Research on Early Warning Technology for Highway Geological Disasters Induced by Precipitation Conditions in Changbai Mountains

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Abstract: This study uses 10 types of data, including geological disaster data, precipitation data, elevation data, and vegetation data, to quantify the factors that affect geological disasters, and uses the analytic hierarchy process to analyze each influencing factor, which obtains the weight value of each factor, and conducts risk assessment of geological hazards in the Changbai Mountain area. In addition, it analyzes the data of geological disasters induced by precipitation conditions to obtain the effective precipitation threshold that induces geological disasters. The meteorological early warning levels of geological disasters are divided based on the effective precipitation threshold, and a geological disaster early warning model with precipitation conditions as the inducement is established. The results show that continuous rain is the most important type of rainfall that causes geological disasters in the Changbai Mountains, and what is more likely to cause disasters is heavy rain phenomena that occur during continuous rain. When the rainfall in continuous rain exceeds 30mm, the number of landslides and collapse disasters increases rapidly. When the cumulative rainfall is 30-80mm, landslides and collapse disasters occur in large numbers. As the continuous rainfall increases, the number of landslides and collapses also shows an increasing trend; when the cumulative rainfall reaches 80mm, the curve shows a downward trend.

Keywords: Precipitation; Geological Disaster; Early Warning; Changbai Mountain Area

1. Introduction

The Changbai Mountain area has complex geological environmental conditions and diverse topography. It is an area prone to geological disasters such as landslides, collapses, and debris flows [1-3]. The development and distribution of these geological disasters have obvious regional characteristics. Most of the geological disaster hazard points are mainly distributed in the Changbai Mountain Scenic Area and both sides of the tourist highway. The flood season from June to August occurs most frequently [4], seriously threatening tourists and work in the scenic area. It also affects the safety of people's lives and creates obstacles to tourism infrastructure and highway traffic.

In current highway geological hazard early warning research, susceptibility assessment using GIS and remote sensing technology effectively integrates terrain, soil, vegetation and climate data to comprehensively assess the spatial distribution of geological hazard risks [5, 6]. By analyzing meteorological data such as rainfall, rainfall threshold analysis methods can identify critical precipitation conditions where geological disasters may occur [7-10]. Machine learning and artificial intelligence not only reveal the complex relationship between environmental factors such as rainfall, topography, and soil moisture and the occurrence of geological disasters, but also improve the ability to analyze and process large-scale data sets [11-13]. Advances in on-site monitoring and sensing technology—such as the widespread application of ground radar and seismometers—provide the necessary means for real-time monitoring of geological activities, which is extremely critical for disaster prediction and early warning systems [14-16]. The timely transmission of early warning information and the construction of decision support systems further improve the response ability to geological disasters and ensure the effectiveness of disaster risk management [17]. In summary, the integrated application of these technologies and methods has significantly enhanced the effect of highway geological disaster early warning and provided solid technical support for the field of geological disaster management.

This study combines statistical analysis of historical disaster data, uses the probabilistic relationship model and analysis results between effective precipitation and landslide and debris flow disasters to assess the risk of traffic geological disasters, and divides and evaluates disaster areas; it also combines monitoring data from national meteorological observation stations , refine the grid weather forecast data, establish a highway traffic meteorological and geological disaster forecast in the Changbai Mountain Reserve, and form a meteorological early warning of highway traffic meteorological and geological disasters. It provides scientific basis and decision-making support for formulating prevention and emergency measures for geological disasters.

2. Data and Research Area

The study area is located at the northern foot of the Changbai Mountains, with geographical coordinates 127°48'E-128°42'E, 42°01'N-42°40'N, Figure 1. The general terrain characteristics are high in the southwest and low in the northeast. The ground elevation is about 600 m, and the relative height difference exceeds 2000 m. The main ridges and valleys in the area run NNE and NWW, and the overall slope of the slopes is 15°-20°. The landform types in the study area are mainly volcanic lava landforms and flowing water landforms.

The geological disaster data comes from the Changbai Mountain Highway Geological Survey data and the Resources and Environment Data Center of the Chinese Academy of Sciences. The elevation, soil and land use data come from the Earth Resources Data Cloud Platform. The fault data comes from the Geological Cloud Platform 1:500,000 geological map and lithology data. Sourced from 1:500,000 geological map, NDVI data comes from USGS website.

