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Susceptibility Evaluation of Debris Flow Disaster in Plateau Hydropower Cascade Development Reservoir Area

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ABSTRACT

The Rumei Hydropower Station is a typical cascade hydropower development project in a plateau area. The dam site is located in an area with complex topography, lithology, and geological structure. Geological disasters are developed in the area, mainly debris flow. Thus, taking the dam site and the surrounding areas as key evaluation objects, the engineering geological characteristics, geological environment characteristics, and the susceptibility and risk of geological disasters that may be caused are predicted and evaluated. The main methods used in this assessment are the binary logistic regression model and expert evaluation. The results show that the susceptibility to geological disasters is small and medium. The results of this study could provide a scientific basis for the rationality of the general layout and site selection of the project construction in the plateau water elevator level development reservoir area.

INTRODUCTION

Debris flow is one of the most common geological disasters in mountainous areas. Determinants of debris flow are abundant sources, sufficient hydrodynamics, and favorable topography. The Rumei Hydropower Station is located southeast of the strong uplift area of the Qinghai-Tibet Plateau. The geographical structure in the region is active and affected by topography, geological structure, seismic activity, and human activities. The terrain is undulating, and the spatial distribution of rainfall is extremely uneven, Geological disasters (collapses, landslides and debris flows) are often prone to occur (Cui et al. 2020, Li et al. 2021b). This poses a threat to the safety of the Rumei Hydropower Station, camp, access roads, and diversion tunnels, which is not conducive to the transformation of local resource advantages into economic advantages and the promotion of the economic and social development of Tibet. Therefore, exploring the susceptibility of debris flow disasters in the reservoir area of plateau hydropower cascade development is of great significance because it can provide certain theoretical support and reference for the rationality of the general layout and site selection of reservoir engineering construction and disaster risk assessment.

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The development process of debris flow is affected by many factors such as topography, lithology, hydrology and meteorology, rainfall conditions, vegetation, and human activities (Guo et al. 2021, Xiong et al. 2021, Yang et al. 2021), and a very obvious regional development difference can be observed. The total area of hills, plateaus, and mountains in China accounts for two-thirds of the land area. The geological conditions are complex, and geological disasters such as landslides, collapses, and debris flows are frequent. Debris flow has the characteristics of a sudden outbreak, rapid flow, and serious damage, often causing a large number of casualties and property losses (Xiong et al. 2021). The work on the risk assessment of debris flow is deepening, and many scientific researchers have made great achievements. For example, most researchers use certainty factor rate and the logistic regression model (Liu et al. 2021), logistic regression and frequency ratio models (Achour et al. 2018), information value and logistic regression coupled model, power-law thresholds and logistic regression models (Nikolopoulos et al. 2018), borderline-SMOTE method (Li et al. 2021a), numerical simulation (Hu et al. 2019), TRIGRS and flow-R coupled models (Nie et al. 2022), GIS (Sung et al. 2020), PCA-GRNN model (Wang et al. 2020), RS-GIS (Zhang et al. 2012), Grey correlation analysis method (Wu et al. 2017), etc. to evaluate the risk of debris flow. This combined method is used to evaluate the susceptibility to debris flow and quantitatively evaluate the risk of debris flow under different rainfall intensities. The most widely used methods are the binary logistic regression model and the analytic hierarchy process. The AHP and GIS technology process different factors into raster, and then obtain the risk assessment of debris flow under the effects of different factors. However, the disadvantage of this method is that the selection of factors is highly subjective, and it has a high demand for data, causing differences in the evaluation results obtained by the same evaluation factors in the same region. Therefore, the evaluation results of the susceptibility to geological disasters may have different results. In factor selection, the binary logistic regression method can determine factors and weights through objective methods, which compensate for the shortcomings of AHP. The expert evaluation method is to interpret the data obtained from remote sensing interpretation and on-site investigation based on expert experience and evaluate and analyze the results of the investigation to reduce misjudgment.

Based on the advantages and disadvantages of the above methods, this paper adopts binary logistic regression combined with the expert judgment method to evaluate debris-flow susceptibility to reduce misjudgments, thereby improving the accuracy of the debris-flow susceptibility assessment. Thereby, provides certain theoretical support and reference for the susceptibility evaluation of debris flow disasters and the disaster prevention and mitigation of debris flow and further provides a certain scientific basis and reference for the rationality of the general layout and site selection of construction projects in the reservoir area of plateau hydropower cascade development.

