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Comprehensive Geological Hazard Risk Assessment in Southern Tieling Region

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Abstract: *Geological disaster risk assessment is crucial for regional disaster prevention and mitigation, playing a vital role in strengthening natural disaster prevention capabilities. This study focuses on southern Tieling, constructing a comprehensive geological disaster risk assessment system. An AHP-information quantity coupling model is employed, with hydrological slopes as evaluation units. Information quantities of nine susceptibility indicators, including geomorphology, geological structures, and vegetation hydrology, are calculated. Hazard assessment is conducted by synthesizing weighted inducing factors, which are then integrated with data on disaster-bearing elements like population, buildings, and roads. Risk zoning is determined using a risk matrix. Results indicate that high-risk geological disaster areas are mainly distributed east of the line connecting Pingdingpu, Xiongguantun, and Yaopu towns, characterized by steep slopes and significant topographic relief. Notably, all disaster points are located within high-risk zones. These findings provide essential support for disaster management, and territorial spatial planning, and offer valuable insights for infrastructure development and social planning in southern Tieling.*

Keywords: *Southern Tieling; Geological Disasters; Information Content Model; Risk Assessment*

1. Introduction

China has a complex terrain and geomorphology, with diverse disaster-causing conditions. Coupled with the frequent occurrence of extreme weather and the intensification of human engineering activities, geological disasters occur frequently. Since the new century, there have been 419,555 geological disasters in China, resulting in 49,435 casualties and a direct economic loss of 94.675 billion yuan[1], which seriously threatens the safety of people's lives and property.

Scholars at home and abroad began to study the theory of geological disaster risk assessment in the 1960s and proposed a variety of quantitative assessment methods and models. Then, according to the definition of disaster risk given by the United Nations Department of Humanitarian Affairs (UNDHA), scholars at home and abroad focused on key dimensions such as the risk of geological disasters and the vulnerability of disaster-affected bodies, and used knowledge-driven assessment methods and data-driven assessment methods[2] to construct models and carry out research and practice on risk quantification and assessment. Among them, knowledge-driven assessment methods mostly determine assessment indicators based on the existing knowledge structure of experts and use weighting methods such as the Analytic Hierarchy Process[3-5], Fuzzy Comprehensive Evaluation Method[6-7], or Entropy Weight Method[8-9]to quantify risks. The assessment process can be structured and easy to understand, but there is a certain degree of subjectivity and a high dependence on the experience or knowledge structure of experts.

With the rapid development of computer technology and the continuous improvement of the functions of the GIS platform, experts and scholars began to use data-driven assessment methods such as machine learning methods or statistical models to conduct assessments of the susceptibility or risk of geological disasters. At the same time, some scholars have discussed the impact of the scale of assessment units on the results of disaster risk assessment. Some scholars use machine learning methods such as Random Forest[10-12], Decision Tree[13], Support Vector Machine[14], and Neural Network[15-16]to conduct assessments of the susceptibility or risk of geological disasters. The assessment process is relatively efficient and ensures a certain range of prediction accuracy. However,

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compared with other types of assessment methods, it requires a larger scale of decision-making data the data decision-making process is not clear, and the interpretability is poor.

At the same time, other scholars use statistical model methods such as the Information Amount Model[5] and the Weight of Evidence Model[17] combined with factors such as the disaster-causing conditions and inducing conditions of geological disasters to conduct assessments of the susceptibility and risk of geological disasters, which have been widely applied. However, it has a relative lack of analysis of the disaster-causing laws and patterns, and it is easy to ignore the differences in the relative importance and influence of various factors. Therefore, considering the limitation of the scale of decision-making data, in the general assessment area of geological disasters, data-driven statistical model methods can be applied to conduct susceptibility assessments for medium and small-scale geological disaster risk assessments, and then coupled with knowledge-driven comprehensive assessment methods to conduct geological disaster risk assessments. It is advisable to use slope units as the assessment scale to reduce problems such as high local assessment values.

The terrain and geological conditions in the southern area of Tieling, Liaoning Province are complex, with the development of active fault structures. The spatial and temporal distribution of rainfall is uneven and concentrated in the mountainous areas in the east and south. Human engineering construction and mining activities are relatively intense, and geological disasters occur frequently, which have caused certain losses to the lives and property of the local people. Therefore, this paper takes the southern districts and counties of Tieling as the study area, establishes an assessment index system for geological disasters such as collapses and landslides, and uses the Analytic Hierarchy Process (AHP) and the Information Amount research method to successively carry out the classification of the risk and vulnerability levels of geological disasters in the study area and the risk assessment, to provide basic support and decision-making for the regional territorial space planning and the high-quality construction and development of the social economy.

2. Materials and methods

2.1. Theory of Disaster Risk

According to the disaster risk system theories at home and abroad[18-21], the risk of geological disasters refers to the expected value of losses caused by various types of disasters triggered by different inducing factors to disaster-affected bodies such as people's lives and property, and social economy within a specific time and space. To quantify the risk of geological disasters in a region, it is necessary to consider the disaster-causing environments such as topography and geomorphology, geological structures, meteorology, and hydrology, as well as the possibility of disasters caused by inducing factors such as heavy rainfall and human activities, and analyze the severity of the damage to the disaster-affected bodies caused by the disasters. In this study, the relevant factors of disaster risk and the vulnerability of the disaster-affected bodies are quantified. The comprehensive risk of geological disasters reflects the susceptibility controlled by the geological conditions of disaster occurrence and the influence of inducing factors, and its risk can be expressed by formula (1).

$$F = f_R\left(f_P\left(f_S(S), f_H(H)\right) \bullet f_V(V)\right) \tag{1}$$

In the formula, $f_S(S)$, $f_H(H)$, $f_V(V)$ successively represents the index synthesis results of the susceptibility element S, the disaster-causing factor or inducing factor H, and the vulnerability element V. $f_P(.)$ represents the synthesis method of disaster hazard. In this study, the weighted synthesis method is proposed to be adopted. F represents the result of the geological disaster risk assessment, and $f_R(.)$ represents the synthesis method of disaster risk. According to the relevant technical specifications for geological disaster risk investigation and evaluation issued by the Office of the Leading Group for the Comprehensive Census of Natural Disaster Risks, the study will adopt the risk matrix assessment method.

