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Dynamic Analysis and Hazard Assessment of Debris Flows in Donghaolitaogao

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Abstract: ***Utilizing the FLO-2D software, the motion processes of debris flows in Donghaolitaogao under 20-year, 50-year, and 100-year return periods of rainfall are analyzed, revealing that as the rainfall return period increases, the debris flow velocity, accumulation depth, and accumulation area all significantly expand. Specifically, under the 20-year, 50-year, and 100-year rainfall conditions, the maximum debris flow velocities are 1.85 m/s, 1.95 m/s, and 1.99 m/s, respectively, while the maximum accumulation depths are 1.31 m, 1.33 m, and 1.35 m, and the total accumulation areas are 27,267.8 m^2, 31,500.6 m^2, and 33,901.3 m^2, respectively. Using the depth of debris flow and the product of debris flow depth and velocity as evaluation indicators, the debris flow hazard assessment indicates that the Donghaolitaogao debris flow is primarily characterized by low- and medium-risk areas, with high-risk areas scattered sporadically along the central part of the channel. Moreover, as the rainfall return period increases, the area of high-risk zones continues to expand, gradually accounting for a larger proportion of the total hazard zone.***

Keywords: Dynamic analysis of debris flow, Hazard assessment, FLO-2D.

1. Introduction

Debris flows refer to solid-liquid mixed fluids formed by rainfall, snowmelt, and other factors on hillsides and valleys. They are a common type of geological disaster in nature, characterized by complex formation processes, suddenness, and strong destructive power [1]. Research on debris flows can be traced back to the mid-19th century, when European countries such as Germany reduced the occurrence of debris flows by building protective embankments and other measures, providing early evidence for debris flow prevention and control. Research on debris flows can be traced back to the mid-19th century, when European countries such as Germany reduced the occurrence of debris flows by building protective embankments and other measures, providing early evidence for debris flow prevention and control. Welder et al. [2] made significant contributions to the development of debris flow studies by summarizing and consolidating the early research findings on debris flows. Their efforts have greatly advanced our understanding of this natural hazard. Through field investigations of debris flows in Soviet regions and with reference to dynamics, Breiman [3] defined debris flows as high-speed fluids with a high volumetric concentration. Japanese scholar Velikonov et al. [4] building upon the debris flow mechanics model established by Soviet scientists, authored the book "Debris Flows and Their Prevention Methods." This book provides a detailed introduction to the prevention and control methods of debris flows under various topographical and geomorphological conditions. American scholar Johnson [5] discovered through physical experiments that the relationship between the flow velocity and stress of debris flows is not linear, and proposed a debris flow motion equation based on the Bingham viscoplastic flow model. Roman scholar Francesco [6] proposed a debris flow mobility prediction model by statistically analyzing the relationship between the flow distance of debris flows and their solid volume.

Japanese scholars were the first to achieve results in debris flow numerical simulation. Takahashi et al. [7] conducted a simulation of the movement state of debris flows with water and rock as the material source. In the simulation process, they combined a semi-empirical and semi-theoretical erosion rate formula with an expanding body model, successfully constructing a Bagnold expanding body model for debris flows. The experimental results obtained were basically consistent with field investigations and verifications. Dr. O'Brien [8] successfully developed the FLO-2D software based on the Bingham model and the dilatancy model. Savage et al. [9] found that the Lagrangian method exhibits significant advantages through their research on the specific collapse and sliding processes on rough inclined planes. Brufau et al. [10] improved the finite volume method to solve the one-dimensional differential motion equation and employed the solid-liquid mixing dynamics equation to simulate the dynamic process of debris flow. Iverson et al. [11] developed a numerical model based on Coulomb's criterion by studying the interactions and constitutive relationships between particles. Bertolo et al. [12] conducted research on the movement process and accumulation range of debris flows in small watersheds by selecting appropriate numerical simulation software based on actual conditions. In summary, with the continuous development of computer technology, experts and scholars have made significant achievements and progress in debris flow numerical simulation, and the rationality and accuracy of simulation results have continued to improve. However, due to limitations such as assumptions, long simulation times, and incomplete parameter settings, further research and improvements are still needed. Zhao et al. [13] utilized unmanned aerial vehicle imagery to create a 3D realistic model of high and steep rock slopes, providing a novel approach for establishing debris flow dynamic analysis models. Song et al. [14] selected nine influencing factors, including the degree of slope weathering and slope gradient, as indicators for landslide risk assessment, and applied catastrophe theory to this assessment, thereby establishing a new stability evaluation model. Song et al. [15] established a new model for debris flow risk assessment along reservoir banks based on the concept of connection expectation, which allows for a unified analysis of the interval forms and evolutionary trends of debris flow risk assessment indicators.

2. The Characteristics of the Donghaolitaogao Debris Flow

The Donghaolitaogao debris flow, located in a high-susceptibility area, has occurred twice, in 1998 and 2021 respectively, causing the complete destruction of 600 mu (approximately 40 hectares) of farmland and resulting in direct economic losses of over ¥ 600,000. Therefore, this debris flow has been selected as a typical case for research. Donghaolitao debris flow is situated in the Baranzhelimu Town, Horqin Right Middle Banner, with a watershed area of approximately 0.92 km^2 and slopes along its banks ranging from 30° to 40°. The watershed's highest elevation is 711 m, while the lowest is 461 m, resulting in a relative relief of 250 m. The watershed exhibits a leaf-shaped topography, as depicted in Figure 1.

