

2.2. Disaster Mitigation Needs

For this kind of debris flow mitigation, there is a significant disparity between the large amount of loose material sources and the limited retaining conditions. According to a geological survey, there is, in total, $3.343 \times 10^6 \text{ m}^3$ of loose material in the Xiaogangjian gully, and the possible dynamic reserve involved in the debris flow activities measures $1.568 \times 10^6 \text{ m}^3$. The calculated loose sources per km² are $2.458 \times 10^6 \text{ m}^3/\text{km}^2$, which indicates that the debris flow was controlled by the transport of material in the 5–10 years following the earthquake [23].

However, because of the narrow and steep terrain conditions, the effective intervention area for retaining works, such as checking dams, is limited to only 15% of the total area of the basin. Moreover, the width–depth ratio of the ditch is only 1.0~1.5, so the dam locations that are suitable for construction and the reservoir capacity are very limited. Once debris flow occurs in the upper reaches, the old loose deposits in the lower reaches of the basin will be cut through in order to increase the supply sources along the gully and increase the scale of the debris flow.

From above, due to the need to prevent the formation of loose deposits at the terminus of the gully and to protect the highway on the fan and change the angle of the debris flow entering the Mianyuan River, it is necessary to build a drainage channel in order to quickly drain the rush-out materials from the middle regions to the outside of the gully (Figure 2). The channel will pass over the highway and enter the desilting field. Therefore, a DCLG must be adopted.

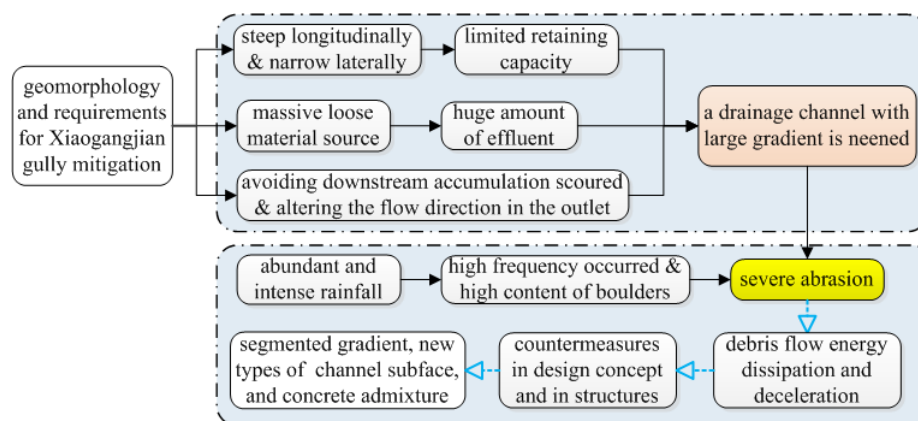


Figure 2. Analysis of design needs for drainage channel of Xiaogangjian debris flow. (The continuous arrows indicate that a drainage channel with a large gradient (DCLG) is needed for the mitigation and it will encounter abrasion, and the dashed arrows show the countermeasures for reducing the abrasion; the two blocks with different colors indicate key nodes in the design.).

2.3. The Abrasion Behavior of DCLG

Abrasion phenomena are caused by the local jet or circulation which is formed at the bottom of the structural plane by the turbulent flow of fluid with high kinetic energy, which drives the repeated impact and scour of the block stone and gravel. Abrasion behavior varies due to the changes in fluid properties, movement characteristics and channel characteristics. Debris flows with high bulk density and high viscosity have the characteristics of wide gradation, huge particles, complex interactions and energy exchange between solid and liquid phases. As a result, the abrasion mechanism of a debris flow drainage channel is also very complex, and it is obviously different from other types of

abrasion behavior such as mechanical friction, wind sand flow, high sediment flow and so on. Under the combined action of debris flow slurry erosion and coarse particle impact, the lining surface of the drainage channel shows the process of “shear or impact → strength weakening → crack generation and expansion → local stress concentration producing eddy current → gravel abrasion → gradual wear expansion and deepening → bottom stripping, cutting groove or potholes”. It could eventually cause the entirety of the bottom of the channel to be damaged, maybe even causing the side wall to overturn or wear through the bottom, thus losing the drainage function.

2.3.1. Characteristics of Abrasion Morphology (AM)

According to field investigation in the study area, the AM of debris flow on structures is mainly divided into four categories (Figure 3): (a) Relatively uniform surface peeling (USP); that is, the scraping on the surface is basically flat and creates a smooth layer by layer thinning, which appears on the bottom surface of the drainage channel and the inner faces of the side walls, when the particles in the fluid are relatively uniform and the flow state is stable; (b) Plowing groove along the streamline direction (PG), which generally appears at the bottom of a fully lined drainage channel, which is steep and long, with the fluid viscous, the bulk density high and the fluid composed of hard and angular block stones; (c) Jumping erosion pits (JEP), which are similar to the “potholes” developed on the bed rock of the high sandy rivulets and rivers in mountain areas [24], which mainly occur on the bottom of a fully lined channel with a large longitudinal slope or under the drop-sills—the flow is turbulent and easily forms eddy currents; (d) Surface wear of the ground sills (SWGS), mainly in the middle of the rib sill, forming a transverse slope from both sides to the middle.



Figure 3. Typical abrasion morphology of mitigation works of debris flow. (a) uniform surface peeling (USP) in Yinxingping gully, Wenchuan county; (b) plowing groove (PG) in Haermu gully, Lixian county; (c) jumping erosion pits (JEP) in Xiaogangjian gully, Mianzhu county; (d) surface wear of the ground sills (SWGS) in Qinglinwan gully, Beichuan county.

In field investigations, several forms of AM usually exist at the same time. With a change in working conditions, different forms of wear have different primary and secondary causes.

2.3.2. Composition and Influencing Factors of Abrasion System

From the perspective of tribology, the debris flow and channel surface can be regarded as a tribological system [25] (Figure 4a). The abrasive process has both sliding friction properties and rolling friction and micro-corrosion friction properties [26]. As a multiphase and multi-ingredient fluid, debris flow should be considered as a structural fluid composed of slurry and coarse particles [27,28]. Special friction pairs are formed by debris flow and the structural surface of a drainage channel, forming the macro-phenomenon of scour, abrasion or deposition upon the structural surface.