ENVIRONMENTAL BACKGROUND OF THE RESEARCH AREA

Geomorphic Environment

The assessment area is located in the south-eastern part of the strong uplift area of the Qinghai-Tibet Plateau, where the geomorphological forces are intertwined and complex, resulting in many types of landforms, large morphological changes, and complex geomorphic combinations. The area has the following types of landforms: (1) modern seasonal ice and snow effects and freezing weathering landforms in the ridge area with an altitude of more than 4000 m, (2) ice edge of the alpine shrub-meadow belt above the forest line at an altitude of 3800 m geomorphology, (3) quaternary residual geomorphology above 2500 m above sea level, (4) slope disaster geomorphology and (5) dry-hot valley geomorphology. The above-mentioned main landforms are grouped into three basic types: alpine, sloping, and valley landforms, as well as active mountain geological hazard landforms. There are four large debris flow basins within 5 km upstream and downstream of the dam site.

Geological Structure

The assessment area is located in the south-eastern part of the strong uplift area of the Qinghai-Tibet Plateau. The plateau is bounded by the main boundary faults and adjacent to the surrounding ancient block depression belts. The two areas have a huge height difference, and the areas have strong tectonic movement, seismic activity, geothermal activity, and Cenozoic magmatism. The characteristics of neotectonic movements are mainly large-scale integral and intermittent uplifting, and the inheritance, regeneration, and difference of faults and fault-block activities are obvious. The larger grade II structural plane (Fz01) near the dam site is 0.2 km, mainly in the structural plane of grade IV and V. The larger grade II structural plane (Fz01) near the dam site is 0.2 km, mainly in the structural plane of grade IV and V. Structural fissures are relatively developed, mostly steeply dipping fissures. After investigation, three groups of slope rock mass were identified: (1) N50ºE, NW75º, (2) N56ºW, SW80º, and (3) N80ºE, SE73º. The fissures are mostly straight and rough, and the spacing is generally 0.3 m to 3 m. The rock masses on both sides of the fissure are mostly altered and brown. The dacite and rhyolite in the reservoir area have gentle bedding joints, mostly N57°W, NE25°, but with poor continuity, mostly in the form of general joints.

Hydrometeorology

The closest weather station to the camp in the Rumei Hydropower Station is the Mangkang Weather Station. The straight-line distance between the two places is 48km, and its elevation is 3870 m. According to the 30-year meteorological data from the Mangkang Meteorological Station from 1981 to 2010, the rainfall in this area is mostly concentrated from June to September, accounting for about 85% of the annual rainfall, and the inter-annual variation is small. The average relative humidity for many years is 61.1%, the average annual rainfall for many years is 575.4 mm, the maximum daily rainfall is 55 mm, and the number of precipitation days ≥ 30.0 mm is mainly concentrated from July to September. The Rumei Hydropower Station is

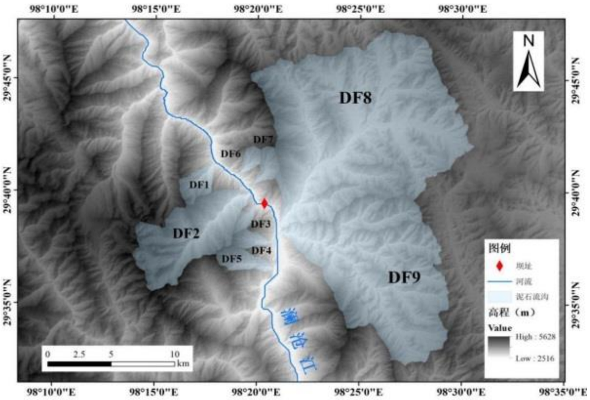

Fig. 1: Spatial distribution of debris flow geological hazards in the assessment area.

located in the Lancang River Valley. The high altitude of the basin is surrounded by mountains, making it conducive to the development of vertical air movement and condensation of water vapor. The rainy season in this area is dominated by bursts of precipitation, and there is more rain at night. The annual average rainfall days are 114.4 days, the annual average evaporation for many years is 1632 mm (20 cm evaporation dish), the annual average wind speed is 1.15 m.s^{-1}, the maximum regular wind speed is 11 m.s^{-1}, the most wind direction for many years is south, the annual sunshine is 2686h and the monthly average temperature is 2.77–25.9 Celsius. There are about 110 frost-free days throughout the year.