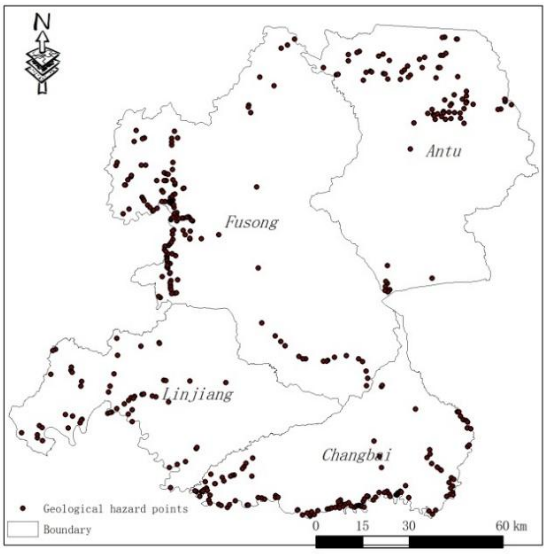

Figure 1. Schematic Diagram of the Distribution of Geological Hazards in the Changbai Mountains

3. Research Methods

3.1 Multivariate Statistical Method for Binary Dependent Variables

Assume P is the probability of an event occurring, and the value range is 0-1, then 1-P is the probability that the event does not occur. Substitute the data of each influencing factor into the R software for calculation, and perform stepwise regression to obtain the regression model:

$$Y=C_0+C_1X_1+C_2X_2+\ldots+C_nX_n \quad (1)$$

Among them: Y is the weighted linear combination of various geological hazard influencing factors, C_0 is the intercept of the model, C_i (i =1, 2,..., n) is the regression coefficient, n is the number of geological hazard influencing factors, X_i (i = 1, 2,…,n) are factors affecting geological hazards. After Logit P=Ln[Y/(1-Y)] conversion, the probability of geological disasters is obtained as follows:

$$P=1/(1+e^{-Y}) \quad (2)$$

P is the probability of occurrence of geological disasters, the output range is from 0 to 1, a value of 0 means that geological disasters will not occur, and a value of 1 means that geological disasters will definitely occur.

3.2 Dispersion Standardization Method

Min-max standardization, also called dispersion standardization, is a method of linearly transforming the original data so that the resulting values are normalized to [0-1]. The conversion function is as follows:

$$X^*=(X-X_{min})/(X_{max}-X_{min}) \quad (3)$$

In the formula: X is the original data, X* is the normalized data, X_{max} and X_{min} are the minimum and maximum values of the data respectively. There are a total of 420 geological disaster points in the study area, and the corresponding nearest fish net points are 420. Considering that the actual geological disaster is an area, in order to avoid errors, this article implements a 600-meter buffer for all geological disaster points. the sample points of non-local disaster points are randomly selected from the fishing net points outside the buffer zone. For each group of samples, 4,200 non-geological disaster sample points were randomly selected (approximately 10 times the number of geological disaster sample points), and finally a total number of 4,620 samples was obtained. And assign the probability of occurrence of all known geological disaster points to 1, and assign the probability of occurrence of geological disasters to 0 for 6,000 sample points without geological disasters.

3.3 Effective precipitation model

Its calculation formula is

$$Rc = R_0 + \sum_{i=1}^{n} \alpha^i R_i \quad (4)$$

In the formula: Rc is effective rainfall; R0 is rainfall on the day; Ri is rainfall the day before; a is effective rainfall coefficient; i is the number of days before the geological disaster occurs. Research shows that n is set to 10 days, a is obtained by optimizing the historical rainfall data that induces geological disasters, and taking the minimum quotient of the standard deviation of effective rainfall and the maximum effective rainfall as the objective function. The calculation results are shown in Table 1. When a = 0.8, the correlation coefficient between effective rainfall and geological disasters is the largest.

Table 1. Correlation Between Effective Rainfall and the Number of Geological Disasters under Different Coefficient Conditions

a	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
Correlation coefficient	0.88	0.90	0.87	0.86	0.83	0.80	0.78	0.77

Thus, the effective rainfall formula is:

$$Rc = R_0 + \sum_{i=1}^{n} 0.8^i R_i \quad (5)$$

Combined with the correlation of rainfall and land disasters in mountainous areas, the critical rainfall values in the three states of forecast (start), early warning (acceleration), and warning (disaster) corresponding to each geological disaster risk level are determined. The corresponding forecasts use R Forecast, R warning, R alert indication.