2.2. Methodology

In this study, based on the systematic coupling of disaster-causing environmental elements and the disaster-inducing mechanism, a quantitative assessment model for the susceptibility and hazard of

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geological disasters was constructed, and the exposure parameters of disaster-affected bodies such as population distribution, infrastructure, and economic density were incorporated into the analysis framework[22]. Given that the assessment of hazard and vulnerability involves the weighted synthesis of a multi-source heterogeneous index system, it is necessary to use scientific methods to standardize, weigh, and perform integrated calculations on multi-dimensional indices.

2.2.1. Coupling of Information Amount and Analytic Hierarchy Process (AHP)

The susceptibility assessment value is obtained by summing up the information amounts of each disaster-causing factor (Formula 1). The information amount calculation method of the statistical model based on information theory can conveniently and objectively convert the measured situation of damage occurring in the regional stability factors into information amounts, to quantify the susceptibility of geological disasters. Among them, for a specific geological disaster, the information amount I of an assessment unit with n influencing factors is represented by Formula (2).

$$I = \sum_{i=1}^{n} I_i = \sum_{i=1}^{n} \ln \frac{N_i/N}{S_i/S} \tag{2}$$

In the formula, N_i is the number of occurrences of this type of geological disaster within the entire state range of a specific assessment factor, N is the total number of occurrences of this type of disaster. Correspondingly, S_i is the area where this type of geological disaster occurs within the entire state range of a specific assessment factor, S represents the total area where this disaster occurs. Generally speaking, the larger I is, the greater the possibility of the occurrence of this geological disaster.

Given the differences in the disaster-causing mechanisms and distribution laws of different types of geological disasters (such as landslides and collapses), this study adopts the Information Amount-AHP Coupling Method to assess the susceptibility of disasters. By analyzing the disaster-causing factors, taking the susceptibility of geological disasters as the target layer, topography and geomorphology, geological structures, and hydrological vegetation as the criterion layers, representative indicators are selected to establish a susceptibility assessment model and a judgment matrix. The weights of each disaster-causing control indicator are obtained through eigenvector calculation and consistency tests. The formulas are as follows:

$$fs(S) = \sum_{i=1}^{n} W_{Si} I_i \tag{3}$$

Formula (3), $f_s(s)$ is the total sum of the weighted information amounts within a specific disaster assessment unit, and it is also the susceptibility of the disaster. W_{si} is the weight value of a certain assessment factor, I_i is the information amount of the index classification.

2.2.2. Weighted Superposition of Multiple Factors

The hazard of geological disasters is formed by the comprehensive superposition of the susceptibility of disasters and inducing factors, and the contribution degrees of various factors to different disasters are different. The impacts of geological disasters on vulnerability also vary. Therefore, in this study, the multi-factor weighted superposition method is adopted to calculate the assessment values of hazard and vulnerability, and the dimensionless treatment is carried out for each index before superposition. Among them, the susceptibility of a specific disaster can be calculated by Formula (3). Assuming that the specific disaster has m inducing factors, the hazard of the disaster can be evaluated according to Formula (4).

$$f_P(P) = \sum_{j=1}^{m} W_S f'_s(S) + W_{Hj} H_j \tag{4}$$

In addition, according to Formula (4), $f'_s(S)$, H_j are the normalized values of the susceptibility of the disaster and the inducing factors respectively, while W_S and W_{Hj} are the weight values corresponding to the susceptibility and the inducing factors respectively, and the sum of the two is 1.

Similarly, considering that there are k indicators, the assessment value of the vulnerability of the disaster can be calculated by Formula (5).

$$f_V(V) = \sum_{l=1}^{k} W_{Vl} V_l \quad (5)$$

Among them, $f_v(V)$ is the calculated value of the vulnerability of the assessment unit, W_{Vl} is the weights of vulnerability respectively, and V_l is the normalized vulnerability index value of the assessment unit.

3. Overview of the Study Area

The study area is located in the northeastern part of Liaoning Province, belonging to the mid-temperate continental monsoon climate. Rainfall is concentrated from June to August, and the main rivers include the Liao River, Chai River, Fan River, etc. The terrain is higher in the east and lower in the west, situated at the junction of the Liaohe Plain and the mountainous and hilly areas in eastern Liaoning, with a relatively large elevation difference. In the mountainous and hilly areas in the east, mixed granite, diabase, gneiss, etc. are exposed, while the Liaohe Plain area in the west is widely covered by Quaternary loose deposits. Active faults such as the northeast-trending Yilan-Yitong Fault and the nearly east-west trending Mishan-Dunhua Fault are developed in the study area and its surroundings, and the geological structure is complex (Figure 1). Human activities such as unreasonable land use, mining, construction, and road building have intensified the risk of geological disasters, which may lead to problems such as soil erosion and slope instability. According to the geological disaster prevention and control plan, collapses and landslides account for more than 90% of the total geological disasters in the region, making them the main types of disasters. In conclusion, the geographical, geological, climatic, and human activity factors in the southern area of Tieling are interwoven, and it faces a serious risk of collapse and landslide disasters. Carrying out risk assessment based on applicable theories and scientific data systems can better identify and manage potential risks, and protect the safety of residents and resources.