CHARACTERISTICS AND DISTRIBUTION OF DEBRIS FLOW DISASTER

A total of nine debris flow geological disasters were investigated in the dam site and the surrounding area of Rumei Hydropower Station, distributed mainly along both sides of the Lancang River. According to “specification of geological investigation for debris flow stabilization”, debris flows are classified according to the scale of the outbreak. They were divided into two large, two medium, and five small. The debris flow line density in the evaluation area reached 1.25 km/strip (Fig. 1 and Table 1).

Rongsong debris flow gully is located upstream of the dam site, distributed on the right bank of Lancang River, about 1.3 km from the dam site (Fig. 2a). The elevation of the highest point of the basin is 5376 m, the elevation of the lowest point is 2680 m and the elevation difference is 2696 m. The basin area is 40.5 km^2. The length of the main gully is 8.6 km, and the average longitudinal slope is 173.5‰ (Fig. 2b). The No. 2 debris flow gully is located 400 m upstream of the dam site and is distributed in the right bank of Lancang River, about 400 m away from the dam site (Fig. 2c). The highest point elevation of the basin is 4826 m, the lowest point elevation is 2656 m, the elevation difference is 2170 m, the basin area is 2.1 km^2 and the main gully is 1.62 km long. The Zhuka No. 1 debris flow gully is located downstream of the dam site and distributed on the right bank of the Lancang River, about 3.8 km from the dam site (Fig. 2e). The elevation of the highest point of the

Table 1: Statistical table of the basic situation of geological disasters that threaten construction projects.

Name	Site	Longitude	Latitude	Volume ($10^4 m^3$)	Scale	Susceptibility assessment		Risk
						Present situation	Trend	
DF1	No.1 debris flow gully 5 km upstream of the dam site	98° 18’1.35”	29° 41’17.70”	1.5	small	mild	medium	small
DF2	Rongsong debris flow gully	98° 19’44.7”	29° 39’57.26”	18.5	medium	medium	medium	small
DF3	No. 2 debris flow gully 400 m upstream of the dam site	98° 19’59.2”	29° 39’29.07”	1.8	small	mild	medium	small
DF4	Zhuka No. 1 debris flow gully	98° 21’2.94”	29° 37’41.94”	13.2	medium	medium	medium	medium
DF5	No.1 debris flow gully 5 km downstream of the dam site	98° 20’54.1”	29° 36’34.72”	1.7	small	mild	mild	small
DF6	No. 3 debris flow gully 3 km upstream of the dam site	98° 19’1.38”	29° 40’42.74”	1.3	small	mild	medium	small
DF7	No. 4 debris flow gully 1.7 km upstream of the dam site	98° 19’34.7”	29° 40’9.29”	1.5	small	mild	mild	small
DF8	Rongqu debris flow gully	98° 21’3.02”	29° 38’29.51”	47.8	large	medium	medium	medium
DF9	Duiba debris flow gully	98° 21’5.18”	29° 38’10.89”	36.5	large	medium	medium	medium

Note: DF1, DF2, DF3, DF6 and DF7 pose a threat to the Rumei Hydropower Station. DF4 and DF5 pose a threat to Hydropower Station camp. DF8 and DF9 pose a threat to the left bank entry highway.

(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 2: (a) and (b) are the Rongsong debris flow gully channel form and Rongsong debris flow gully upstream left bank view, respectively. (c) shows the remote view of the left bank downstream of the No. 2 debris flow gully mouth at 400 m upstream of the dam site. (d) is the gully mouth of Duiba debris flow gully and the bedrock on both sides. (e) and (f) are the remote views of the old debris flow accumulation fan in Zhuka No. 1 gully and the natural ‘drainage groove’ on the old debris flow accumulation fan in Zhuka No. 1 gully, respectively. (g) and (h) are the panorama of the main channel of the Rongqu debris flow gully and the accumulation thickness of the main channel of the Rongqu debris flow gully, respectively.