4. Results and Analysis

4.1 Construction of Geological Disaster Impact Index System

Taking comprehensive consideration of the geographical and environmental conditions in the Changbai Mountains, this article selects three types of geological disaster influencing factors to evaluate the susceptibility of geological disasters. These three types of influencing factors are: 1. Topographic and geomorphological factors (elevation, slope, slope position, aspect, curvature, micro-landforms, forwaard and revesrse slopes); 2. Geological environmental factors (lithology, distance from faults, distance from water systems), Normalized Difference Vegetation Index (NDVI), distance from road); 3. Inducing factors (effective rainfall). The first two types of influencing factors are used to establish geological disaster susceptibility zoning. On this basis, the effective rainfall of a single landslide geological disaster is considered to establish a geological disaster early warning model. Extract various geological hazards in the Changbai Mountain area and classify them, as shown in Figure 2.

4.2 Evaluation Results and Zoning of Geological Disaster-prone Areas

The evaluation formula for geological disaster-prone areas is:

$$Y = A_1X_1 + A_2X_2 + A_3X_3 + A_4X_4 + A_5X_5 + A_6X_6 + A_7X_7 + A_8X_8 + A_9X_9 + A_{10}X_{10} \quad (6)$$

Among them, Y is the susceptibility of geological disaster-prone areas, Ai is the evaluation score of each risk evaluation index;

Xi is the influence weight of each risk evaluation index. By substituting the data into R software for calculation, the regression coefficients of the 10 influencing factors were obtained and substituted into the logistic regression model formula. The results are as follows:

$$Y=4.00393-5.50874X_1-2.85696X_2-0.05918X_3+0.49135X_4-0.14495X_5+0.31267X_6-0.20996X_7-2.01859X_8-0.72673X_9-1.91579X_{10} \quad (7)$$

Among them, Xi (i=1, 2,…,10) are respectively elevation, normalized vegetation index (NDVI), slope position, micro-landform, lithology, slope, curvature, distance from faults, distance from water systems, and distance from roads. influence weight.

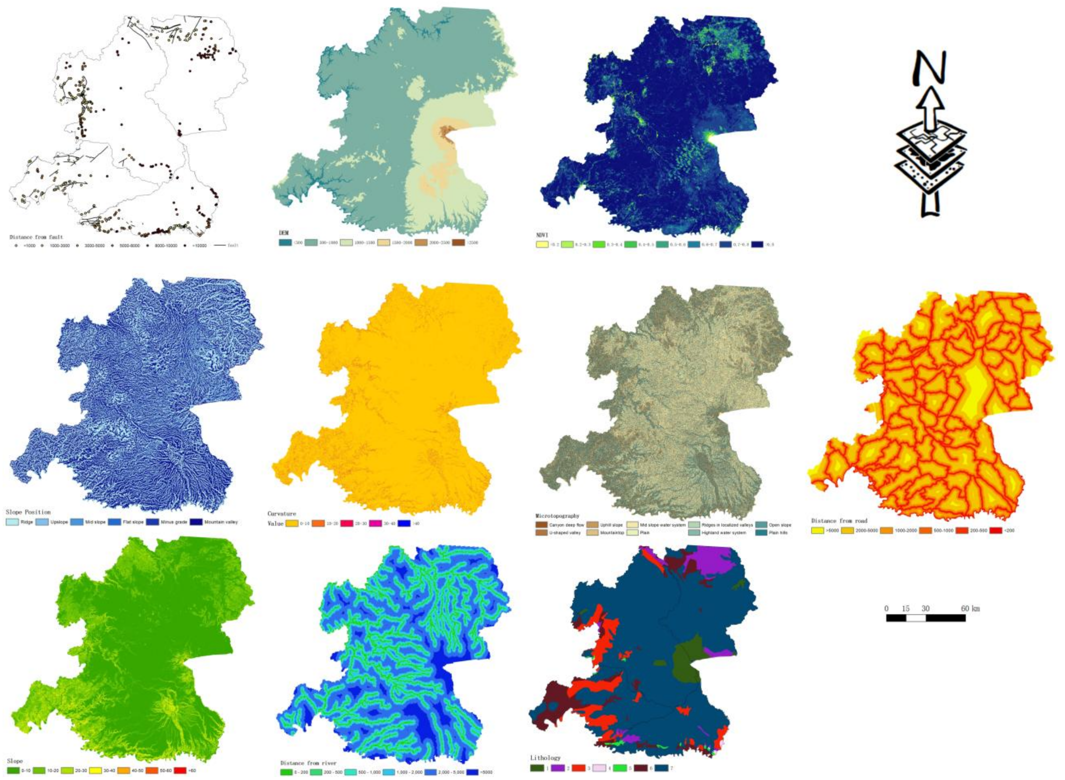

Figure 2. Grading Diagram of Various Influencing Factors in Changbai Mountain Area