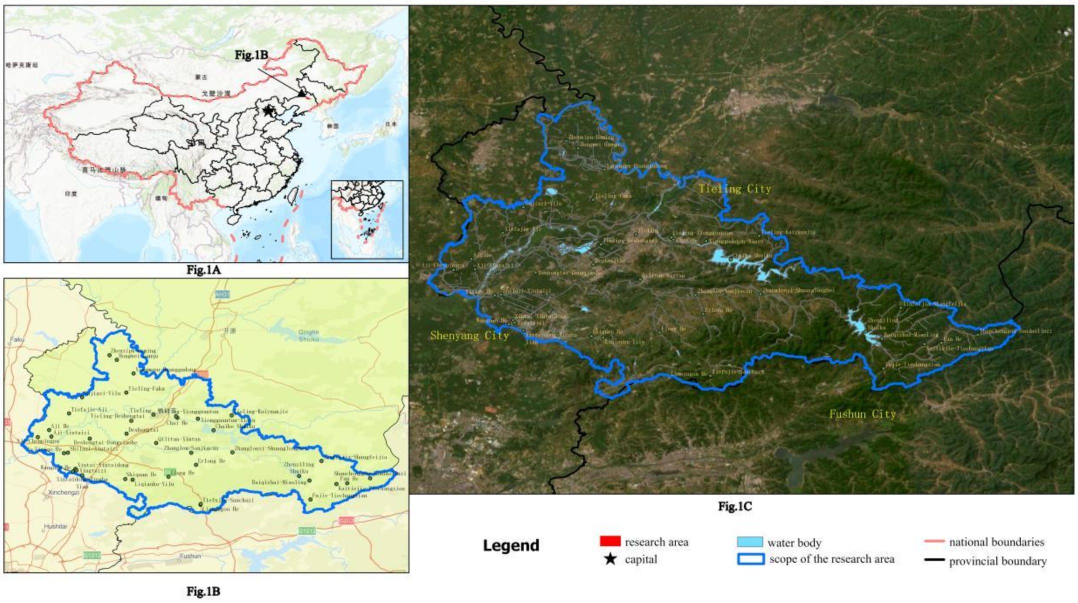


Figure 1: Overview of the Study Area

4. Risk Assessment of the Research Area

According to the "Code for Assessment of Geological Disaster Hazard" (GB/T 40112-2021), risk assessment requires conducting a susceptibility evaluation of disaster-causing factors by disaster type in specific evaluation units, determining the hazard in combination with the inducing factors, determining the vulnerability according to the situation of the disaster-affected bodies, and using a risk

ISSN 2616-5872 Vol.7, Issue 3: 1-15, DOI: 10.25236/AJEE.2025.070301

matrix to determine the risk. Considering that using grid cells as assessment units may lead to scattered results and a small scope, this study adopts the analysis of slope units to improve the reliability and rationality of the assessment.

4.1. Slope Unit Division

A slope unit is an independent evaluation unit divided based on similar geological features, geomorphic forms, and disaster-causing conditions. Its reasonable division can improve the reliability and accuracy of the results of geological disaster risk assessment, and make the division of prevention and control areas and the formulation of measures more feasible. In this study, the "catchment overlapping method" is used to divide slope units. The positive and negative digital elevation models are used to extract and integrate ridge lines and valley lines, and manual correction is carried out in combination with mountain shadows, remote sensing images, and lithology. A total of 898 slope units are obtained (Figure 2). This division, together with the analysis of topography and geological structures, helps to understand and analyze the constituent elements of risks, to construct a scientific index system, and improve the quality and effectiveness of risk assessment.

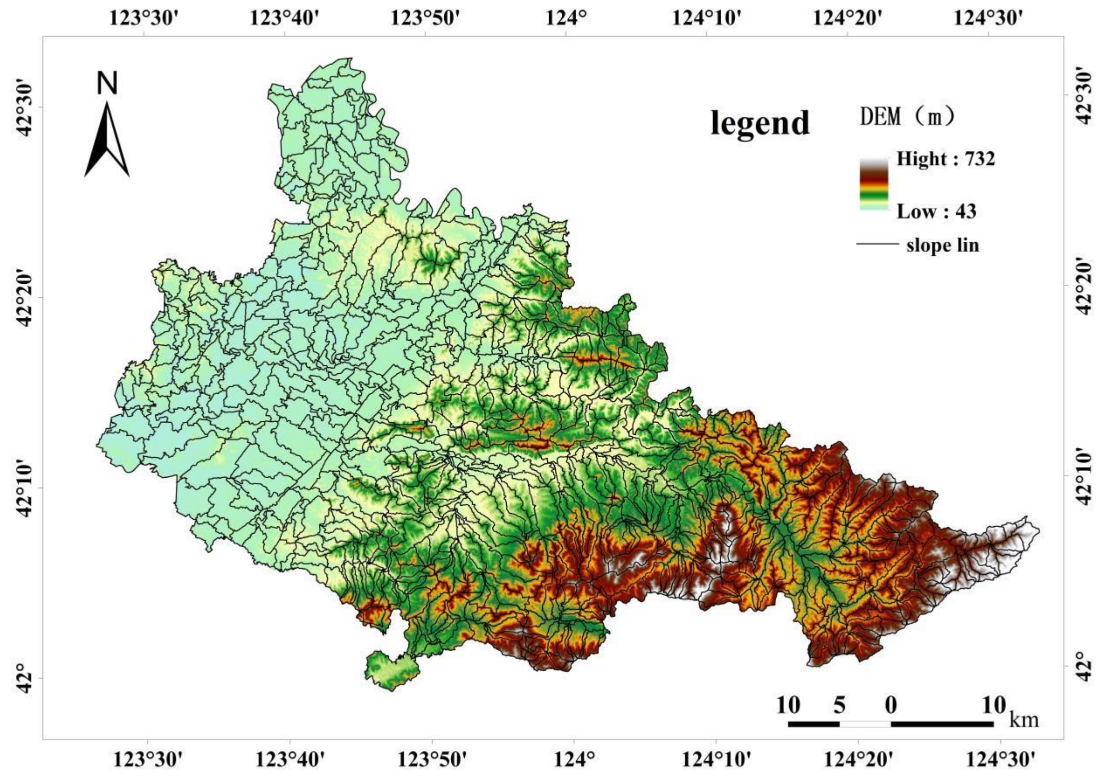


Figure 2: Division Results of Slope Units

4.2. Analysis of Geological Disaster Susceptibility

4.2.1. Establishment of Evaluation Indexes

Geological disasters are affected by a variety of factors, mainly including topography and geomorphology, geological structures, water systems vegetation, etc. Studies have shown[23] that geology and topography provide the material and potential energy basis for disasters, and vegetation coverage affects the richness of the material source, thereby influencing the stability of the soil mass and the occurrence of collapses and landslides. Based on this, combined with the experience of predecessors and the distribution laws of disasters, three major categories of 9 assessment factors have been selected: Firstly, those related to topography and geomorphology: slope gradient, relative height, plan curvature, and profile curvature; Secondly, those related to geological features: distance from faults, engineering geological rock groups, and slope types; Thirdly, those related to water systems and vegetation: distance from water systems and vegetation coverage rate(Figure 3).