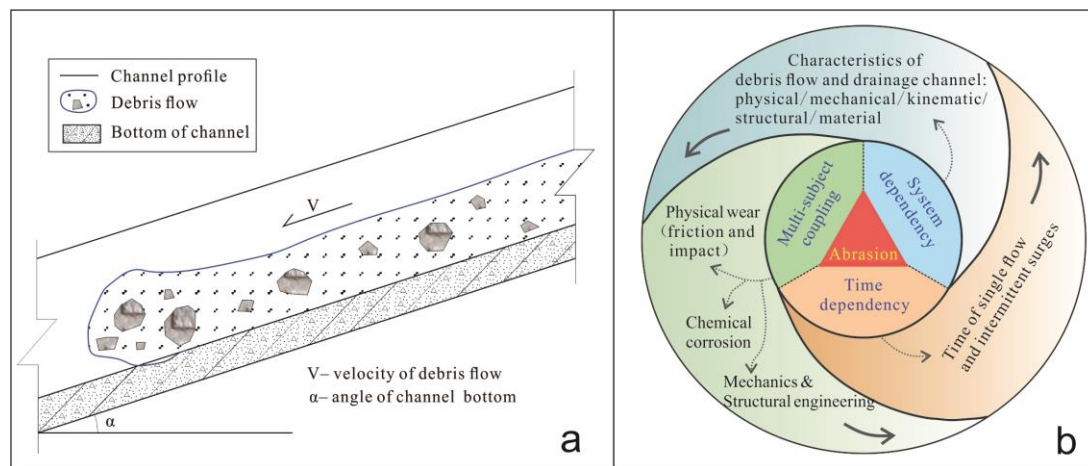


Figure 4. Schematic diagram of abrasion system of DCLG. (a) Profile of debris flow in the drainage channel; (b) elements of abrasion system of DCLG.

As a tribological system, abrasion can be studied from the effects of system dependence, time dependence and multi-disciplinary coupling (shown in Appendix A) [29]. The abrasion behavior is system dependent, and the characteristics of its elements are time dependent. The elements of the abrasion system of the DCLG are shown in Figure 4b. In the abrasion system, relative motion and interaction occur between the debris flow and the structure surface, and the two friction pairs have their own properties. The attributes of debris flow include the physical, mechanical and kinematic properties, and the attributes of a drainage channel are the structure types and materials. In terms of the disciplinary properties, these include the physical wear effects of sliding, impinging and friction on the bottom surface of the drainage channel by the block stones in the debris flow that occurred during the abrasion process, as well as the chemical corrosion between the slurry and concrete. Moreover, the abrasion is also closely related to the disciplines of mechanics (fluid mechanics, solid mechanics, and so on) and structural engineering. These attributes and behaviors are concentrated and coupled in the system, and they vary with the system's state and time.

Analyzing in terms of energy, when the debris flow passes through the drainage channel, it overcomes the shear resistance of the structural surface, and some of the energy is dissipated [30]. At the same time, some of the energy will be dissipated when the fluid collides with the structure's surface and with the particles inside the fluid. Therefore, the abrasion power of the debris flow is mainly related to such factors as bulk density, velocity, particle composition, duration, mud depth and scouring angle [28,31,32], while the abrasion resistance of the drainage channel is related to section type, material strength (shear strength, compressive strength), aggregate grading and hardness.

Based on the influencing factors, the abrasion quantity could be expressed as follows:

$$H = f(\gamma, v, \tau_0, \mu, F_D, d_{90}/d_{10}, \sigma, \alpha, E) \quad (1)$$

where γ , v , τ_0 , μ and F_D respectively represent the density, velocity, initial shear force, viscosity coefficient and drag force; d_{90} and d_{10} represent the particle size of the debris flow, which refers to the particle size of a sample when the cumulative percentage of particle size distribution reaches 90% and 10%; σ , α and E respectively represent the positive pressure, scouring angle and elastic modulus of the channel bottom.

2.3.3. Dynamic Source of the Abrasion

The dynamic source of the abrasion is the high potential energy of the debris flow. As they originate on high and steep hillsides, the longitudinal slopes of debris gullies are far larger than those of common rivers (Figure 5). With the high potential energy caused by the large height difference, debris flow washes against the DCLG, and the potential energy is rapidly converted into kinetic energy, with the flow velocity increasing along the path. The large particles contained in the fluid also move and jump rapidly under the action of gravity and drag force, which causes the impact, peeling and furrowing of grooves on the drainage structure.

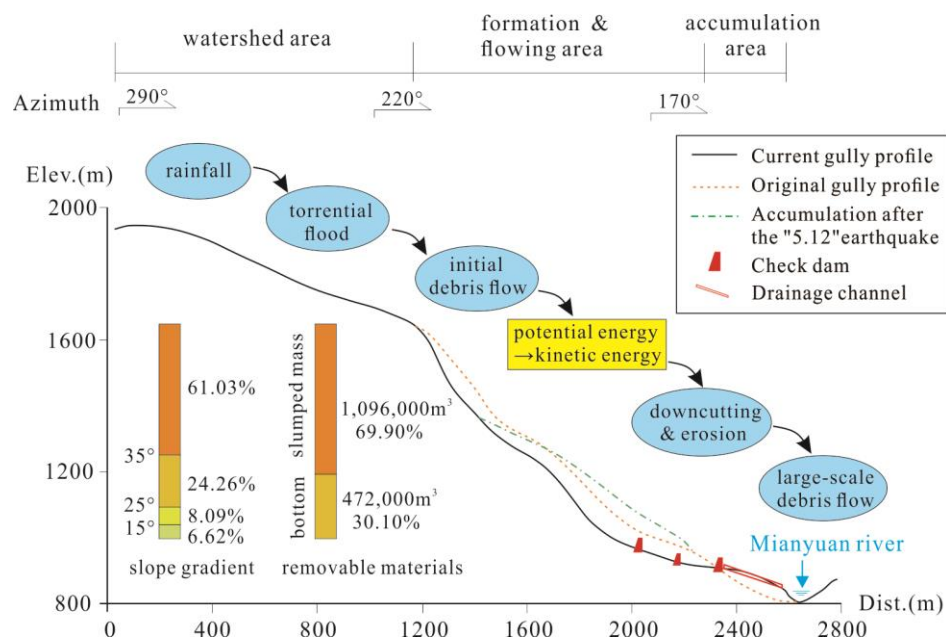


Figure 5. Source of debris flow kinetics in narrow-steep gullies.