The Donghaolitaogao debris flow forms in a low mountain and hilly terrain, with a vast catchment area. The formation zone boasts an open terrain, dominated by weeds, and the main source of debris is the sediment accumulated at the bottom of the ravine, as shown in Figure 2. Within the flow zone, there is an artificial retaining dam (constructed in 2010) with a height of 7 m, as depicted in Figure 3a. The flow zone is relatively tortuous, with a downcutting depth of 2-2.5 m. It is primarily composed of loose accumulations that turn into a muddy consistency when the water content is high. The accumulation zone has a fan-shaped appearance, with a railway traversing it. Along the railway, there is a 2.5 m high masonry retaining wall, as illustrated in Figure 3b. Furthermore, there is a square culvert beneath the railway to guide the flow, as shown in Figure 3c. However, concerns arise that the culvert's functionality may be compromised due to potential siltation in the future, thereby increasing the risk of debris flow impacting the railway and nearby villages.

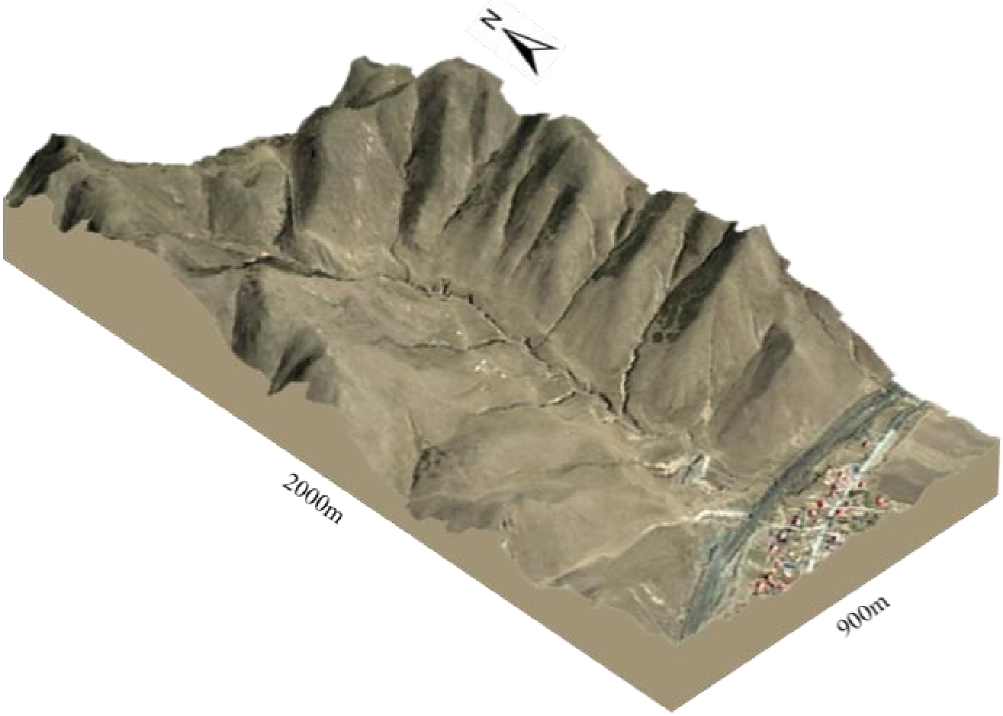


Figure 1: Three-dimensional terrain map of Donghaolitaogao debris flow

Figure 2: Source of Sediment Accumulation at the Bottom of the Ravine

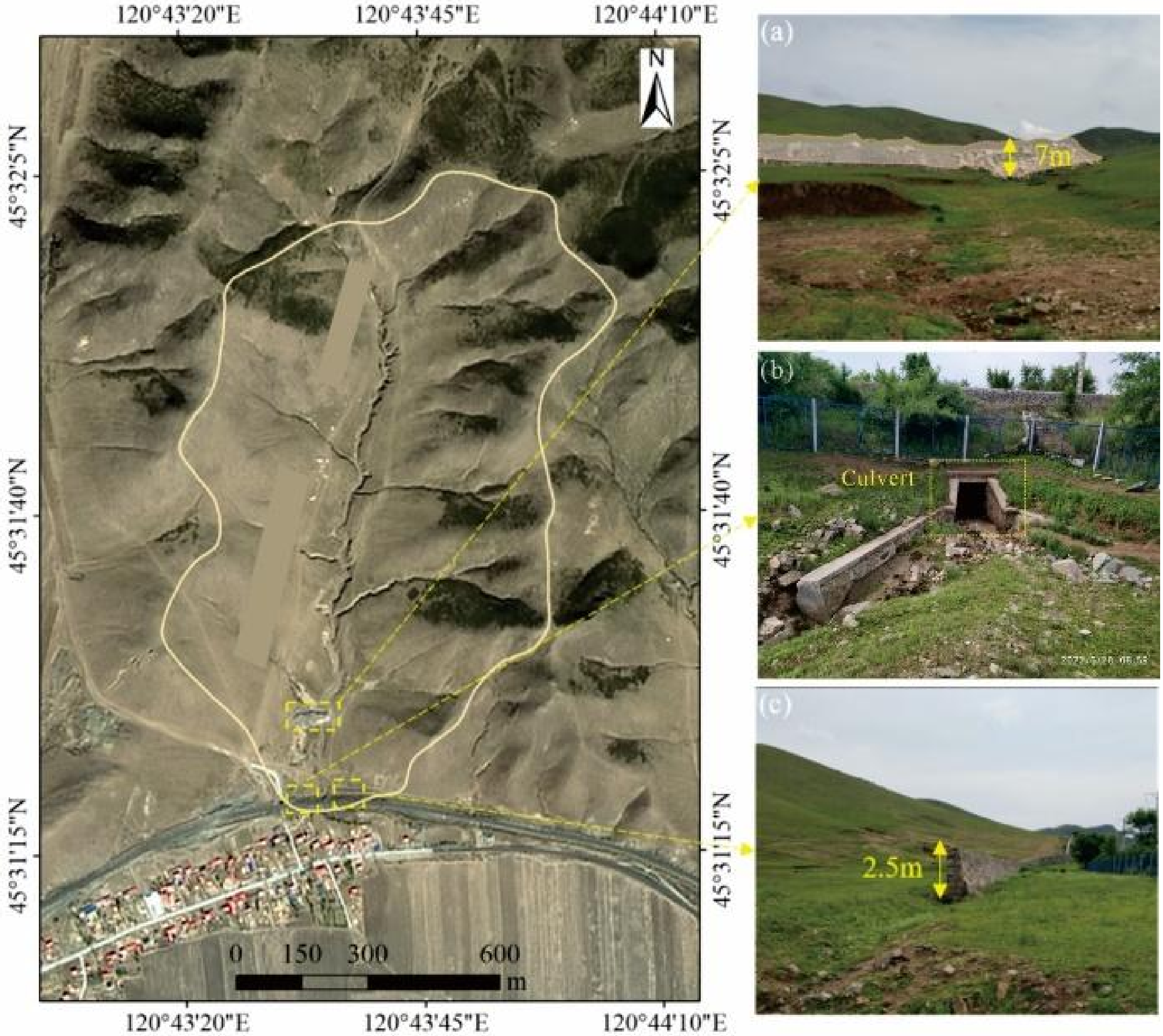


Figure 3: Overview of Donghaolitaogao Debris Flow

3. Dynamic Analysis of Typical Debris Flows

3.1 Simulation of the Movement Process of Donghaolitaogao Debris Flow

3.1.1 Selection of Simulation Parameters

1) Volumetric weight

The bulk density of debris flow, a crucial parameter in numerical simulations, directly influences the degree of damage and impact range of debris flows. It is influenced by various factors such as the solid content and material composition of the debris flow. Additionally, the bulk density is also affected by the magnitude of the peak rainstorm flow. Currently, the main methods for determining the bulk density of debris flow include field slurry preparation and table lookup methods.

In this study, the table lookup method is adopted to determine the bulk density of the Donghaolitao debris flow, based on Appendix G of the "Code for Investigation of Debris Flow Disaster Prevention and Control Projects." Appendix G outlines 15 influencing factors, each of which can be categorized into four levels: extreme, moderate, mild, and unlikely to occur. Each level corresponds to a specific score, and the total score for the Donghaolitao debris flow is obtained by summing the scores of all influencing factors. Finally, the bulk density of the Donghaolitao debris flow is derived by referring to the bulk density table in the code. Through field investigations and expert scoring, the Donghaolitaogao debris flow is assessed to have a susceptibility score of 74, and the corresponding bulk density (γ_c) is determined to be 1.509 t/m^3 using the table lookup method.

2) Volume concentration

