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Construction of Rules for Recognizing Landslides Along Highways Induced By Rainfall

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ABSTRACT

After the "7-20" concentrated rainfall, many landslides occurred along the highways in Jiaozuo City, which seriously threatened the transportation safety and brought serious economic losses to the government and the residents along the highways. In order to investigate the development pattern and distribution characteristics of landslides along highways under extreme weather, we took Jiaozuo City Highway as the research object, based on the Sentinel-2 remote sensing data, and on the basis of analyzing the spectral characteristics of landslide hazards, we used the band ratio method to establish the identification rules of loess landslides along highways; based on the topography, geology, human impacts, and meteorological and hydrological selected 11 impact factors, and used geoprospectors to investigate the The driving factors of landslides. The following conclusions and understandings were obtained: (1) a total of 256 landslides along the highway in Jiaozuo City were identified, and the overall identification accuracy of 69.9% was obtained through visual interpretation and on-site research; (2) the ratio of the surface true reflectance of red and green light fused with the slope (>15°) can be used to carry out the identification of landslides in large-scale post-disaster situations; (3) the human activities and topography have a greater impact on landslide development; (4) the identification rule has a greater impact on the development of landslides with similar geological backgrounds. rule is useful for the identification and prevention of landslides along highways in low-hill loess-covered areas with similar geologic backgrounds.

KEYWORDS

Highway Alignment; Extreme Rainfall; Spectral Analysis; Landslide Identification; Jiaozuo City

1. INTRODUCTION

According to the statistics of the Geological Disaster Disaster Circular issued by the Ministry of Natural Resources, from January 2020 to May 2022, a total of 13,164 geological disasters occurred nationwide, of which 7,353 were landslides, accounting for 55.86%, and landslides have become one of the geological disasters with the greatest impacts and causing the most serious losses in China. Nearly 65% of China's territory is mountainous and hilly, with large slopes, and the natural environment of high mountains and deep valleys and gullies provides spatial conditions for the development of landslides, and extreme rainfall is one of the main factors triggering geologic hazards in mountainous areas that harbor disasters[1] , and the increase in regional extreme weather events exacerbates the occurrence of landslide disasters, resulting in serious losses of life and property[2,3] .

Landslide along the highway refers to a class of geologic hazards formed along the highway under the geomorphological conditions of mountain slopes, gullies and mountain basins, etc., which are mostly distributed on the slopes along the mountain highway, especially on the high side slopes and steep mountains.[4] Through the analysis of the loess landslide disaster events along the S316 highway in Xinjiang from 1998 to 2015, it can be seen that the highest frequency of landslides during the year occurs in the month of March to June, and the time period is The rainfall is abundant and the temperature is high, which shows that loess landslides are controlled by the water-heat combination conditions of regional rainfall and temperature[5] . There are more than 100 loess landslides distributed in bands or groups along the 80Km Bali (Lan)-Lin (Xian) highway located in the north-central part of the Lvliang Mountain Range, and the monolithic landslides along the highway show the characteristics of large-scale landslides, complex geotechnical structures, poor stability, and susceptibility to precipitation, etc. Moreover, the human engineering activities will have a greater impact on the stability of the highway slopes or even induce landslides[6] . Calculation of the contribution of each influencing factor to landslides in the watersheds along the China-Pakistan Highway in the context of climate change shows that rainfall and temperature have a greater influence on the landslide hazard zones along the highway[7] . The hazards of landslides along the highway are mainly reflected in the impact on highway traffic, which will not only cause road interruption and traffic congestion, but also may lead to the destruction of roadbed, bridges, culverts and other highway facilities, which will bring a threat to people's lives and properties, and the rapid access to the location and impact range of the landslide disaster after the disaster can reduce the losses and provide scientific guidance for the post-disaster relief[8] . With the development of remote sensing technology, the use of remote sensing images for the identification of large-scale landslides has the characteristics of small danger, rapidity, wide coverage and automatic identification can be realized, and is widely used in the identification of landslides. The methods of landslide identification based on remote sensing features are mainly classified into five categories: visual interpretation of single image features, multi-temporal optical remote sensing change detection method[9,10,11] , image element-based classification method[12] , object-oriented classification method and deformation monitoring[13,14] . The visual interpretation method is more subjective and relies on expert knowledge, which is not easy to identify landslides on a large scale; the effect of the change detection method in identifying landslides is affected by the quality of the image data and the change information of features over time; the image-based landslide information extraction method relies on the spectral attributes of features and classifies them based on a single image, but it does not take into account the spatial location information of pixels but only the change of spectral values, which is not enough to utilize the data; the deformation monitoring method does not make sufficient use of data; and the deformation monitoring method does not make sufficient use of data. Insufficient utilization; deformation monitoring in the actual identification and monitoring of landslides, affected by high vegetation cover, atmospheric humidity, etc., resulting in interferometric image pairs of incoherence, which leads to the problem of decorrelation, and the actual deformation is greatly affected by human activities, which is not conducive to the identification of landslides in human activity zones[15] .