basin is 4830 m, the elevation of the lowest point is 2639 m and the elevation difference is 2191 m (Fig. 2f). The basin area is 3.6 km^2. The length of the main gully is 2.6 km, and the average longitudinal slope is 334.3‰. The Rongqu debris flow gully is located downstream of the dam site and distributed on the left bank of the Lancang River, about 2.4 km away from the dam site. The maximum elevation is 4700 m, the minimum elevation is 2637 m, the elevation difference is 2063 m, the basin area is 181.2 km^2, the main gully length is 16.2 km and the average longitudinal slope is 89.9‰. Duiba debris flow gully is located downstream of the dam site and is distributed on the left bank of Lancang River, about 3.0 km away from the dam site (Fig. 2d). The highest point elevation of the basin is 4752 m, the lowest point elevation is 2630 m, the height difference is 2122 m, the basin area is 108.4 km^2, the main gully length is 11.4 km and the average longitudinal slope is 31.5‰.

EVALUATION OF SUSCEPTIBILITY

The comprehensive evaluation of the susceptibility of debris flow gully is based on the survey results of the current situation of debris flow, as well as according to the comprehensive index reflecting the susceptibility of debris flow gully in the ‘Specifications of geological investigation for debris flow stabilization’ (DZ/T0220-2006). In this work, the stability of the nine potential geological hazard points of debris flow caused by the proposed construction of the Rumei hydropower station in the plateau hydropower cascade development reservoir area is identified qualitatively, and the hazard level is determined according to the hazard of each disaster point to the proposed construction project. The hazard level is determined according to the hazards of each disaster point to the proposed project. Among the nine debris flow geological disaster sites, 0 disaster sites are at high risk, 3 sites are medium risk and 6 sites are at low risk. The risk of geological disasters is small and medium. These disaster spots pose a threat to the safety of Rumei Hydropower Station, camps, access roads, and water diversion tunnels to varying degrees. Hence, the prevention and control of these debris flow geological disasters cannot be ignored in engineering construction.

Binary Logistic Regression Model

The logistic regression model is the earliest discrete choice model. It is widely used in sociology, economics, geography, geology, and other fields. The model is a multivariate statistical analysis method formed based on linear regression combined with logistic function. It is suitable for studying the relationship between the results of binary classification and its influencing factors. The influencing factors of geological disasters in the region are independent variables. Through logistic regression model analysis, the weights of independent variables can be obtained and we can understand that these factors are the main factors causing geological disasters, and at the same time, according to the weights of the influencing factors, the probability of disaster occurrence can be predicted. The predicted result value is between 0 and 1. Because the logistic regression model is fast to solve, easy to apply, and has unique advantages in the free distribution of data, it has been widely used in geological disaster susceptibility evaluation and mapping. Its function is the following formula:

$$p = 1/[1 + e^{-(\alpha+\beta_1 x_1+\cdots+\beta_i x_i)}] \quad \ldots(1)$$

Where α is the constant term, P is the probability of disaster occurrence, β is the regression coefficient and i is the number of types of evaluation factors. Taking the natural logarithm on both sides of Equation (1), we get the following:

$$Ln[P/(1-P)] = \alpha + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_i x_i = \alpha + \beta x \quad \ldots(2)$$

The independent variable of the logistic regression model, that is, the unit of the evaluation factor is different. Before establishing a logistic regression model, the secondary division values of each evaluation factor must be normalized into standardized values. In this paper, the ratio of the disaster area in each evaluation factor to the total disaster area is divided by the ratio of the area of each grading factor to the total area as the index value, and the index values are standardized. The calculation formula is as follows:

$$x_{ij} = Z_{ij} / S_{ij} \quad \ldots(3)$$

$$X_{ij} = x_{ij} \Big/ \sum_{j=1}^{m} x_{ij} \quad \ldots(4)$$

where Z_{ij} is the proportion of the disaster area in the secondary classification of each factor to the total disaster area, S_{ij} is the ratio of the secondary classification area of each factor to the total area, i is the serial number of each evaluation factor (i = 1,2...6,7), j is the secondary classification number of each evaluation factor (j = 1,2...,m), x_{ij} is the initial calculated metric value and X_{ij} is the standardized value of the secondary classification of each factor.