ISSN 2616-5872 Vol.7, Issue 3: 1-15, DOI: 10.25236/AJEE.2025.070301

4.2.2. Constructing the evaluation model and index weight matrix

Based on the 9 evaluation indicators corresponding to the 3 influencing factors, a hierarchical model for evaluating the susceptibility of landslide and collapse disasters is constructed. Based on the concept of the analytic hierarchy process, the weight values of each evaluation factor in the two types of geological disasters, namely landslides and collapses, are calculated, as shown in Table 1.

Table 1 Hierarchy and Weights of Hazard Susceptibility Assessment

Objective Level	Criterion Level	Landslide Criterion - level Weight(%)	Collapse Criterion - level Weight(%)	Indicator Level	Landslide Indicator - level Weight(%)	Collapse Indicator - level Weight(%)
Assessment of Geological Disaster Susceptibility	Topography and Geomorphology	44.29	38.73	Slope Gradient	18.12	13.87
				Relative Height	15.49	16.69
				Plan Curvature	3.65	2.85
				Profile Curvature	7.02	5.33
	Geological Features	38.73	44.29	Distance from Fault	6.58	18.21
				Engineering Geological Rock Group	17.15	14.54
				Slope Classification	15	11.53
	Hydrology and Vegetation	16.98	16.98	Distance from The Water System	12.74	11.32
				Vegetation Coverage Rate	4.25	5.66

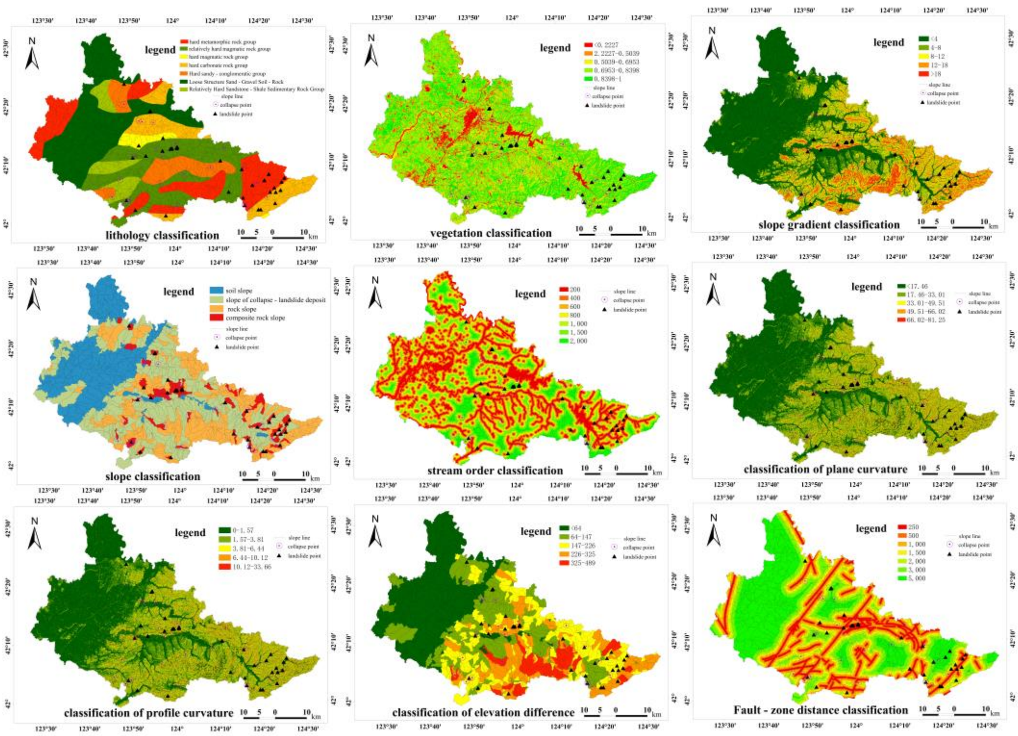


Figure 3: Evaluation Factor Maps

ISSN 2616-5872 Vol.7, Issue 3: 1-15, DOI: 10.25236/AJEE.2025.070301

Table 2 Information Quantity Table of Each Evaluation Factor

Factor	Factor Classification	Area	Collapse			Landslide		
			Number of Disaster Points	Proportion of Disaster Points(%)	Information Quantity	Number of Disaster Points	Proportion of Disaster Points(%)	Information Quantity
Slope Gradient	<4	1295.9523	3	12.5000	-1.4542	8	22.8571	-0.8506
	8	358.5672	5	20.8333	0.3415	16	45.7143	1.1274
	12	328.3056	8	33.3333	0.8997	6	17.1429	0.2347
	18	320.3811	3	12.5000	-0.0567	3	8.5714	-0.4340
	>18	118.6281	5	20.8333	1.4477	2	5.7143	0.1541
Relative Height	<64	780.9138	0	0.4149	-	0	0.2841	-
	147	583.3575	10	41.4938	0.5439	9	25.5682	0.0597
	226	506.8809	10	41.4938	0.6844	14	39.7727	0.6420
	325	374.5926	3	12.4481	-0.2172	12	34.0909	0.7903
	>489	176.0895	1	4.1494	-0.5609	0	0.2841	-
Plan Curvature	<17.46	437.4396	8	33.3333	0.6127	10	28.5714	0.4586
	33.01	461.4129	6	25.0000	0.2717	12	34.2857	0.5875
	49.51	422.4771	5	20.8333	0.1775	6	17.1429	-0.0174
	66.02	486.882	4	16.6667	-0.1875	3	8.5714	-0.8525
	81.25	613.6227	1	4.1667	-1.8052	4	11.4286	-0.7962
Profile Curvature	<1.57	1249.4187	3	12.4481	-1.4218	3	8.5714	-1.7949
	3.81	620.3781	6	24.8963	-0.0285	10	28.5714	0.1092
	6.44	337.2651	5	20.7469	0.3986	7	20.0000	0.3620
	10.12	164.538	10	41.4938	1.8095	12	34.2857	1.6187
	33.66	50.2344	0	0.4149	-	3	8.5714	1.4188
Distance from Fault	<250	239.3307	3	12.5000	0.2350	9	25.7143	0.9563
	500	226.3095	1	4.1667	-0.8077	4	11.4286	0.2013
	1000	379.0575	9	37.5000	0.8738	8	22.8571	0.3787
	1500	304.8147	2	8.3333	-0.4123	4	11.4286	-0.0965
	2000	238.0068	4	16.6667	0.5282	4	11.4286	0.1509
	3000	336.5325	3	12.5000	-0.1059	3	8.5714	-0.4831
	>5000	697.7826	2	8.3333	-1.2405	3	8.5714	-1.2124
Engineering Geological Rock Group	Loose-structured soil rock group with sandy gravel	694.9935	0	0.4115	-	2	5.6980	-1.6167
	Relatively hard magmatic rock	549.7956	12	49.3827	0.7772	13	37.0370	0.4895