According to the analysis of the debris flow activities in the Xiaogangjian gully from 2009 to 2013, the formation process is shown in Figure 5. The gully was covered by a layer of very thick loose overburden, and a free surface developed. Once the debris flow is formed under the action of a rainstorm, it will rapidly drain along the steep gully, which is easily cut and eroded. The most important process is the conversion of the high potential energy into high kinetic energy.

2.3.4. Calculation Method of Debris Flow Abrasion

The abrasion behavior of debris flow on the concrete of a drainage channel is as follows: a bed load with a large particle size acts on the surface of the structure by rolling friction, jumping impact, sliding friction, etc., and the suspended sediment scours the surface with the flow fluctuation, which is similar to the abrasion effect of sand in high-speed sand flow on a hydroelectric spillway. According to the theory of abrasive wear energy in sediment laden flow [33], the function of the bed load and

suspended load is expressed in a unified way and the bulk density of the debris flow is considered. The simplified expression can be written as follows:

$$I_{\alpha} = \left\{ \begin{array}{l} [\frac{1}{2\varepsilon}(V_s \sin \alpha - K)^2 + \frac{1}{2\varphi} V_s^2 \cos^2 \alpha \sin(n\alpha)](\gamma - \gamma_w)/(\gamma_s - \gamma), (\alpha \leq \alpha_s) \\ [\frac{1}{2\varepsilon}(V_s \sin \alpha - K)^2 + \frac{1}{2\varphi} V_s^2 \cos^2 \alpha](\gamma - \gamma_w)/(\gamma_s - \gamma), (\alpha > \alpha_s) \end{array} \right\} \quad (2)$$

where I_{α} is the concrete weight loss rate of abrasion (%); α is the scouring angle ($^{\circ}$); α_s is the critical angle of abrasion ($^{\circ}$); V_s is the velocity of the large particles in the debris flow (m/s); γ , γ_s and γ_w are the bulk density of the debris flow, solid particles and water (g/cm^3); K , ε , φ and n are the critical velocity (m/s), the energy consumption factor of the impact wear ($\text{kg}\cdot\text{m}^2/\text{g}\cdot\text{s}^2$), the energy factor of the micro-cutting wear ($\text{kg}\cdot\text{m}^2/\text{g}\cdot\text{s}^2$) and the horizontal resilience factor (dimensionless), which can be determined by the concrete wear resistance experiment.

2.4. Research Procedures

Theoretical analysis, field investigation, engineering practice and ongoing status observations were addressed in this study. Firstly, based on the investigation of the landform conditions and source distribution of the Xiaogangjian debris flow, the design parameters were put forward and the design concept of the DCLG was presented. Secondly, cases of drainage channels with similar natural geographical environments in the study area were investigated in order to determine the influencing factors of the abrasion. Then, the anti-wear countermeasures and details of the structure were designed and constructed. Finally, field observation was carried out during the debris flow's outbreak period, including the abrasion development process, wear morphology and the distribution and amount of damage to the lining structure caused by the debris flow's scour. Moreover, the response characteristics of the anti-wear measures of the DCLG were analyzed.

3. Results

3.1. Anti-Wear Measures of DCLG

Structure type and size were designed according to the discharge demand and terrain characteristics. The designed structural parameters of the drainage channels are shown in Table 2. The main body of the channel was cast with C25 reinforced concrete, with a full lining structure.

Table 2. The structural design parameters of the drainage channel of the Xiaogangjian debris flow.

Length (m)	Height (m)	Mean Gradient (‰)	Maximum Gradient (‰)	Width (m)	Depth (m)	Sectional Form
170.8	45.2	264.64	349.0	6.0	3.5	compound rectangle

The drainage channel was designed in three sections along the flow direction: the inlet drainage section (A), the middle steep straight section (B) and the outlet deceleration section (C), as shown in Figure 6. When the debris flow enters the drainage channel, it first decelerates from the flat gradient of section A, then turns into the steep section B to accelerate, and it finally decelerates in the outlet section C. The length of section B was 95 m and the gradient was 349‰.

Without energy dissipation (ED) measures, the velocity of the debris flow in the fully lined drainage channel can be calculated according to the improved Manning formula [34]:

$$V_c = \frac{1}{n_c} (R_c^{\frac{2}{3}} \times I_c^{\frac{1}{2}}) \quad (3)$$

where V_c is the average velocity of the debris flow (m/s); n_c is the roughness coefficient of the gully bed value according to the bottom condition of drainage channel; R_c is the hydraulic radius of the calculation section (m); and I_c is the hydraulic gradient of the debris flow.

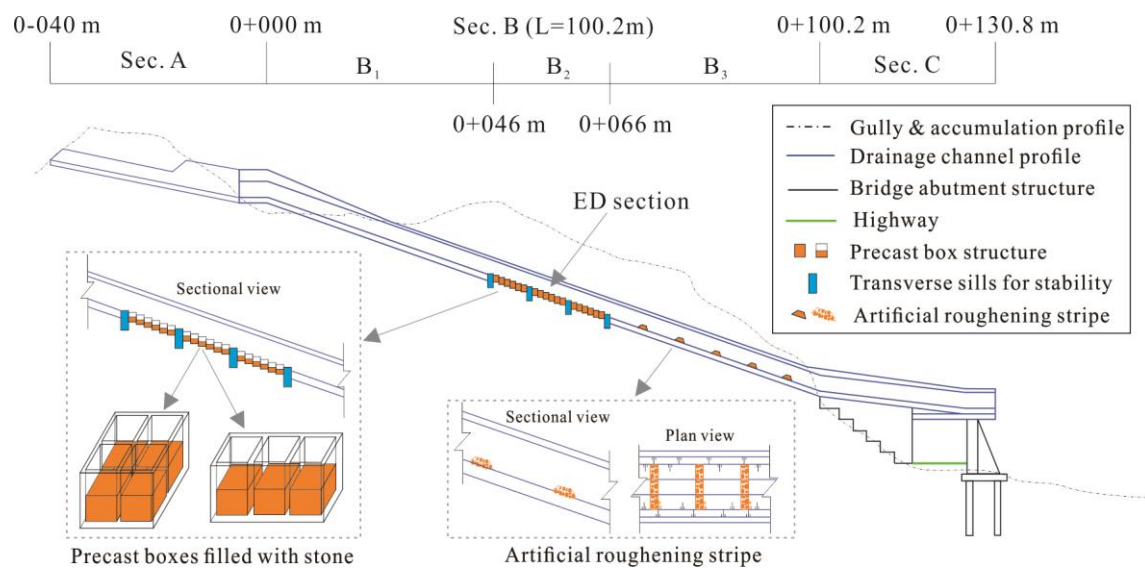


Figure 6. Design drawing of longitudinal section of DCLG in Xiaogangjian gully.