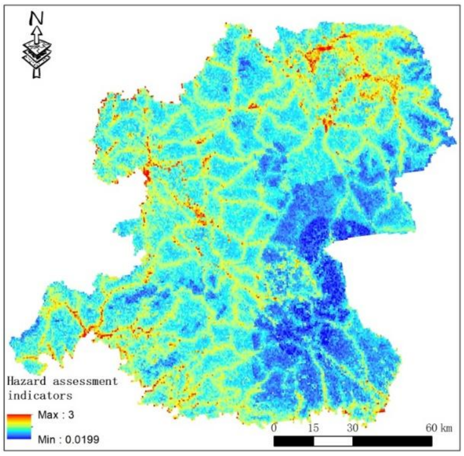

Figure 3. Risk Evaluation Indicators

Calculate the probability of occurrence of geological disasters through Logit P= Ln[Y/(1-Y)] conversion:

$$P=1/(1+e^{-Y}) \quad (9)$$

The entire calculation process is carried out in the field calculator in the ArcGis grid data attribute table. After obtaining the occurrence probability P of geological hazards in the entire region, the "point to raster" command in ArcGis is used to generate the geological hazards in the Changbai Mountain area based on the probability value P. Susceptibility evaluation chart and re-grading the evaluation results. The obtained geological hazard susceptibility evaluation map was reclassified in ArcGis, and the study area was divided into five levels: extremely low, low, medium, high and extremely high based on expert experience. After reclassification, the geological hazard risk was obtained Sexual zoning map, as shown in the figure. The probability ranges of each susceptibility level are shown in Table 2.

Table 2. Susceptibility grade classification

P	<0.05	0.05-0.15	0.15-0.25	0.25-0.35	>0.35
Level	Very	Low	Low	Medium	High

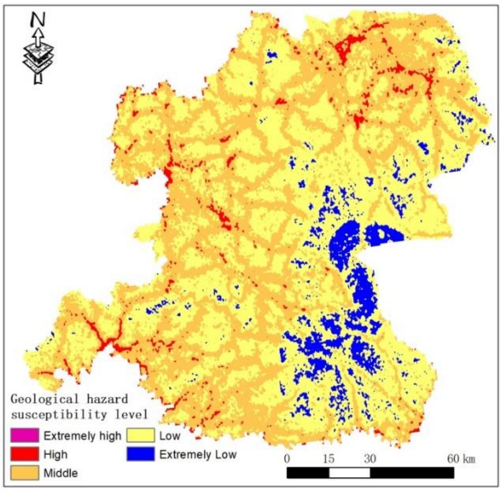

Figure 4. Classification of Geological Disaster Susceptibility Levels

By counting the number of geological disaster points at each level in Figure 4 and the area of the area at that level, the results show that areas with extremely low probability of geological disasters in the study area account for 60.31% of the total area of the study area, and geological disaster points There are 69 disaster spots, accounting for 11.37% of the total; areas with low probability of occurrence account for 11.18% of the total area of the study area, and there are 38 local disaster points, accounting for 6.26% of the total; areas with medium probability of occurrence account for 11.18% of the total area of the study area. 17.41% of the total area, with 164 local disaster points, accounting for 27.02% of the total; areas with high probability of occurrence account for 6.16% of the total area of the study area, with 144 local disaster points, accounting for 23.7% of the total; occurrence Areas with extremely high probability account for 4.94% of the total area of the study area, and there are 192 local disaster points, accounting for 31.63% of the total.

4.3 Early Warning Forecast based on Effective Rainfall

Different types of rainfall have different effects on the number and intensity of geological disasters. In terms of impact time, continuous rains generally have low intensity due to the long rainfall cycle. Such rainfalls easily penetrate the surface. In addition, there are often heavy rains during continuous rains. The occurrence of such rainfall combinations can easily induce the occurrence of large-scale geological disasters. From the perspective of disaster causes, heavy rainfall and continuous rain play different roles in the formation of geological disasters.