ISSN 2616-5872 Vol.7, Issue 3: 1-15, DOI: 10.25236/AJEE.2025.070301

	group							
	Relatively hard sedimentary rock group of sandstone and shale	142.0983	0	0.4115	-	0	0.2849	-
	Hard magmatic rock group	53.8254	0	0.4115	-	2	5.6980	0.9415
	Hard carbonate rock group	281.3274	4	16.4609	0.3486	6	17.0940	0.3863
	Relatively hard sedimentary rock group of sandstone and conglomerate	214.7769	3	12.3457	0.3308	1	2.8490	-1.1355
	Hard metamorphic rock group	485.0172	5	20.5761	0.0271	11	31.3390	0.4478
Slope Type	Soil slope	647.0379	0	0.4149	-	0	0.2841	-
	Debris-collapse accumulation slope	976.5531	1	4.1494	-2.2740	1	2.8409	-2.6528
	Rock slope	636.4377	1	4.1494	-1.8458	0	0.2841	-
	Composite rock slope	161.8056	22	91.2863	2.6147	34	96.5909	2.6712
Distance from The Water System	<200	528.8454	7	29.0456	0.2853	11	31.4286	0.3641
	400	425.2149	4	16.5975	-0.0562	4	11.4286	-0.4294
	600	382.4658	5	20.7469	0.2729	6	17.1429	0.0821
	800	319.554	1	4.1494	-1.1569	3	8.5714	-0.4314
	1000	244.3185	3	12.4481	0.2102	2	5.7143	-0.5684
	1500	334.0935	4	16.5975	0.1849	5	14.2857	0.0349
	>2000	187.3422	0	0.4149	-	4	11.4286	0.3903
Vegetation Coverage Rate	0.2227	157.122	8	33.3333	1.6366	4	11.4286	0.5662
	0.5039	194.0283	2	8.3333	0.0394	9	25.7143	1.1662
	0.6953	458.1099	8	33.3333	0.5666	10	28.5714	0.4124
	0.8398	1012.7898	4	16.6667	-0.9199	8	22.8571	-0.6041
	1	599.7843	2	8.3333	-1.0892	4	11.4286	-0.7733

4.2.3. Zoning of Geological Disaster Susceptibility

The classification information quantity of each index is calculated according to Formula (2), as shown in Table 2. The obtained information quantity data are superimposed and analyzed according to the weights using Formula (3), and the total value of the information quantity is divided by the natural breakpoint method. Finally, the susceptibility to geological disasters in the study area is classified into four levels: non-susceptible, low-susceptible, medium-susceptible, and high-susceptible(Figure 4 and

ISSN 2616-5872 Vol.7, Issue 3: 1-15, DOI: 10.25236/AJEE.2025.070301

5).

Table 3 Area Proportion of Collapse and Landslide Susceptibility Zoning

susceptibility zoning	proportion of collapse - prone zones	proportion of landslide - prone zones
non - susceptibility	24.67%	30.90%
low susceptibility	11.27%	17.24%
moderate susceptibility	33.33%	45.56%
high susceptibility	30.73%	6.30%

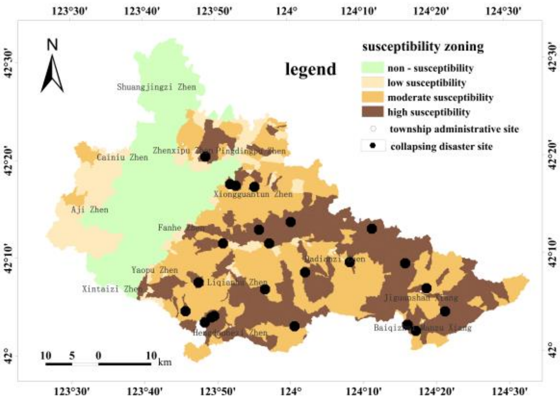


Figure 4: Susceptibility Zoning Maps for Collapse

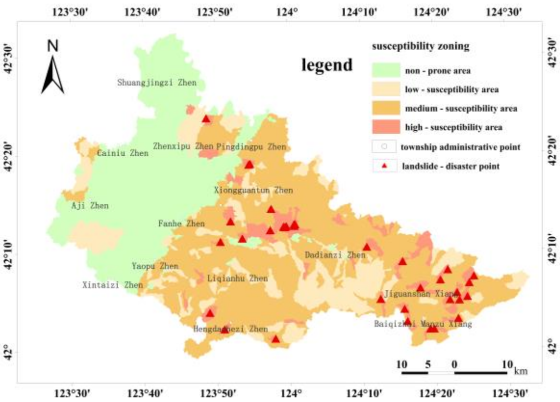


Figure 5: Susceptibility Zoning Maps for Landslides

Combined with the analysis of the susceptibility evaluation results (Figure 4 and 5) and the proportion of the area of disaster zones (Table 3), it can be seen that the overall susceptibility of collapses and landslides in the area shows a trend of being higher in the east and lower in the west. Among them, the proportion of the medium and high susceptibility zones in the east exceeds 65%.

The eastern landform is mainly mountainous and hilly areas. With a large slope gradient, and relatively high values of relative height, profile curvature, and plan curvature, it provides dynamic conditions for the occurrence of disasters. Faults are well-developed in the region, and relatively hard rock groups and composite rock slopes are widely distributed. In addition, the synergistic distribution of water systems and vegetation is disrupted by the terrain, resulting in a decrease in soil stability and providing an abundant material source for disasters, thus causing significant differences in susceptibility from east to west.