According to Formula (3), the calculated velocity of the debris flow in each channel section is listed in Table 3.

Table 3. Segmented design parameters of Xiaogangjian drainage channel.

Section	Length (m)	Discharge (m ³ /s)	n_c	R_c (m)	I_c	Velocity (m/s)
A	40.0	53.33	0.025	0.66	0.117	10.40
B	100.2		0.017	0.40	0.349	19.06
C	30.6		0.017	0.54	0.120	13.53

It can be seen from Table 3 that the designed gradient and velocity of this drainage channel exceeded the design properties of the concrete materials. In addition, the bulk density of the debris flow reached 2100 kg/m³, which can cause serious abrasion at the bottom of the channel and affect the durability and safety of the structure. Therefore, appropriate energy dissipation and anti-wear measures must be considered.

Three measures were introduced in the channel:

- The A section of the energy dissipation (ED) structure was set in the middle of the drainage channel (Figure 6, Sec. B₂). The bottom of the channel was lined with prefabricated reinforced concrete (PRC) boxes, arranged in a ladder shape along the flow direction, so as to reduce the kinetic energy and flow velocity;
- In the lower section of the drainage channel (Figure 6, Sec. B₃), a number of roughening strips were added, which were perpendicular to the flow direction and protruded from the bottom of the trough, so as to increase the roughness of the trough bottom and change the boundary conditions of the debris flow's movement;
- A wear-resistant layer with a 50 mm thickness, made of C30 steel fiber concrete, was laid on the surface of the channel bottom of Sec. B₁ and Sec. B₃ (Figure 6) to improve the wear resistance of the structure.

3.2. ED Structure Lined With PRC Boxes

The construction methods of the ED section lined with PRC boxes were as follows [35,36]: (1) On the transverse, the cavity size of a single box was set to 1.0 m × 1.2 m, which could be combined into different horizontal rows according to the design width of the channel bottom; (2) In the longitudinal

direction, it was of stepped form according to the design gradient of the channel, and each row of boxes reduced step by step along the flow direction, and the height difference of adjacent steps should be adjusted according to the gradient; (3) A deep buried rib guard was set every 6 m, with a buried depth of 2.5 m, as a longitudinal control node, to provide stable support and protection for the whole section; (4) For the detailed design of the box materials, C30 steel fiber concrete was used for key anti-scour parts; (5) The lower half of each box was filled with boulders, and the upper half was left with empty grooves, as a space for debris flow falling, mixing and material exchange, in order to promote the effective energy dissipation of the debris flow.

The whole ED section was designed with 18 rows of boxes and four rib sills, so the total length was 22 m. The four walls and bottom plates of the box were equipped with steel mesh. Drainage holes and connection holes were left on the box wall. The box was made in the prefabrication yard and cured as required, before being transported to the site for assembly. Compared with an in-situ placing channel structure, this had the advantages of easier manufacture, fast installation and good adaptability to the terrain conditions (Figure 7).



Figure 7. Pictures of energy dissipation (ED) section lined with prefabricated reinforced concrete (PRC) boxes completed. (a): From an upstream perspective of ED section, (b) Structural details of PRC boxes.

After the acceleration of the debris flow through the upper section (Figure 6, Sec. B₁), it enters the middle of the ED section (Figure 6, Sec. B₂), and the surge head firstly falls into the box body. Through the repeated process of "falling → stirring → rising and climbing → falling again", the particles in the fluid collide, displace and replace each other, and they rub with the box walls, mixing with the boulders which were pre-placed in the boxes. The energy is partially dissipated and the speed is decreased. As a result, the acceleration process of the debris flow is interrupted, and the continuous increase of the flow velocity and abrasion are prevented, with the threat of the debris flow to the lower channel section being reduced.

3.3. Roughening Belts for Channel Bottom Turbulence

After being affected by and controlled by the energy dissipation section, the debris flow enters into the lower section of the channel (Figure 6, Sec. B₃). The acceleration process starts again, which may still cause abrasion damage. In order to further control the increase in flow velocity, a series of transverse roughening belts are set up at the bottom of the channel to increase the roughness. The raised stones in the belt cause disturbances by colliding with the particles in the fluid, so as to change the flow regime of the underlying fluid, reduce the flow velocity, and then reduce the kinetic energy of the debris flow and, hence, the erosion.

The structure of the roughening belt was a strip bulge that ran horizontally through the bottom, with the top of the strip protruding from the bottom slab. The design width along the flow direction was 1.0 m, and the transverse length was the same as the width of the channel bottom. The spacing between adjacent strips was 5.0 m. Hard and wear-resistant block stones (hard sandstone, granite, etc.)

were selected to be buried in the concrete of the bottom, and blocks of different particle sizes were staggered to give the top of the whole strip both concave and convex shapes, with a raised height of 5 cm~20 cm and a buried depth of 1/2~2/3 of the particle size of the block stone (Figure 8).



Figure 8. Pictures of roughening belts for channel bottom turbulence completed. (a): From an upstream perspective of roughening belts, (b) Structural details of roughening belts.

4. Observation and Discussion

After the completion of the mitigation project, the Xiaogangjian gully encountered heavy rainfall on many occasions during the flood season of 2012–2015, which led to eight debris flows, including four flows with a scale of more than $1 \times 10^4 \text{ m}^3$, and a total scale of more than $2.2 \times 10^5 \text{ m}^3$ of deposited sediment.

4.1. Observation and Analysis of ED Effect of PRC Boxes

From the field observation of the Xiaogangjian debris flow in 2012, the regulation effect on debris flow of the PRC boxes was mainly shown in two ways: (1) the velocity of debris flow before and after passing through the section B₂; and (2) the concrete abrasion on the upstream and downstream baseplate of the section B₂.

4.1.1. Influence on the Velocity of Debris Flow before and after the ED Section

Using the debris flow video recorded in the flood season, the time of flow through each control section was found. According to the distance and the time intervals between the adjacent control sections, the average velocity of the debris flow on the plate of this section was accurately calculated (Figure 9). The selected control sections were divided into four parts: the starting point of the steep channel (0 + 000 m), the starting point of the PRC box section (0 + 046 m), the starting point of the PRC box section (0 + 066 m) and the endpoint of the steep slope section (0 + 100.2 m). In total, the flow time data of 15 debris flows were given.