Selection and Grading of Susceptibility Evaluation Factors

The evaluation unit is the smallest and indivisible space used for geological hazard evaluation and can have a regular or irregular shape. In practical applications, an appropriate evaluation unit can be selected according to research needs. In this paper, the grid unit is used as the evaluation unit for the susceptibility evaluation of geological disasters. For the convenience of calculation, the grid size of the study area is taken as 30 m.

There are three main types of geological disasters in hydropower stations: landslides, collapses, and debris flows. The accuracy of susceptibility zoning depends on the selected evaluation factors. Therefore, an in-depth understanding of the contribution of each influencing factor to regional disasters and the cumulative effect between factors could improve the susceptibility evaluation and zoning accuracy of geological hazards. Therefore, investigating geological disasters, the stability of the disaster-prone environment, the risk of disaster-causing factors, and the vulnerability of disaster-affected bodies in the study area is necessary. After analysis, six factors including daily rainfall, slope gradient, aspect, elevation, slope curvature, and stratum lithology are selected as the evaluation factors of geological disaster susceptibility in hydropower stations. The classification indices for each factor are shown in Table 2.

The analysis of interpreting the spatial distribution law of debris flow geological disasters is performed through the spatial statistical analysis function of GIS. First, the raster layer of each factor is prepared, and each factor is divided into grades (for example, divide the daily rainfall into <10, 10-25, 25-50, 50-100, 100-250 and >250). Then, through GIS spatial analysis, the relative occurrence probability of disasters in each factor classification is calculated and normalized. The higher the numerical value of a factor classification, the stronger the positive correlation between it and the probability of disaster occurrence. This paper selects six factors (Table 2) among the three types of factors and calculates the density of geological hazards in each factor classification and the area occupied by each factor in the total study area through the spatial statistical analysis function of GIS. The results are then normalized. Each evaluation factor is classified according to the grading index, and the relationship between each evaluation factor and geological hazards is studied statistically to evaluate the spatial correlation and importance of each factor classification and the distribution of geological hazards.

Evaluation Results of Geological Hazard Susceptibility

The distribution map of the probability value of disaster susceptibility is obtained using the ArcGIS spatial grid overlay function according to the obtained regression coefficients of each factor combined with formula (1). Through the natural discontinuity method, it is divided into

Table 2: Index classification of geological disaster susceptibility evaluation factors in the water-level development reservoir area in the plateau area.

First level factor	Secondary evaluation factor	series	Index grading
Rainfall factor	daily rainfall	6	<10, 10-25, 25-50, 50-100, 100-250 and >250
Topographic factor	Slope (°)	7	<10, 10-20, 20-30, 30-40, 40-50, 50-60 and >60
	Slope direction	9	flat, north, northeast, east, southeast, south, southwest, west and northwest
	Elevation (m)	10	<2200, 2200-2400, 2400-2600 and 2600-2800, 2800-3000, 3000-3200, 3200-3400, and 3400-3600, 3600-3800 and >3800
	curvature	3	<-0.5, -0.5-0.5 and >0.5
Geological factors	stratigraphic lithology	6	Quaternary, Triassic, Permian, Carboniferous Permian, Carboniferous, Devonian

Table 3: Risk prediction table of engineering construction exacerbating existing geological disasters

Name	Site	Disaster types	Volume (m^3)	Scale	Susceptibility/P
DF1	No.1 debris flow gully 5 km upstream of the dam site	debris flow	15000	small	Medium /0.43
DF2	Rongsong debris flow gully	debris flow	185000	medium	Medium /0.56
DF3	No. 2 debris flow gully 400 m upstream of the dam site	debris flow	18000	small	Medium /0.45
DF4	Zhuka No. 1 debris flow gully	debris flow	132000	medium	Medium /0.61
DF5	No.1 debris flow gully 5 km downstream of the dam site	debris flow	17000	small	Mild /0.25
DF6	No. 3 debris flow gully 3 km upstream of the dam site	debris flow	13000	small	Medium/0.33
DF7	No. 4 debris flow gully 1.7 km upstream of the dam site	debris flow	15000	small	Mild/0.19
DF8	Rongqu debris flow gully	debris flow	478000	large	Medium/0.68
DF9	Duiba debris flow gully	debris flow	365000	large	Medium/0.64

Note: DF1, DF2, DF3, DF6 and DF7 pose a threat to the Rumei Hydropower Station. DF4 and DF5 pose a threat to the hydropower station camp. DF8 and DF9 pose a threat to the left bank entry highway.