In the study of debris flows, the volume concentration directly affects the rheological properties of the fluid and the accuracy of numerical simulations. Debris flow is a dense sediment flow containing a large number of solid particles. Due to the uneven distribution of liquid and solid, the ratio of solid to liquid has a significant impact on the rheological properties of debris flow. According to the rheological equation of the model, the volume concentration of debris flow has a significant impact on the mechanical relationship between particles, determining the viscosity and flow characteristics of debris flow fluid. The formula for calculating the volume concentration.

$$\text{Volume concentration}=\frac{v_s}{v_s+v_w} \quad (1)$$

In the formula: v_s represents the volume content of solid material, and v_w represents the volume content of water. This article refers to the recommended values in the FLO-2D user manual and combines actual conditions to determine the volume concentration of debris flow in Donghaolitaogao as 0.35 and 0.40.

3) Yield stress and viscosity coefficient

Yield stress and viscosity coefficient are two important parameters in simulating the flow process of debris flows. Yield stress represents the minimum stress required for debris flow to deform under force, while viscosity coefficient indicates the magnitude of resistance encountered during the flow of debris flow. These parameters are obtained through inversion of previous experimental results and have been widely used in numerical simulations. The empirical formula for these parameters is as follows:

$$\tau_y = \alpha_2 e^{\beta_2 C_V} \quad (2)$$

$$\eta = \alpha_1 e^{\beta_1 C_V} \quad (3)$$

In the formula: τ_y represents the yield stress, represents the viscosity coefficient, and α_1, $_2$, $_1$ and $_2$ represent empirical coefficients. By consulting the FLO-2D manual and combining with previous studies [16], the final values of α_1=0.811, $_2$=0.0462, $_1$=13.72 and $_2$=11.24 are determined.

4) Manning's coefficient

The Manning coefficient, represented by the symbol 'n', is a dimensionless constant that reflects the roughness of the ground surface. A higher value of the Manning coefficient indicates a rougher surface. During the simulation process using FLO-2D, the Manning coefficient significantly impacts factors such as debris flow velocity and deposition depth. When there are differences in the micro-geomorphological characteristics of the study area, different Manning coefficients should be set based on actual conditions.

In this study, the selection of the Manning coefficient is made according to the FLO-2D manual and the actual conditions of the study area. Due to the differences in micro-geomorphological characteristics between the flow zone and the deposition zone, the selection of the Manning coefficient is divided into two regions based on the values chosen in previous studies by other scholars: In the sparsely vegetated flow zone, the Manning coefficient is set to 0.15, while in the deposition zone with building distributions, the Manning coefficient is set to 0.40.