The change trend of the average velocity of each debris flow in the different channel sections showed that the process of the debris flow in the three sections was as follows: acceleration → deceleration → reacceleration. Except in the case of No.1, the debris flow was gradually slowed down by the roughening belts and lay on the bottom of section B₃ due to the small scale. The other data basically conformed to this change trend. By calculating the velocity attenuation in each section, the average velocity of the debris flow was reduced by 5.7~37.1% in the ED section lined with PRC boxes (Figure 10). The attenuation rate (R_a) of velocity in the ED section can be calculated by Equation (4):

$$R_a = \frac{V_{B1} - V_{B2}}{V_{B1}} \quad (4)$$

where R_a is the rate of velocity reduction in the ED section (sec. B₂), and V_{B1} and V_{B2} is the velocity of the debris flow in section B₁ and section B₂ (m/s).



Figure 9. Observation of flow velocity change of debris flow in drainage channel (17 August 2012). Lengths of each section are $LB_1 = 46$ m, $LB_2 = 20$ m, $LB_3 = 34.2$ m.

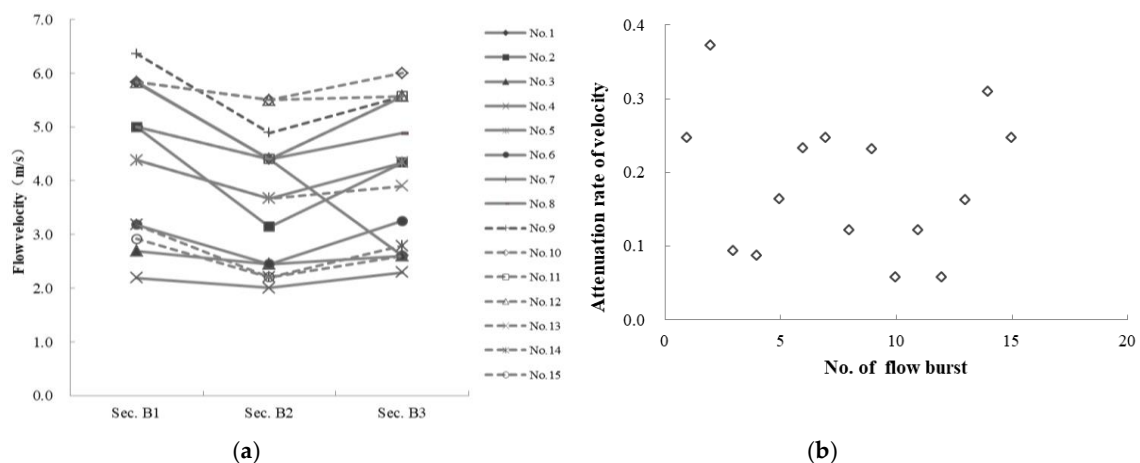


Figure 10. Observation data of velocity of debris flow. (a) Velocity change before and after ED section; (b) attenuation rate of velocity in the ED section.

Moreover, the change trend of the debris flow's velocity in the channel could also be seen from the measurements of the mud depth. Figure 11a shows that the mud trace of the debris flow which occurred on 26 July 2012 suddenly became higher in the initiating terminal wall of the ED section and stayed higher, indicating that the velocity of the debris flow in this section became slower and the mud depth was greater. Figure 11b shows that the boulders with larger particle sizes were concentrated and deposited in the ED section, which also shows that the flow velocity slowed down and the carrying capacity of the debris flow weakened. It could be seen that the flow pattern of the debris flow changed from flowing through normally to local deposition, which meant that the kinetic energy decreased.

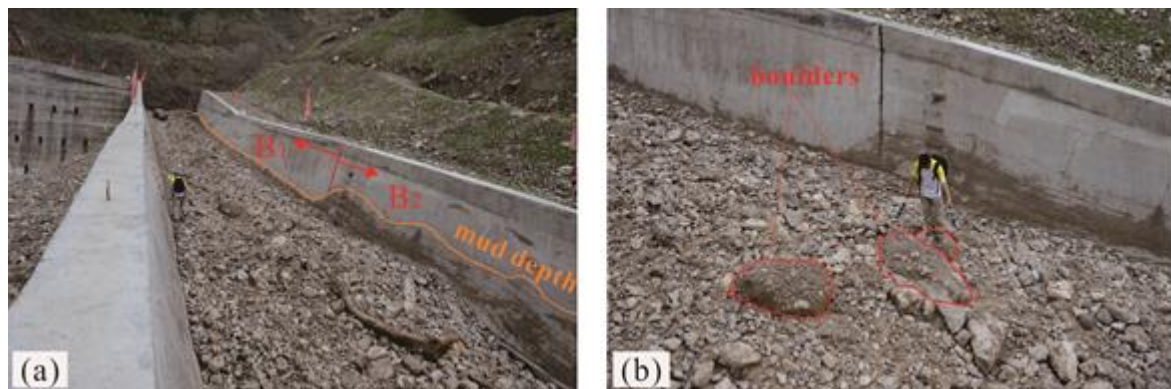


Figure 11. Photos of mud marks and siltation from the debris flow that occurred on 26 July 2012, in the ED section. (a) The mud depth of the 26 July 2012 debris flow in sec. B₁ and B₂ (ED sec.); (b) boulders deposited in the ED section.

4.1.2. Abrasion on Upstream and Downstream Baseplates of the ED Section

According to the field investigation after the debris flow occurred, the variation in the concrete abrasion at the bottom of the channel was measured, as shown in Figure 12. Photos taken on site are shown in Figure 13, which indicate that the abrasion of section B₁ (Figure 13a) was stronger than that of section B₃ (Figure 13b).