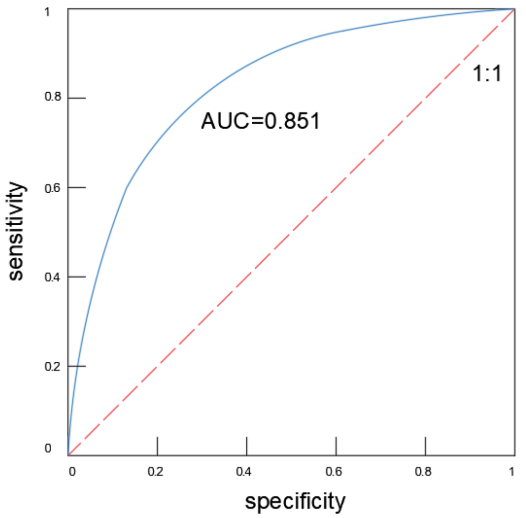

Fig. 3: ROC curve for evaluating the susceptibility to geological hazards in hydropower development zones.

five areas from small to large: low, low, medium, high, and relatively high-prone areas. Table 3 shows the degree of debris-flow susceptibility of the Rumei hydropower station based on the logistic regression model.

Verification of Geological Hazard Evaluation Results

The accuracy of geological disaster susceptibility evaluation results is related directly to the reliability of the model and affects economic development and social progress directly or indirectly. Therefore, it is very necessary to test the accuracy of the susceptibility rating results. The classification performance of different susceptibility evaluation models can be compared accurately by checking the accuracy of geological disaster susceptibility evaluation results so that the best susceptibility evaluation model suitable for a certain area can be selected. The ROC curve and success rate curve are the most commonly used methods to test the performance of the geological hazard susceptibility evaluation model. The accuracy of the model can also be evaluated by using the ROC curve (Wu et al. 2019). Taking the proportion of units without disasters that are predicted correctly as the abscissa and the proportion of units with disasters being predicted correctly as the ordinate, a curve is drawn. The closer the curve is to the upper left corner, the higher the accuracy of the model classification as shown in Fig. 3.

The Area Under Curve (AUC) value is defined as the area below the ROC curve to the abscissa, and the value ranges from 0.5 to 1. The higher the AUC value, the higher the model accuracy. The evaluation model AUC = 0.851, which means it has good accuracy.

CONCLUSION

(1) The area of assessment area is about 2.03 km$^{2.}$ The types of geological disasters are mainly medium-sized debris flows, and the susceptibility to debris flows is mainly moderate. The hazard to the Rumei Hydropower Station is small, while the hazard to the hydropower station camp and the left access road is medium.

(2) The risk of engineering construction causing and exacerbating geological disasters is small. However, there is still a possibility that geological disasters could be caused or aggravated in the excavation and filling of local engineering slopes, excavation and soil dumping in engineering construction and in the construction and use of construction camps and access roads.

(3) According to the evaluation results of this paper, for Zhuka No.1, Rongqu and Daba debris flow basins, disaster prevention and mitigation measures, such as source fixation and construction of sand dams can be taken, and the construction camp is relatively far from the slope toe area.

(4) Overall, the advantages of this method are the application of a binary logistic regression model for debris flow susceptibility evaluation, which is combined with the expert evaluation method. Experts can reduce the misjudgment of evaluation results by explaining the data obtained from remote sensing interpretation and field investigation and evaluating and analyzing the survey results. Finally, the accuracy of the model can be evaluated using the ROC curve to determine whether the model had good accuracy. The shortcomings of this paper are as follows. In the selection of geological hazard susceptibility evaluation factors, only three main influencing factors, namely rainfall, topography, and geology are considered, and relatively minor evaluation factors, such as distance from fault and fault line density in the region are not considered. However, these shortcomings have little influence on the evaluation results. In the future, when selecting the evaluation factors of geological disaster susceptibility, these secondary evaluation factors can be considered to increase the accuracy of the model, and the evaluation results are closer to the actual situation, which provides a more reliable scientific basis and theoretical support for disaster prevention and mitigation of geological disasters.

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