5) Laminar flow resistance coefficient

Debris flow exhibit the characteristic of stratified flow, and the degree of friction between various flow layers is commonly represented by the laminar flow resistance coefficient K. A higher value of K indicates a greater degree of friction between layers.

Based on the research data provided in the FLO-2D user manual and combined with actual field investigation results, this study determines the laminar flow resistance coefficient K for the Donghaolitaogao debris flow to be 2285.

6) Peak flow rate of rainstorm flood

By consulting relevant data and specifications, the point design storm rainfall for the study area under different rainfall return periods (20 years, 50 years, 100 years) has been obtained, as shown in Table 1. The duration of this debris flow simulation is designed to be 30 minutes.

Table 1: Point design storm rainfall amount

Return period /year	20	50	100
Rainfall amount /mm	33.30	38.42	42.10

According to the empirical formula proposed by the China Highway Research Institute, when the debris flow basin area F<3 km^2, the formula for calculating the peak flow rate of the rainstorm flood is:

$$Q_p = \psi F I \quad (4)$$

In the formula: Q_p represents the peak flow rate of the rainstorm flood (m^3/s) under a certain rainfall return period; Ψ represents the runoff coefficient, which is determined based on the empirical table of runoff coefficients in the "New Mining and Mining Design Manual"; F represents the catchment area (km^2); and I represents the point design storm rainfall amount (mm).

Using Eq (4), the peak flow rate of the rainstorm flood for the Donghaolitaogao debris flow is calculated as shown in Table 2:

Table 2: Peak Flow Rate of Rainstorm Flood under Different Rainfall Return Periods

Catchment area /km^2	Runoff coefficient	Peak flow rate of rainstorm flood /m^3·s^{-1}		
		20a	50a	100a
0.92	0.3	9.2	10.6	11.6

7) Peak discharge of debris flow

According to the "Code for Engineering Geological Investigation of Debris Flow Disaster Prevention and Control", the formula for calculating the peak discharge of debris flow can be expressed as:

$$Q_c = (1+\varphi) Q_p D_c \quad (5)$$

Where: Q_c represents the peak discharge of debris flow (m^3/s); φ represents the sediment correction coefficient; Q_p represents the peak flow of rainstorm under a certain rainfall recurrence interval (m^3/s); D_c represents the debris flow blockage coefficient, which is determined according to the field survey table. The peak discharge of debris flow in Donghaolitaogao obtained from Eq (5) is shown in Table 3.

Table 3: Peak discharge of debris flow under different rainfall recurrence intervals

φ	D_c	Peak discharge of debris flow /m^3·s^{-1}		
		20a	50a	100a
0.467	1.5	20.2	23.3	25.5

8) Clear water flow hydrograph

The flow hydrograph is a critical element in the dynamic simulation process of debris flow. In this paper, based on the pentagon method, the simulation duration of debris flow is divided into two time nodes, which are 1/3 and 2/3 of the total duration, respectively. Then, 1/4 and 1/3 of the peak flow value of clear water are assigned to these time nodes, respectively. Finally, a clear water flow hydrograph is successfully plotted, as shown in Figure 4.