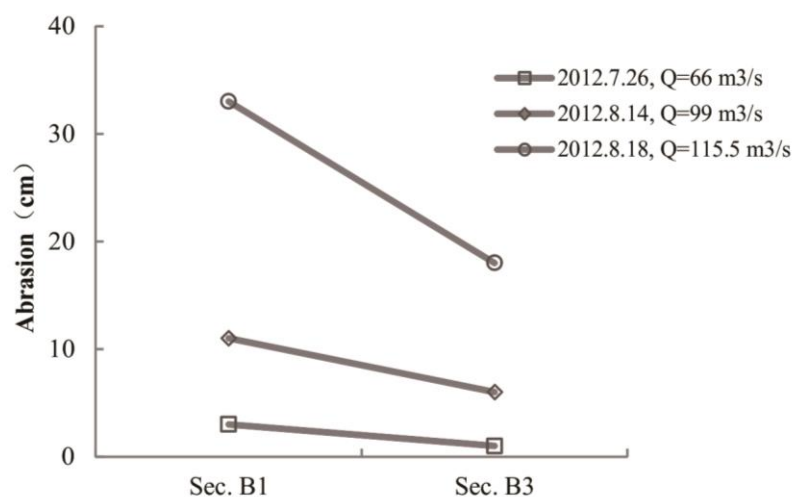


Figure 12. Development of abrasion at the bottom of the upper and lower sections of the ED section.



Figure 13. Abrasion at the bottom of the upstream and downstream sections of the channel. (a) The steel bar at the bottom of the section B₁ was almost destroyed; (b) the section B₃ was only partially exposed.

4.2. Observation and Analysis of Roughening Belt on the Bottom of the Channel

Figure 14a shows the mud depth on the side wall and the abrasion on the bottom of the roughening belt section (sec. B₃) after the debris flow of 26 July 2012, with Figure 14b showing the flow pattern of the 14 August 2012 debris flow passing through the roughening belts.

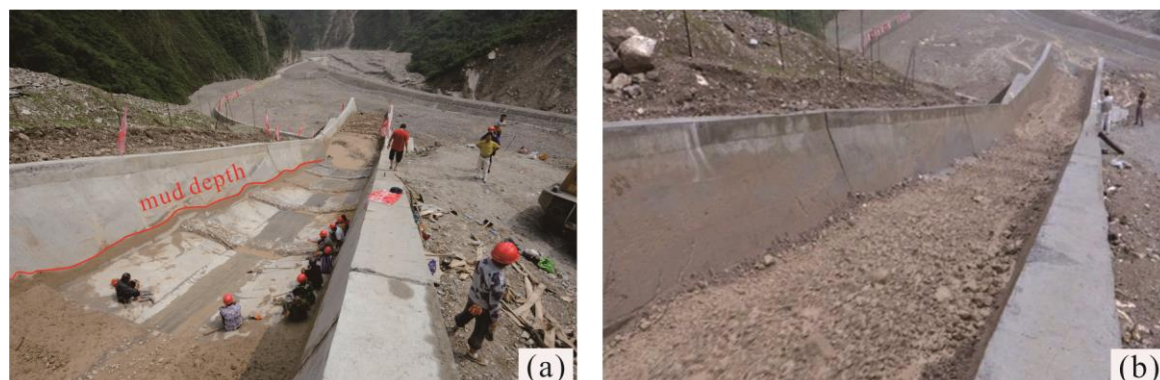


Figure 14. Mud depth and flow pattern of debris flow in the roughening belt section. (a) Mud depth on the side wall of sec. B₃ after the 26 July 2012 debris flow; (b) flow pattern of the 14 August 2012 debris flow.

It could be seen from the mud trace of the 7.26 debris flow that the mud depth was 20 cm~30 cm higher than that of the upstream and downstream regions when the roughening belt was laid at the bottom of the channel, indicating that the roughening belt had changed the flow pattern of the debris flow and caused a flow pattern of the “rise up → drop” type in the underlying fluid. Similarly, the 8.13 debris flow also showed a disturbance in the roughening belt section, forming a flow pattern of “waves moving forward”. The bumps in the roughening belts collided and rubbed with the particles in the debris flow, consuming part of the kinetic energy, thus reducing the abrasion force.

According to the investigation of the abrasion on the concrete at the bottom of the channel in the section B₃, it was relatively uniform throughout the section, and abrasion at the tail end was not more serious than that at the leading end, which showed that the velocity and the abrasion force of the debris flow were not obviously increased along the section B₃. That is to say, the roughening belts had restrained the development of concrete abrasion to a certain extent.

4.3. Applicability of Anti-Wear Measures

(1) Analysis on the different effects of abrasion resistance. Both the PRC box and the roughening belt are designed to reduce the flow velocity and abrasion by changing the roughness coefficient of the channel bottom [37]. The roughness coefficient of a drainage channel with abrasion resistance structures is always larger than that of a smooth rectangular drainage channel because of the different boundary conditions at the channel baseplate. However, there are differences in the extent of the two values. The reason is that, compared with the roughened belt, the debris flow in the PRC box obtains a larger drop range and a more intensive drop frequency, resulting in a larger dissipation of kinetic energy.

(2) The design method needs to be improved and the applicability of specific structure types and sizes needs to be analyzed. Limited to the strength and impact resistance of the block stone material, the raised height of the roughening belt in the current design is not high enough. Hence, it can only affect the fluid in the bottom layer, which is more suitable for a wide-shallow type channel; for a narrow-deep channel with a high mud level, its deceleration and wear resistance effect may not be significant. In order to enhance the effectiveness of the roughening belt, high-strength and impact-resistant materials (hard sandstone, steel, etc.) should be adopted for use as a bulge. The height of the bulge should be increased and its layout optimized. In addition, the width and spacing of the

roughening belt should be adjusted appropriately, taking into account the differences in longitudinal slope and the flow velocity.

(3) The performance of the ED structure could be enhanced in the next step. During the flood season of 2012, the PRC boxes in the ED structure had been filled with debris flow sediments, and they evolved into a stepped structure. In this situation, the sediments should either be delivered by follow-up torrential floods or be removed artificially. On the other hand, the side walls of the PRC boxes were not thick or strong enough to withstand the impact force of boulders in the debris flow. As a result, the tops of the boxes were partially damaged by local impact, and the height of the boxes became uneven, which partly affected the falling range of the debris flow. In the future, the structural type of the boxes, the width of the row and the height difference between different rows should be designed more rationally in order to avoid damage by the debris flow's deposition or impact. For example, the channel bottom of the frame formed by the cast-in-place foundation beam could be adopted.

5. Conclusions

(1) Due to its high potential and kinetic energy, the DCLG experiences high velocity and strong abrasion. There are four types of abrasion morphology in regard to debris flow drainage channels: (a) uniform surface peeling (USP); (b) plowing groove along the streamline direction (PG); (c) jumping erosion pits (JEP); (d) surface wear of the ground sills (SWGS).