In conclusion, landslide disasters mostly occur in hilly areas in the east within 200 meters of water systems, with a slope gradient of 4°-8°, a profile curvature of 10.12-33.66, relatively hard rock groups, composite rock slopes, and areas with low vegetation coverage. Collapse disasters mostly occur in mountainous and hilly areas with a slope gradient of 8°-18°, a profile curvature of 6.44-10.12, relatively hard rock groups, composite rock slopes, and low vegetation coverage. This environment provides the formation conditions for the occurrence of disasters.

ISSN 2616-5872 Vol.7, Issue 3: 1-15, DOI: 10.25236/AJEE.2025.070301

4.3. Assessment of Geological Disaster Hazard

4.3.1. Determination of Evaluation Indexes

The assessment of the hazard of geological disasters requires the screening and determination of evaluation indicators for inducing factors based on the background and impacts of geological disasters in the southern area of Tieling. Referring to the relevant specifications and combining with the analysis of the geological structures, meteorological and hydrological conditions, etc. in this area, it is found that rainfall has a more significant impact on collapses and landslides. Considering the impacts of unreasonable human activities in the region, rainfall, and human engineering activities are finally selected as the inducing factors for geological disasters of collapses and landslides.

4.3.2. Construct the evaluation model and the index weight matrix

The hazard assessment model, based on the susceptibility assessment, superimposes two inducing factors, namely rainfall and human engineering activities (such as mining and water conservancy facilities construction) (Figure 6). To assess the hazard of geological disasters, it is necessary to couple the susceptibility assessment indicators with the impacts of rainfall and human factors. Based on the analytic hierarchy process, the weight values of the inducing factors for the two types of disasters, namely landslides and collapses, are calculated respectively, as shown in Table 4.

Table 4 Hierarchy and Weights of Triggering Factors for Hazard Risk Assessment

Target layer	Criterion layer	Weight	Index layer	Weight	Total weight of factors
Inducing factors of landslides	Rainfall	0.6651	Rainfall	1	0.6651
	Human engineering activities	0.3349	Mining	0.6901	0.2311
			Water conservancy	0.3099	0.1038
Inducing factors of collapses	Rainfall	0.4160	Rainfall	1	0.4160
	Human engineering activities	0.5840	Mining	0.7837	0.4577
			Water conservancy	0.2163	0.1263

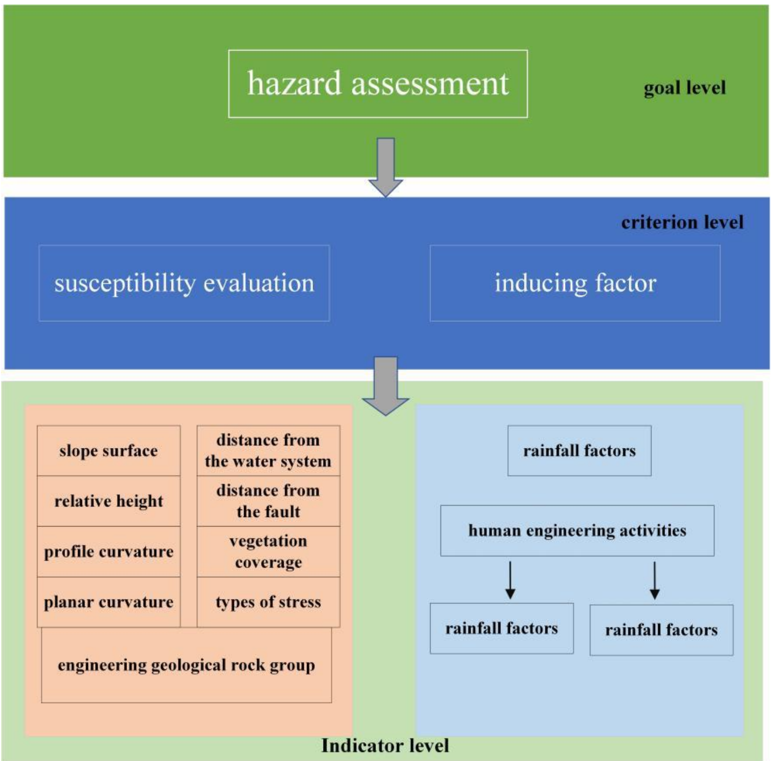


Figure 6: Structure Diagram of Hazard Risk Assessment

4.3.3. Zoning of Geological Disaster Hazard

According to the analytic hierarchy process, the weights of influencing factors are calculated. The indicators of mining and water conservancy facilities are weighted and superimposed with rainfall to

ISSN 2616-5872 Vol.7, Issue 3: 1-15, DOI: 10.25236/AJEE.2025.070301

obtain the inducing factor index under the conditions of rainfall and human engineering activities. The susceptibility assessment data and the inducing factors are weighted and superimposed at a ratio of 2:1 to calculate the hazards of landslides and collapse, and the comprehensive hazard is obtained through Formula (6). The natural breakpoint method is used to divide the hazards of the three into four levels: low, medium, high, and extremely high, and the proportion of the hazard zones of disasters in the study area is determined (Table 5 and Figure 7).

Collapse: The disaster points are mainly concentrated in the central part, and the high and extremely high hazard zones are continuously distributed. The high-hazard zone of collapse accounts for 41.32%, indicating that the collapse risk in the central area is spatially concentrated and covers a large range. The low-hazard zone accounts for 22.36%.

Landslide: Judging from the zoning map, the landslide disaster points are concentrated in the central and eastern parts, and the extremely high and high hazard zones are also mostly distributed there. Combined with Table 5, the high-hazard zone accounts for 37.78%, indicating that the landslide risk in these areas is not only concentrated spatially but also quite prominent in terms of the area proportion in the entire Tieling region. The low-hazard zone accounts for 31.54%, indicating that except for the concentrated high-risk areas, some other regions are relatively safe, which is consistent with the fact that there are no obvious landslide disaster points in some areas on the map.