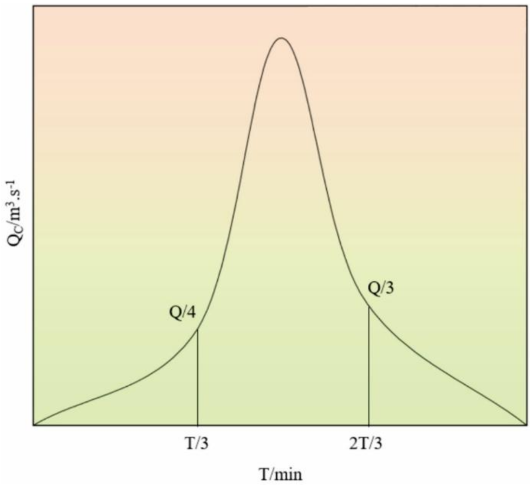


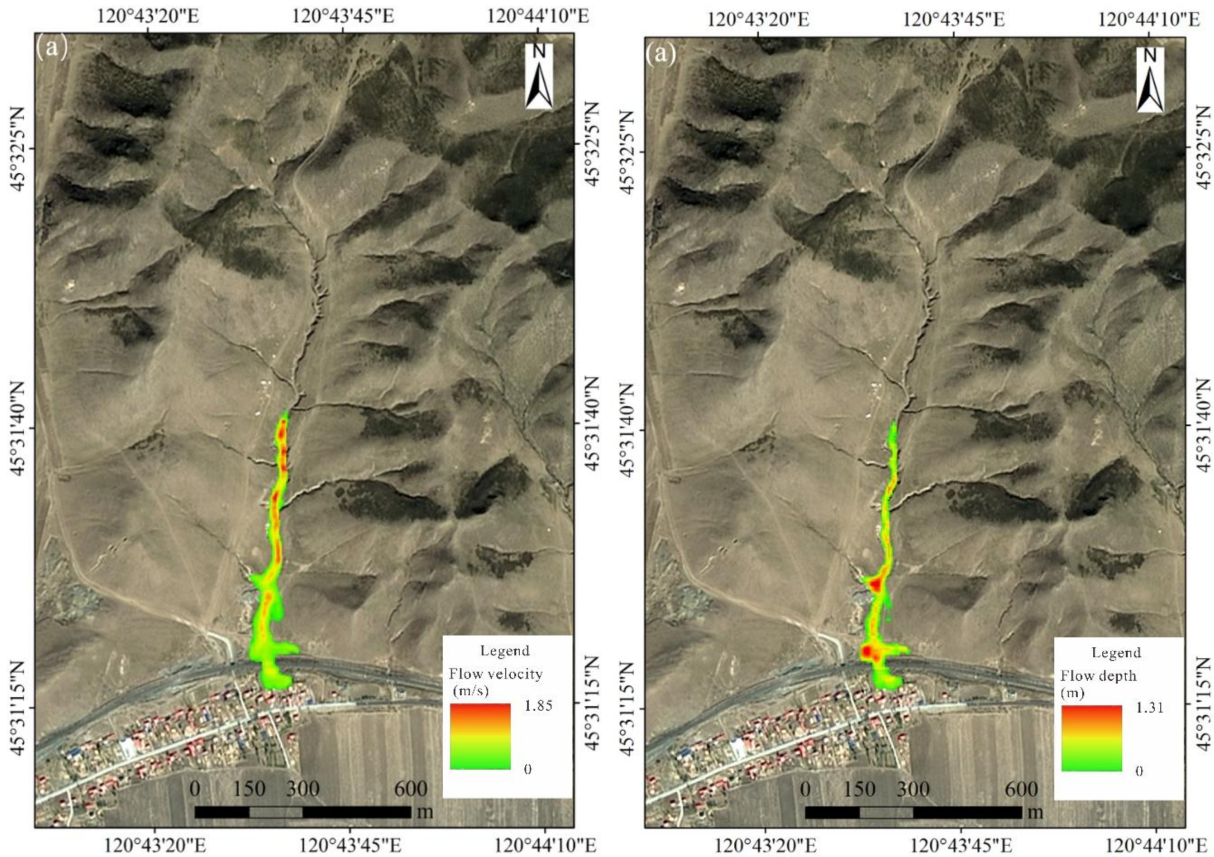
Figure 4: Schematic diagram of the pentagon method

9) Selection of catchment points

The catchment point represents the starting position of debris flow outbreak, which directly affects the numerical simulation results of debris flow. The catchment point is usually set at the intersection of the formation area and the circulation area. However, when there are many tributary gullies in the debris flow, it is necessary to consider the scale of the tributary gullies and the abundance of sediment sources comprehensively. After analyzing the debris flow in Donghaolitao, one catchment point was set at the intersection of the two main tributary gullies. Although there are multiple tributary gullies in this debris flow, the other tributary gullies are relatively small and have less sediment sources, so separate outlet points are not set.

3.1.2 Analysis of simulation results

In this study, the movement process of the debris flow in Donghaolitaogao under extreme rainfall conditions with return periods of 20 years, 50 years, and 100 years is simulated, and the simulation results are shown in Figure 5.



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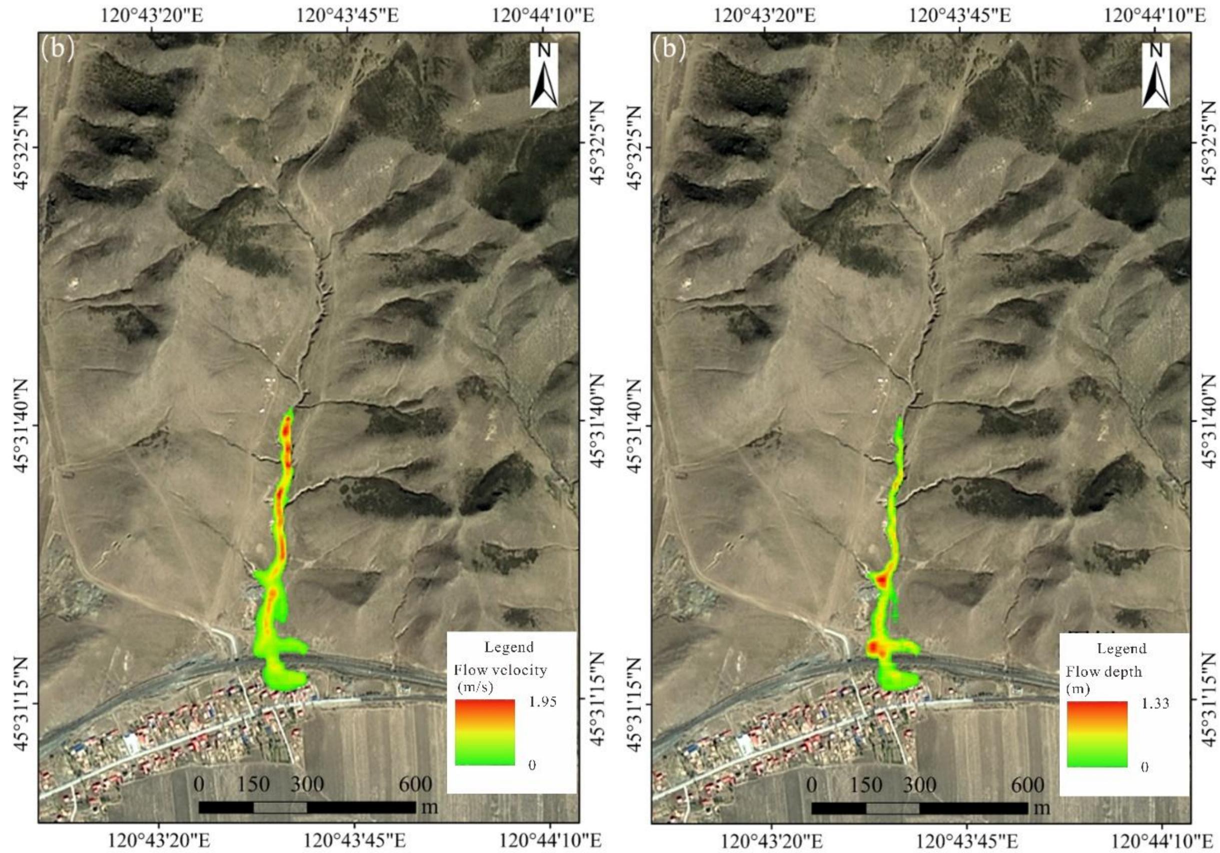