(2) The abrasion system of a debris flow drainage channel has the characteristics of system dependency, time dependency and multidisciplinary coupling. The main influencing factors of abrasion intensity are bulk density, velocity, grain composition, duration, mud depth, scouring angle of debris flow, section shape, material strength (shear strength, compressive strength), aggregate grading and hardness of drainage channel structure.

(3) The engineering measures to reduce debris flow abrasion include the ED structure lined with PRC boxes in the middle section, the roughening strip in the lower section of the drainage channel and the wear-resistant layer of steel fiber concrete on the surface of the channel. Among these, the ED structure lined with PRC boxes is most suitable for the DCLG. Through changing the flow pattern of the debris flow's movement, the kinetic energy is partially dissipated and the impact force and abrasion force are weakened, which can achieve the effect of interrupting the acceleration process of the debris flow and preventing the increase in abrasion along the course. According to observational data from the flood season of 2012, the average velocity of a debris flow is reduced by 5.7%~37.1% in the ED section. The PRC box structure was shown to have the significant effect of slowing down and reducing the abrasion of the debris flow and could reduce the threat of the debris flow to the downstream section of the drainage channel.

(4) The other two structural measures also show a certain degree of abrasion reduction. According to the observations made during the flood season, the flow pattern of the debris flow in the roughening strip zone is changed and the abrasion at the bottom of the channel is relatively uniform after the overflow, which shows that the increase in flow velocity and erosion intensity along the roughened section is not significant, and the roughened zone plays a certain role in reducing abrasion. Adding high-strength fiber wear-resistant material to the concrete at the bottom of the channel is more suitable for medium and small-scale and low velocity debris flows, but the effects on high velocity and long-term debris flows are limited.

Author Contributions: Conceptualization, D.Y. and Y.Y.; methodology, Y.Y.; software, D.Y.; validation, W.Z. and H.H.; formal analysis, D.Y.; investigation, H.S. and Y.L.; resources, W.Z.; data curation, H.H.; writing—original draft preparation, D.Y.; writing—review and editing, D.Y.; visualization, H.H.; supervision and project administration, Y.Y.; funding acquisition, D.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Second Tibetan Plateau Scientific Expedition and Research (STEP) Program (Grant No. 2019QZKK0902); the National Natural Science Foundation of China (No. 41807300); and the China Geological Survey Programs (No. DD20190644 and 20190505).

Acknowledgments: The authors want to thank Xiaoqing Chen for his kind guidance and suggestion with the design of drainage channel. Furthermore, we would like to thank all the anonymous reviewers and editors for their comments.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Definition of System dependence, time dependence and multidisciplinary coupling [29]:

- System dependence: The simple system and any more complex system constituted by the simple system, whose behavior can no longer be independently realized by any one of its elements, but must be unified in the whole system to be realized. As to the abrasion system of DCLG, its elements are the properties of physical, mechanical, and kinematics of debris flow; and the structure type and material of drainage channel.
- Time dependence: In the tribological system, the changes caused by the relative movement and interaction of the surfaces are much faster than those caused by other behaviors in the components. Therefore, a general system, which is usually treated as a time-invariant system, must be treated as a time-varying object in the tribological analysis. In the abrasion system of DCLG, the time refers to the duration of debris flow surges.
- Multi-disciplinary coupling: The tribology system is the study of the law of interaction between different behaviors in the tribological environment, which is beyond the theories and methods of any other discipline to which the behavior belongs. It focuses on behavioral relationships. The disciplines of abrasion system of DCLG may contain physical wear (friction and impact), chemical corrosion, mechanics (fluid, solid and fracture mechanics), and structural engineering.

References

1. Cui, P.; Chen, X.Q.; Zhu, Y.Y.; Su, F.H.; Wei, F.Q.; Han, Y.S.; Liu, H.J.; Zhuang, J.Q. The Wenchuan Earthquake (May 12, 2008), Sichuan Province, China, and resulting geohazards. *Nat. Hazards* **2009**, *56*, 19–36. [\[CrossRef\]](#)
2. Cui, P.; Zhuang, J.Q.; Chen, X.Z.; Zhang, J.Q.; Zhou, X.J. Characteristics and Countermeasures of Debris Flow in Wenchuan Area After the Earthquake. *Adv. Eng. Sci.* **2010**, *5*, 10–19. [\[CrossRef\]](#)
3. Yang, D.X.; You, Y.; Chen, X.Q.; Zhao, W.Y.; Shi, S.W.; Xie, Z.S. Typical characteristics and mitigation of debris flow in narrow-steep gullies in the Wenchuan earthquake areas. *Hydro. Eng. Geol.* **2015**, *42*, 146–153. [\[CrossRef\]](#)
4. Han, Z.; Xu, L.R.; Su, Z.M.; Wang, L.; Chen, S.Y. Research on the method for calculating the bulk density of debris flow based on the integrity coefficient of watershed morphology. *Hydro. Eng. Geol.* **2012**, *39*, 100–105. (In Chinese)
5. Xu, Q. The 13 August 2010 Catastrophic Debris Flow in Sichuan Province: Characteristics, Genetic Mechanism and Suggestion. *J. Eng. Geol.* **2010**, *18*, 596–608. (In Chinese)
6. Gong, X.L.; Chen, K.T.; Chen, X.Q.; You, Y.; Chen, J.G.; Zhao, W.Y.; Lang, J. Characteristics of a Debris Flow Disaster and Its Mitigation Countermeasures in Zechawa Gully, Jiuzhaigou Valley, China. *Water* **2020**, *12*, 1256. [\[CrossRef\]](#)
7. Chen, X.Q.; You, Y.; Cui, P.; Li, D.J.; Yang, D.X. New Control Methods for Large Debris Flows in Wenchuan Earthquake Area. *Adv. Eng. Sci.* **2013**, *1*, 14–22. [\[CrossRef\]](#)
8. Zhou, B.F.; Li, D.J.; Luo, D.F.; Lv, R.R.; Yang, Q.X. *Guidelines For Debris Flow Prevention*; Science Press: Beijing, China, 1991; pp. 125–126. ISBN 7-03-002612-8.
9. Tímea, K.; Gabriel, J.A.; Károly, F. Bank Processes and Revetment Erosion of a Large Lowland River: Case Study of the Lower Tisza River, Hungary. *Water* **2019**, *11*, 1313. [\[CrossRef\]](#)
10. Yang, D.X. Key Technologies of Treatment for Debris Flow in Narrow-Steep Gullies in Wenchuan Earthquake Areas: A Case Study for Xiaogangjian Debris Flow in Mianzhu Country. Master's Thesis, Univ. of Chinese Academy of Sciences, Beijing, China, 2013.
11. Chen, J.G.; Chen, X.Q.; Li, Y.; Wang, F. An experimental study of dilute debris flow characteristics in a drainage channel with an energy dissipation structure. *Eng. Geol.* **2015**, *193*, 224–230. [\[CrossRef\]](#)