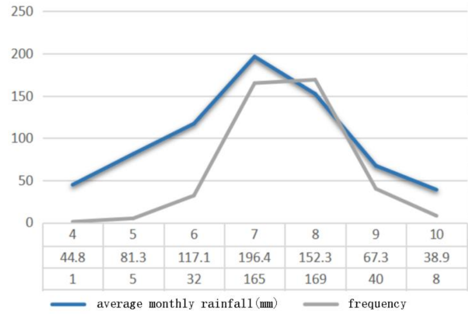

Figure 5. Average Monthly Rainfall and Frequency of Geological Disasters

Statistics on the monthly average rainfall and the frequency of geological disasters are shown in Figure 5: Slopes (including collapses) and debris flows are the main types of disasters in the Changbai Mountains. The number of disaster points with rainfall is 401. The daily rainfall is the rainfall on the day when the disaster occurs. , the rainfall on the previous day is only the rainfall on the day before the disaster, and so on. Based on these 401 disaster points, the relationship between the occurrence of geological disasters and rainfall in the Changbai Mountains was analyzed and studied.

The definition standard of this type of rainfall induced by continuous rainfall is: the number of consecutive rainy days must be more than 3 days, the daily rainfall is greater than or equal to 0.1mm, and the accumulated rainfall in the number of consecutive cloudy days exceeds 10mm.

Based on the analysis and statistics of rainfall and geological disasters in the Changbai Mountains based on the definition of continuous rainfall, Figure 6 shows that there are 266 landslides and collapse disasters induced by continuous rainfall among the 401 disaster points. Among these disasters, the longest period of continuous rainfall was 9 days, and the shortest was 3 days. By analyzing the relationship between these 266 disasters and continuous rainfall, it was found that continuous rainfall induced the most disasters on 3-4 days, with a total of 141 disasters, accounting for 53%; followed by 5 and 6 days, with a total of 96 disasters, accounting for 53%. 36.1% of the total; collapses and landslides caused by continuous rainfall for more than 7 days were less, accounting for 10.9%. As the number of consecutive rainfall days increases, the corresponding number of landslides and collapse disasters gradually decreases.

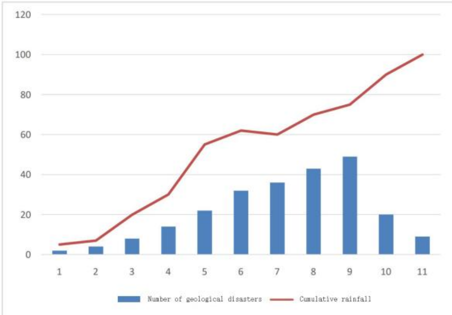

Figure 6 Cumulative Rainfall and the Number of Geological Disasters

Statistics on the cumulative rainfall and the number of geological disasters occur. It can be seen from Figure 7: when the continuous rainfall exceeds 30mm, the number of landslides and collapse disasters increases rapidly. When the cumulative rainfall is 30-80mm, the number of landslides and collapse disasters increases rapidly. Happens in large numbers.

According to the meteorological forecast and early warning classification of rainfall-induced geological disasters, a geological disaster risk threshold table in the Changbai Mountains is drawn based on effective rainfall, as shown in Table 3.

Table 3. Classification Table of Early Warning Levels for Each Danger Area based on Effective Rainfall Thresholds

Danger division	Effective rainfall threshold												
	-25	25-30	30-55	55-60	60-65	65-70	70-90	90-100	100-105	105-110	110-150	150-160	>160
Extremely high	forecast	forecast	forecast	early warning	early warning	early warning	early warning	alarm	alarm	alarm	alarm	alarm	alarm
high	-	forecast	forecast	forecast	early warning	early warning	early warning	early warning	alarm	alarm	alarm	alarm	alarm
medium	-	-	forecast	forecast	forecast	early warning	early warning	early warning	early warning	early warning	alarm	alarm	alarm
low	-	-	-	-	-	forecast	forecast	forecast	early warning	early warning	early warning	alarm	alarm
extremely low	-	-	-	-	-	-	forecast	forecast	forecast	early warning	early warning	early warning	alarm

4.4 Geological Disaster Early Warning Application

In order to test the usability of the model, taking July 1 and 10, 2022 as an example, the geological hazards in the Changbai Mountain Area were simulated, the daily precipitation forecast data in the Changbai Mountain Area was extracted, and the effective value of precipitation was obtained through calculation, combined with the classification of geological disaster susceptibility levels and probability distribution, calculate the geological disaster risk in the Changbai Mountain Area, and then obtain the overall regional early warning in the Changbai Mountain Area, and finally extract the early warning along the highway. The results are shown in Figure 7.