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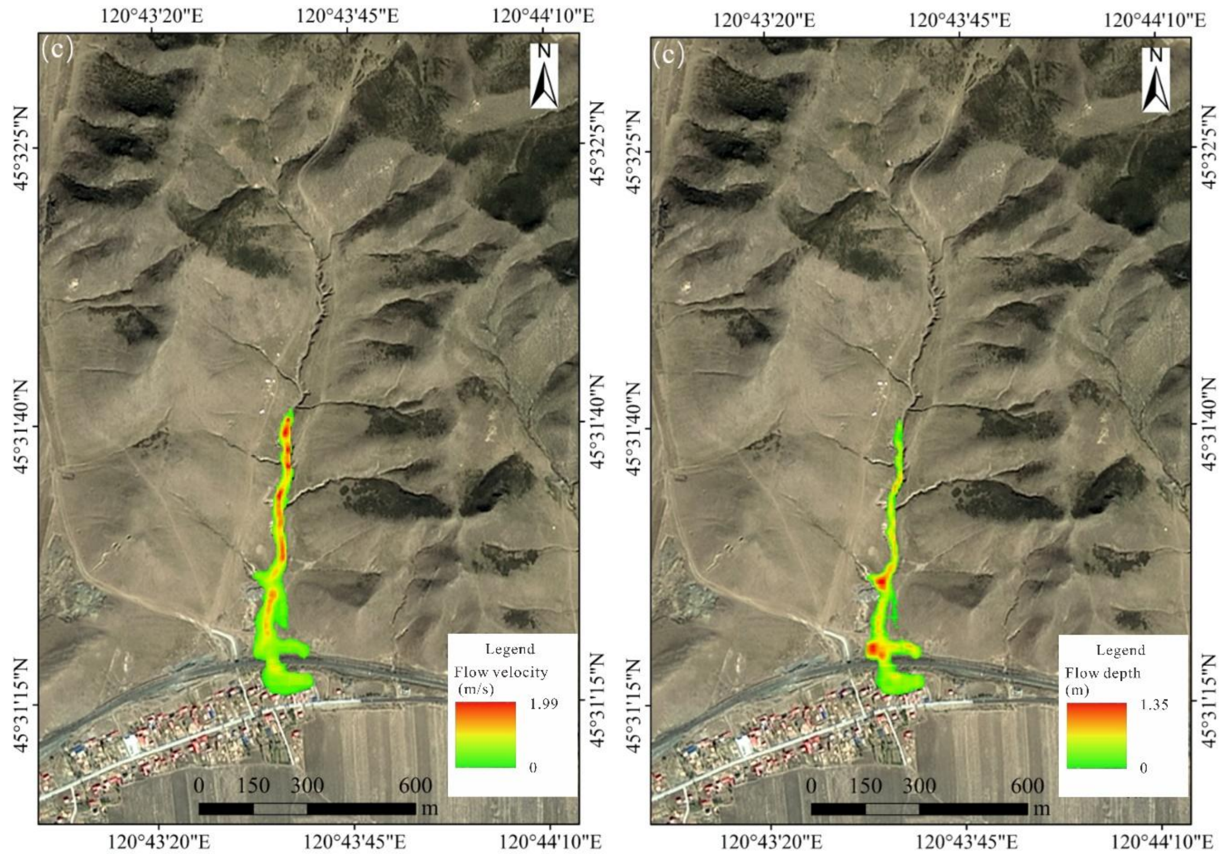


(c)

Figure 5: Debris flow velocity, accumulation depth and accumulation range under different rainfall recurrence periods

Note: (a) 20-year recurrence period, (b) 50-year recurrence period, (c) 100-year recurrence period.

1) Characteristics of debris flow velocity

As shown in Figure 5, under the 20-year rainfall recurrence period, the debris flow velocity gradually increases at the initial stage of the outbreak, reaching a maximum of 1.85 m/s below the catchment point and above the artificial retaining dam. The velocity gradually decreases to below 1 m/s at the front edge of the artificial retaining dam and the railway. Under the 50-year rainfall recurrence period, the debris flow velocity increases compared to the 20-year recurrence period, with a maximum velocity of 1.95 m/s, which is still located below the catchment point and above the artificial retaining dam. The velocity decreases to below 1 m/s at the front edge of the artificial retaining dam and the railway. Under the 100-year rainfall recurrence period, the overall characteristics of debris flow velocity are basically consistent with the other two conditions, with a maximum velocity of up to 1.99 m/s.

Analysis of the debris flow velocity maps reveals that the debris flow flows faster in the circulation area and gradually slows down in the accumulation area. The reasons for this are: (1) The accumulation area has a smaller elevation difference compared to the circulation area, lacking the conditions to convert gravitational potential energy into kinetic energy, resulting in a higher flow velocity in the debris flow channel and a lower flow velocity in the accumulation area. (2) The accumulation area is more obstructed by buildings and other structures compared to the circulation area, hindering the flow of debris flow fluids and causing the flow velocity to slow down. (3) The channel width in the debris flow circulation area is narrower compared to the accumulation area, leading to a concentration of stress directions and accelerating debris flow. In contrast, the accumulation area exhibits a divergent shape, which is not conducive to stress concentration, resulting in a decrease in debris flow velocity.