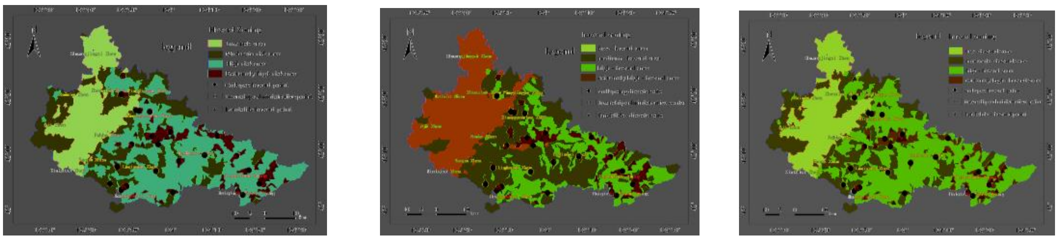
Comprehensive disasters: the extremely high and high hazard zones of the comprehensive disasters are widely distributed, involving the central, eastern, and southern parts. Combined with the proportion table, the high hazard zone of the comprehensive disasters accounts for 41.30%, and the extremely high hazard zone accounts for 5.17%, indicating that these high-risk areas account for a relatively large proportion of the entire region and are key areas for the prevention and control of geological disasters. The low-hazard zone accounts for 24.43%, which also indicates that there are still some areas that are less affected by the combination of the two disasters. Comparison and mutual influence of different disasters: Through comparison, it can be seen that the central area is a high-risk zone in the zoning of landslide, collapse, and comprehensive hazards, and it is the key area for prevention and control. Landslides are more prominent in the eastern part, while collapses are relatively more scattered in distribution.

$$f(Q)=max\{v_i,x_i\} \tag{6}$$

$f(Q)$ represents the final comprehensive hazard zoning of the assessment unit. Among them, V_i and X_i respectively represent the landslide hazard zoning and the collapse hazard zoning. The highest zoning of the two hazards within each slope area is selected as the comprehensive hazard zoning of the area.

Table 5 Proportion of Hazard Risk Zoning

Hazard Zoning	Proportion of Collapse Zoning	Proportion of Landslide Zoning	Proportion of Final Zoning
Low Hazard Zone	22.36%	31.54%	24.43%
Medium Hazard Zone	28.99%	23.64%	29.10%
High Hazard Zone	41.32%	37.78%	41.30%
Extremely High Hazard Zone	7.33%	7.04%	5.17%



(a) Collapse *(b) Landslide* *(c) Final*

Figure .7: Hazard Risk Zoning Map

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4.4. Assessment of Geological Disaster Vulnerability

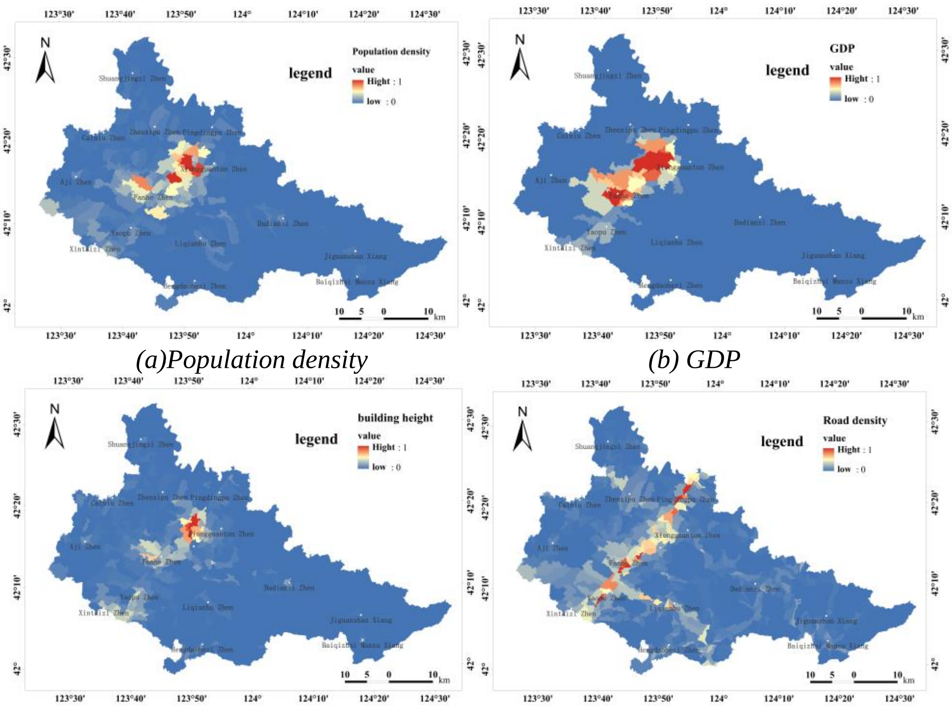
Vulnerability reflects the social attributes of geological disasters. In this paper, through the analysis of the economic development level and the degree of facility development within the region, a reasonable evaluation index system for the vulnerability of the study area is constructed. The regional vulnerability is calculated, and the natural breakpoint method is adopted to partition it.

4.4.1. Establishment of evaluation indexes

Vulnerability is influenced by the local social and economic development level as well as the degree of facility exposure. Based on the characteristics of disaster-bearing bodies within the study area and the vulnerability assessment data, personnel, buildings, roads, and GDP are selected as the evaluation indicators (Figure 8). The weights of the vulnerability evaluation factors are calculated, and the weights of the four factors are obtained (Table 6).

Table 6 Hierarchy and Weights of Influencing Factors for Vulnerability Assessment

Objective level	Criterion level Criterion	level indicators Indicators	Indicator	weights
Vulnerability assessment	Social factors	0.6730	Population density	0.5679
			GDP (Gross Domestic Product)	0.1050
	Facility factors	0.3270	Building height	0.2101
			Road density	0.1170



(a)Population density *(b) GDP*

(c)Building height *(d)Road density*

Figure 8: Vulnerability Indicator Maps

The high-value areas of the population, GDP, building height, and road density in the study area are all concentrated in Yinzhou District in the central part and the surrounding townships (such as Xiongguantun Town, Fanhe Town, etc.), showing the characteristics of population concentration, active economy, dense buildings, and well-developed transportation in this area. In contrast, the eastern and western regions perform poorly in these aspects, with sparse populations, low economic levels, low-rise buildings, and a sparse transportation network.