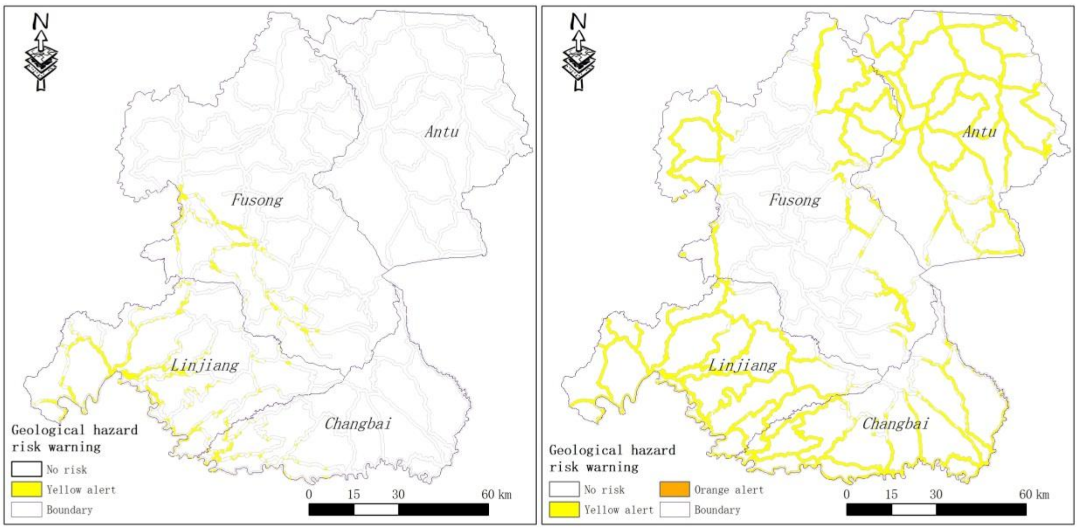

Figure 7. Highway Geological Disaster Warning on July 1 and 10, 2022

5. Conclusion

Among the 401 disaster points, 134 were caused by heavy rainfall in the Changbai Mountains, accounting for 33.4% of the total disasters; according to the definition of continuous rain (rainfall type with rainfall for three consecutive days and rainfall greater than 0.1 mm) statistics, a total of 266 disasters in the Changbai Mountains were caused by continuous rain, accounting for 66.6% of the total. It can be seen that continuous rain is the main type of rainfall that causes disasters in the Changbai Mountains. In the continuous rainy weather, there were 243 heavy rains, accounting for 91.4% of the continuous rains; in the heavy rainfall, there were 112 heavy rains, accounting for 83.5%. It can be seen that the continuous rains are the most important type of rainfall that triggers geological disasters in the Changbai Mountains. What is more likely to cause disasters is heavy rain or heavy rain during continuous rain.

When the rainfall in continuous rain exceeds 30mm, the number of landslides and collapse disasters increases rapidly. When the cumulative rainfall is 30-80mm, landslides and collapse disasters occur in large numbers. As the amount of continuous rain increases, the number of landslides and collapses also shows an increasing trend, but this trend will not continue forever. When the cumulative rainfall reaches 80mm, the curve shows a downward trend, indicating that the cumulative rainfall is above 80mm. Under such circumstances, the number of disasters has decreased rapidly, which is related to the special conditions of the Changbai Mountain Area. The study found that the Changbai Mountain area is in a weak metamorphic rock area, with severely weathered rocks. The surface layer is Quaternary covering. Under rainfall conditions, the covering is easily saturated, causing its weight to increase and its shear strength to decrease. When the rainfall reaches a certain amount, , sliding is easy to occur; however, when the rainfall reaches 150mm, the rainfall is relatively large at this time, and those areas that are prone to sliding have already slid, leaving fresh bedrock and no sliding material. Therefore, disasters occur under such rainfall conditions. The number of times decreased rapidly.

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