2) Depth and extent of debris flow accumulation

As shown in Figure 5 and Table 4, under the 20-year rainfall recurrence period, the total debris flow accumulation area is 27,267.8 m^2, with a maximum accumulation depth of 1.31 m, and an accumulation area of 878.1 m^2 where the mud depth exceeds 1 m. Under the 50-year rainfall recurrence period, the total debris flow accumulation area increases to 31,500.6 m^2, an increase of approximately 16% compared to the 20-year recurrence period. The maximum accumulation depth is 1.33 m, and the accumulation area where the mud depth exceeds 1 m is 1,067.1 m^2. Under the 100-year rainfall recurrence period, the total debris flow accumulation area further increases to 33,901.3 m^2, an increase of approximately 8% compared to the 50-year recurrence period. The maximum accumulation depth is 1.35 m, and the accumulation area where the mud depth exceeds 1 m is 1,248.8 m^2. In all three rainfall scenarios, the debris flow accumulates to the greatest depth at the front edge of the artificial retaining dam and in the accumulation area, and there is a positive correlation between the depth and extent of debris flow accumulation and the rainfall recurrence period. Under the 20-year rainfall recurrence period, the debris flow does not flow out of the gully mouth, posing no threat to the village and railway. But, under the 50-year and 100-year rainfall recurrence periods, the debris flow flows out of the gully mouth, threatening the village and railway.

Table 4: Statistics of debris flow accumulation depth under different rainfall probabilities

Recurrence interval /year	Total accumulation area /m^2	0-0.5m Accumulation area /m^2	0.5-1m Accumulation area /m^2	1-1.5m Accumulation area /m^2
20	27267.8	17763.8	8625.9	878.1
50	31500.6	20719.7	9713.8	1067.1
100	33901.3	22326.7	10325.8	1248.8

Through analysis of the simulation results, the following characteristics of the Donghaolitaogao debris flow are identified: (1) The accumulation depth of the debris flow gradually decreases from the center of the accumulation area towards the outer regions at the front edge of the artificial retaining dam and within the accumulation area. (2) The accumulation depth of the debris flow significantly increases at the bends and turns of the channel. The reasons for these characteristics are analyzed as follows: (1) During the accumulation process of the debris flow, there is a gradual expansion of the accumulation area. As the expansion occurs, the fluid velocity and kinetic energy gradually decrease, resulting in the maximum depth at the center of the accumulation and gradually decreasing depths on both sides. (2) At the bends or turns of the channel, due to obstruction, the velocity of the debris flow slows down, eventually leading to accumulation.

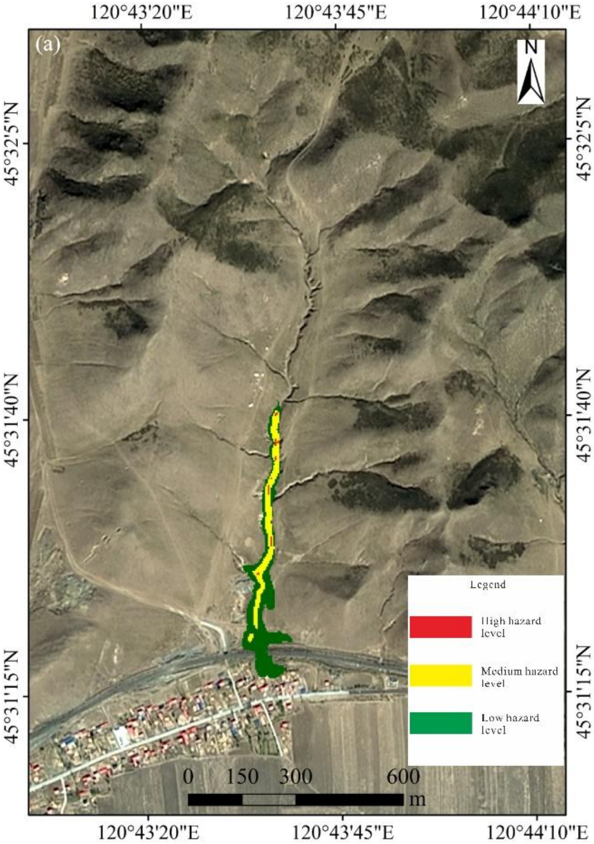
3.2 Hazard Assessment of the Donghaolitaogao Debris Flow

This study assesses the risk of the Donghaolitaogao debris flow based on its actual conditions, specifically categorizing it into three risk zones: high, medium, and low, as shown in Table 5.

Table 5: Debris flow risk assessment table

Risk classification	Mud depth(m)	Relationship	Product of mud depth and flow velocity
High	$H \geq 1.5$	Or	$V \times H \geq 1.5$
Medium	$0.5 \leq H \leq 1.5$	And	$0.5 \leq V \times H \leq 1.5$
Low	$H \leq 0.5$	And	$V \times H \leq 0.5$

In this study, ArcGIS software was used to process the simulation results, ultimately producing a risk zoning map of the Donghaolitaogao debris flow, as shown in Figure 6. Analysis of the debris flow risk zoning map revealed that the high-risk areas are mainly scattered in the center of the channel, the medium-risk areas are concentrated on both sides of the channel, and the low-risk areas are distributed at the outermost edges of the channel and at the deposition site at the mouth of the channel. Under the rainfall recurrence intervals of once in 20 years, once in 50 years, and once in 100 years, the total debris flow risk areas are 33,437.66 m^2, 38,646.8 m^2, and 41,873.5 m^2, respectively. Among these, the high-risk areas are 525.7 m^2, 1,310.4 m^2, and 1,925.2 m^2, accounting for 1.6%, 3.4%, and 4.6% of the total risk area, respectively. As the rainfall recurrence interval increases, both the total debris flow risk area and the high-risk area, as well as the proportion of the high-risk area to the total risk area, increase significantly.