12. Chen, J.G.; Chen, X.Q.; Chen, H.Y.; Zhao, W.Y. Characteristics of viscous debris flow in a drainage channel with an energy dissipation structure. *J. Mt. Sci.* **2016**, *13*, 223–233. [[CrossRef](#)]
13. Chen, J.G.; Chen, X.Q.; Zhao, W.Y.; Yu, X.B.; Wang, X.J. Experimental study on the characteristics of a debris-flow drainage channel with an energy dissipation structure. *Bull. Eng. Geol. Environ.* **2017**, *76*, 341–351. [[CrossRef](#)]
14. Liang, C.F.; Saeed, A.; Hanif, P.; Poorya, T.; Samkele, T. Investigation of Flow, Erosion, and Sedimentation Pattern around V aried Groynes under Different Hydraulic and Geometric Conditions: A Numerical Study. *Water* **2019**, *11*, 235. [[CrossRef](#)]
15. Wang, F.; Chen, X.Q.; Chen, J.G.; You, Y. Experimental study on a debris-flow drainage channel with different types of energy dissipation baffles. *Eng. Geol.* **2017**, *220*, 43–51. [[CrossRef](#)]
16. Chen, X.Q.; Chen, J.G.; Zhao, W.Y.; Li, Y.; You, Y. Characteristics of a Debris-Flow Drainage Channel with a Step-Pool Configuration. *J. Hydraul. Eng.* **2017**, *143*, 04017038. [[CrossRef](#)]
17. Zhou, F.C.; Huang, B.S.; Yang, G.; Chen, H.K. Mechanism of Turbulent Debris Flow Destroying Drainage -canal. *J. Mt. Sci.* **2001**, *19*, 470–473.
18. Horszczaruk, E.K. Hydro-abrasive erosion of high performance fiber-reinforced concrete. *Wear* **2009**, *267*, 110–115. [[CrossRef](#)]
19. Horszczaruk, E. Abrasion resistance of high-performance hydraulic concrete with polypropylene fibers. *Tribologia* **2012**, *1*, 63–72.
20. Lim, T.Y.; Paramasivam, P.; Lee, S.L. Analytical Model for Tensile Behavior of Steel-Fiber Concrete. *Mater. J.* **1987**, *84*, 286–298.
21. Ziad, B.; Jack, Z. Properties of Polypropylene Fiber Reinforced Concrete. *Mater. J.* **1993**, *90*, 605–610.
22. Chithra, S.; Kumar, S.R.R.S.; Chinnaraju, K. The effect of colloidal nano-silica on work ability, mechanical and durability properties of high performance concrete with copper slag as partial fine aggregate. *Constr. Buil. Mater.* **2016**, *113*, 794–804. [[CrossRef](#)]
23. Bovis, M.J.; Jakob, M. The role of debris flow conditions in predicting debris flow activity. *Earth Surf. Proc. Land.* **1999**, *24*, 1039–1054. [[CrossRef](#)]
24. Zhou, S.Z. Are all Potholes Markers of Quaternary Glaciations? *Quat. Sci.* **2006**, *26*, 117–125.
25. Xie, Y.B. On the tribology design. *Tribol. Int.* **1999**, *32*, 351–358. [[CrossRef](#)]
26. Wen, S.Z. Research Progress on Wear of Materials. *Tribology* **2008**, *28*, 1–5.
27. Shu, H.P.; Ma, J.Z.; Yu, H.C.; Marcel, H.; Zhang, P.; Liu, F.; Qi, S. Effect of Density and Total Weight on Flow Depth, Velocity, and Stresses in Loess Debris Flows. *Water* **2018**, *10*, 1784. [[CrossRef](#)]
28. He, Z. Interactions between severe environment and concrete resistance to abrasion and erosion. *J. Hydraul. Eng.* **2015**, *46*, 138–146.
29. Xie, Y.B. Three Axioms in Tribology. *Tribology* **2001**, *21*, 161–166.
30. Pan, H.L.; Huang, J.C.; Ou, G.Q. Mechanism of Downcutting Erosion of Debris Flow Over a Movable Bed. *J. Mt. Sci.* **2015**, *12*, 243–250. [[CrossRef](#)]
31. Huang, X.B.; Yuan, Y.Z.; Wang, S.X. Mechanism and Prediction of Material Abrasion in High-Velocity Sediment-Laden Flow. *J. Hydrol.* **2006**, *18*, 760–764. [[CrossRef](#)]
32. Banihabib, M.E.; Iranpoor, M. Determination of the Abrasion of Aprons of Dams by Debris Flow. *Int. J. Mater. Struct. Integ.* **2015**, *9*, 262–271. [[CrossRef](#)]
33. Li, Y.J. Estimation Method of Sand Abrasion in Hydraulic Structures. *J. Hydraul. Eng.* **1989**, *20*, 60–66.
34. Hu, K.H.; Tian, M.; Li, Y. Influence of flow width on mean velocity of debris flows in wide open channel. *J. Hydraul. Eng.* **2013**, *139*, 65–69. [[CrossRef](#)]
35. Chen, X.Q.; Cui, P.; You, Y.; Li, D.J. Engineering measures for debris flow hazard mitigation in the Wenchuan earthquake area. *Eng. Geol.* **2015**, *194*, 73–85. [[CrossRef](#)]
36. Chen, J.G.; Chen, X.Q.; Zhao, W.Y.; You, Y. Debris Flow Drainage Channel with Energy Dissipation Structures: Experimental Study and Engineering Application. *J. Hydraul. Eng.* **2018**, *144*, 06018012. [[CrossRef](#)]
37. Auel, C.; Albayrak, I.; Boes, R.M. Turbulence Characteristics in Supercritical Open Channel Flows: Effects of Froude Number and Aspect Ratio. *J. Hydraul. Eng.* **2014**, *140*, 04014004. [[CrossRef](#)]