4.4.2. Zoning of Geological Disaster Vulnerability

According to the weights of the evaluation factors, the data of the evaluation factors are weighted and superimposed using formula (5) to obtain the vulnerability data. Then, the reclassification method

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is used to divide the vulnerability into four levels: low, medium, high, and extremely high, accounting for 19.44%, 50.31%, 28.88%, and 1.37% respectively (as shown in Figure 9). The geological disaster vulnerability in the Tieling area shows obvious zonal characteristics: The extremely high vulnerability areas are concentrated in Xiongguantun Town and some areas of Yinzhou District. Due to the dense infrastructure, active economy, and concentrated population, the risk of disaster losses is the highest. The high vulnerability areas expand around the extremely high vulnerability areas, covering townships such as Fanhe Town and Yaobao Town, with a relatively high disaster risk. The medium vulnerability areas are interspersed among them, and the low vulnerability areas are distributed in the marginal areas such as Shuangjingzi Town and Jiguanshan Township, with a relatively low disaster risk. The collapse and landslide disaster points are relatively concentrated in extremely high and high vulnerability areas, indicating that the probability of disasters occurring in these areas is high and the damage is severe. Although there are fewer disaster points in the medium and low vulnerability areas, potential risks still exist.

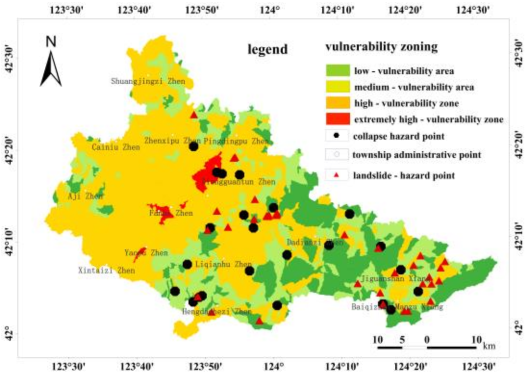

Figure 9: Vulnerability Zoning Map

4.5. Risk assessment and analysis

The results and zoning of geological disaster risk are the key objectives of risk assessment. As supporting data for regional disaster prevention and control decision-making, they are obtained by combining the risk matrix with hazard and vulnerability zoning, incorporating both the natural and social attributes of disasters. The geological disaster risk data are calculated using formula (1) and then classified into four levels through the natural breaks method. As can be seen from Figure 10, the medium-risk areas of geological disasters in the Tieling area account for the largest proportion, which is 58.65%, and are widely distributed in many places within the region. The high-risk areas are mainly concentrated in some areas in the central and southern parts, such as Fanhe Town, Yaobao Town, and Dadianzi Town in Tieling County. The low-risk areas are distributed in areas such as Shuangjingzi Town in the northern part, while the extremely high-risk areas have a very small scope and only appear locally. Combined with the data in Table 7, the high-risk areas have the largest number of disaster points, reaching 38, accounting for 64.41% of the total number of disaster points, indicating that the geological conditions in this area are complex and disasters occur relatively frequently. There are 19 disaster points in the medium-risk areas, accounting for 32.20%, and there are also certain disaster potential hazards. The number of disaster points in the low-risk areas is 0, and there are 2 disaster points in the extremely high-risk areas, accounting for 3.39%. Although the number of disaster points is small, once a disaster occurs in extremely high-risk areas, the destructive power will be extremely great.

Table 7 Proportion of Risk Zoning and Number of Hazard Points in Each Zone

Risk zoning	Proportion of risk zoning	Number of disaster points	Proportion of disaster points
Low-risk area	17.53%	0	0
Medium-risk area	58.65%	19	32.20%
High-risk area	23.37%	38	64.41%
Extremely high-risk area	0.45%	2	3.39%

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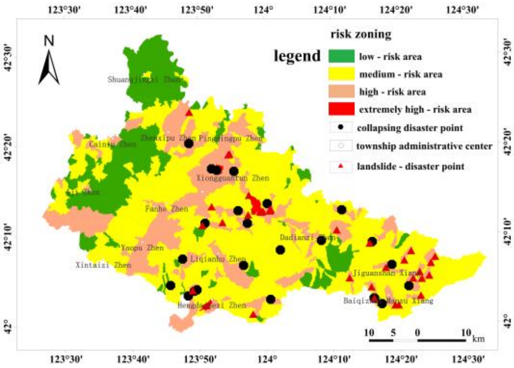

Figure 10: Risk Zoning Map

5. Conclusions

Based on the background influencing factors such as the topography and geomorphology, geological structure, water system, and vegetation in the study area, as well as the characteristics of geological disasters, nine indicators including slope gradient, relative height, profile curvature, plan curvature, distance from faults, engineering geological rock groups, distance from water systems, slope types, and vegetation coverage are selected to construct an evaluation index system for susceptibility at the scale of slope units.

According to the evaluation results of the susceptibility of collapse and landslide disasters, the hazard is further obtained by comprehensively considering the disaster-causing factors, and the vulnerability results are weighted and superimposed. According to the specifications, the risk matrix method is used to obtain the results of the geological disaster risk assessment in the study area. Through analysis, the evaluation results are consistent with the actual distribution, which can provide an important reference basis for formulating regional disaster prevention and mitigation measures.

The high-risk areas of geological disasters in the study area are mainly distributed to the east of the line from Pingdingpu Town to Xiongguantun Town to Yaobao Town and are significantly affected by the structure of rock and soil masses, tectonic movements, and human activities.

The high-risk areas have a large number of disaster points and high risks and should be regarded as key prevention areas. Geological monitoring should be strengthened, early warning capabilities should be improved, and targeted prevention and control measures should be formulated. The medium-risk areas have a large area and a certain number of disaster points, and potential hazards need to be regularly investigated. Although there are currently no disaster points in the low-risk areas, continuous attention should be paid to geological changes. The extremely high-risk areas have a small scope but are extremely dangerous, and immediate protective measures should be taken. When necessary, the relocation and resettlement of the population and facilities can be considered.

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