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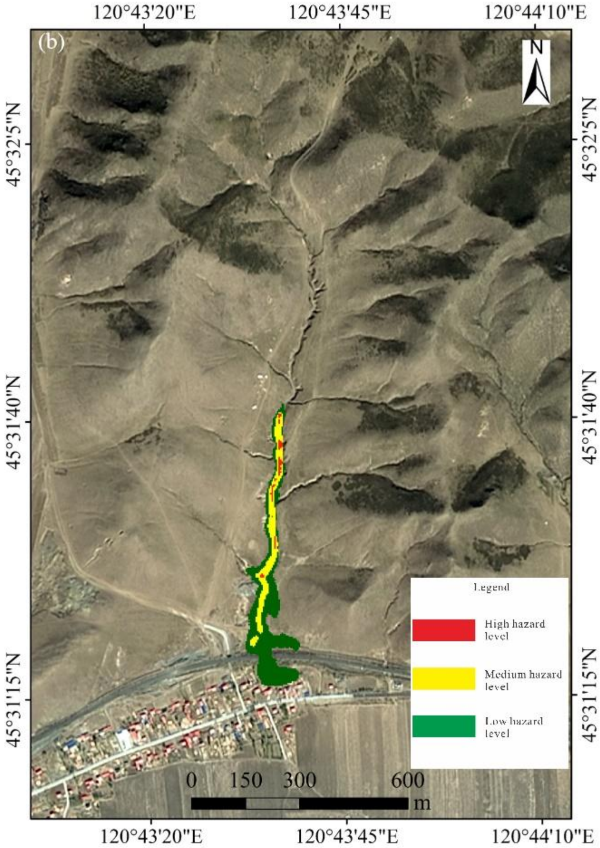

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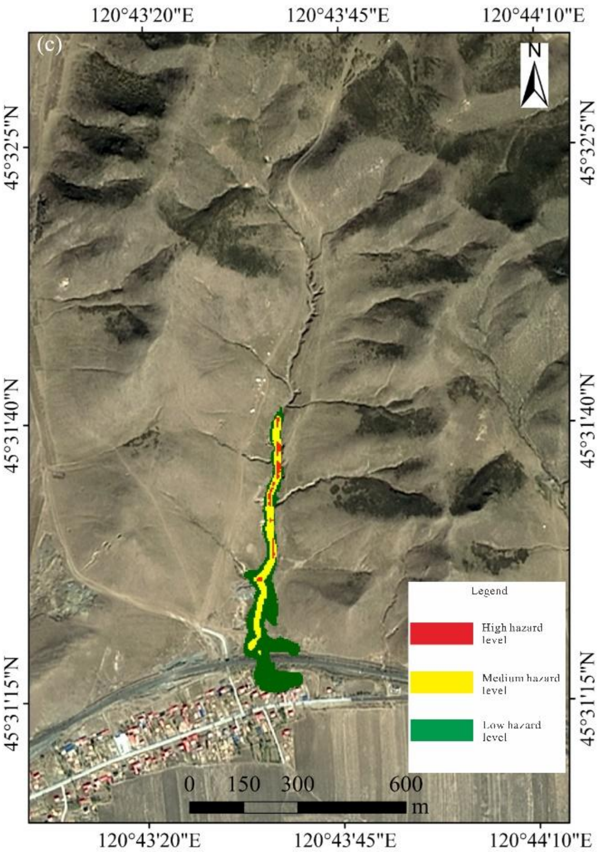

(c)

Figure 6: Debris flow risk zoning under different rainfall recurrence intervals

Note: (a) Once in 20 years, (b) Once in 50 years, (c) Once in 100 years

4. Conclusion

The Donghaolitaogao debris flow, located in a high-susceptibility area, was selected as a representative case for further examination. The FLO-2D software was employed to simulate the dynamic processes of this debris flow under various rainfall recurrence intervals. The specific conclusions are as follows:

(1) The flow velocity, accumulation depth, and total accumulation area of debris flows increase significantly with longer rainfall recurrence intervals. Specifically, under 20-year, 50-year, and 100-year rainfall recurrence intervals, the maximum flow velocities during debris flow movement are 1.85 m/s, 1.95 m/s, and 1.99 m/s, respectively; the maximum accumulation depths are 1.31 m, 1.33 m, and 1.35 m, respectively; and the total accumulation areas are 27,267.8 m^2, 31,500.6 m^2, and 33,901.3 m^2, respectively.

(2) By utilizing debris flow depth and the product of debris flow depth and velocity as evaluation indicators under different recurrence intervals, the risk assessment of the Donghaolitaogao debris flow indicates that the area is dominated by low- and medium-risk zones. High-risk zones are scattered within the center of the channel, medium-risk zones are concentrated along the sides of the channel, and low-risk zones are located at the outermost edges and the deposition site at the mouth of the channel.

Credit Authorship Contribution Statement

Zijian Chen: Writing - original draft, Writing - review & editing. **Shengyuan Song:** Conceptualization, Funding acquisition, Supervision. **Baotian Li:** Funding acquisition. **Ze Yang:** Data curation, Formal analysis, Methodology, Validation, Investigation. **Muye Ma:** Data curation, Formal analysis, Investigation.

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