Jiaozuo City has great topographic changes, is in the transition zone between mountains and plains, and has a fragile geological environment[16] , complex terrain and variable climate. According to the historical meteorological and climatic analysis of Jiaozuo City, there have been many times of torrential rainfall and flooding in history, and the sudden and heavy precipitation has caused serious secondary disasters such as landslides and mudslides.[17] . In 2020, "7-20" extreme rainfall occurred in a large number of landslides along the highways in the northern mountainous areas, seriously threatening the safety of highway operations and the lives and properties of nearby residents. After the "7-20" extreme rainfall in 2020, a large number of landslides occurred along the highway in the northern mountainous area, which seriously threatened the safety of highway operation and the lives and properties of nearby residents. In this paper, we use spectral analysis to analyze the image characteristics of post-disaster landslides in Jiaozuo area on Sentinel-2 remote sensing images, and propose a post-disaster landslide identification rule based on the ratio of surface true reflectance of red and green light fused with slope (>15°) to identify post-disaster landslides along the highways in the northern mountainous areas of Jiaozuo City, and at the same time, consider the effects of elements such as topography, geomorphology, geologic structure, lithology, meteorology and hydrology, and human engineering activities on landslides. At the same time, considering the topography and geomorphology, rock quality, meteorology and hydrology, and human engineering activities and other elements of landslides, we explore the driving factors and distribution characteristics of landslides along highways in Jiaozuo City, so as to provide a basis for the prevention and management of landslides along highways in the low hills and loess-covered areas with similar geologic backgrounds.

2. INTRODUCTION TO THE STUDY AREA

Jiaozuo City is located in the northwestern part of Henan Province, with a geographic location between 35º10′-35º21′ north latitude and 113º4′-113º26′ east diameter, and it is a regional center city of China's Central Plains Urban Agglomeration and Yu-Jin Junction Area as approved by the State Council. Jiaozuo City has a warm-temperate sub-humid monsoon climate with four distinct seasons, rain and heat in the same season, and a complex and diverse climate, with a multi-year average temperature of 14.5°C, multi-year average precipitation of 568.5 mm, and multi-year average evaporation from water surfaces of 993.3 mm. It is known from the analysis of the monthly and yearly rainfall of Jiaozuo City for the last ten years in Fig. 2, that the highest rainfall is recorded in June-September of each year, and in July of 2021, the monthly rainfall amounted to 703.7mm, which is higher than the average annual rainfall in the past years, and the concentrated high-intensity rainfall is more likely to induce geologic disasters.

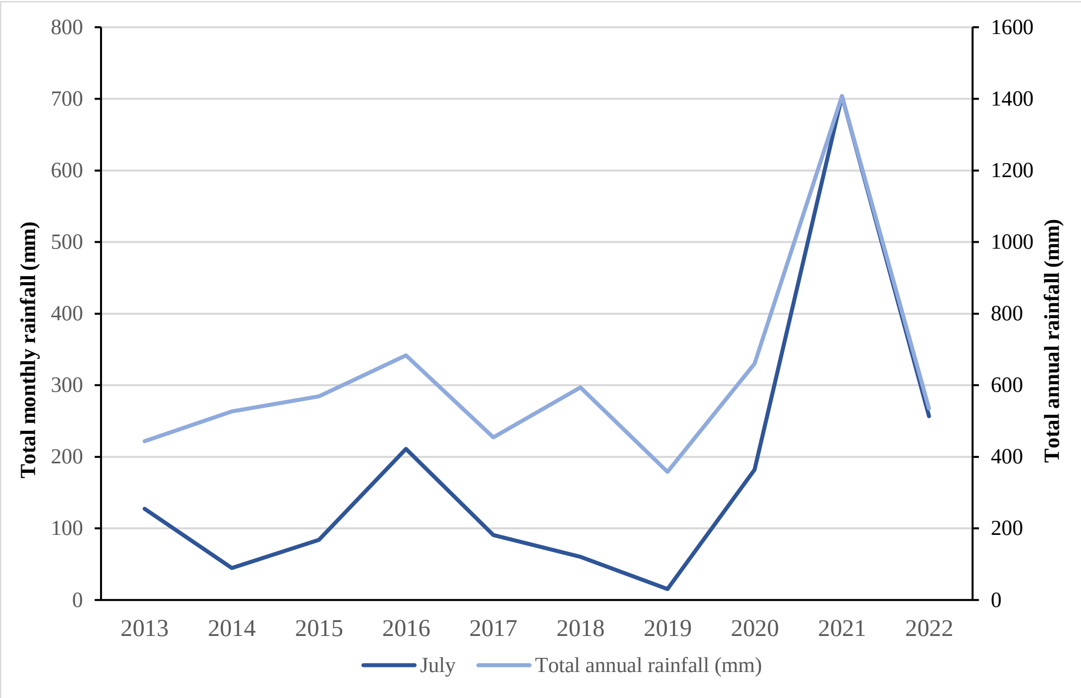


Fig. 1 Line graph of total July, annual rainfall, 2013-2022

(Data from China Meteorological Network)

3. DATA AND RESEARCH METHODS

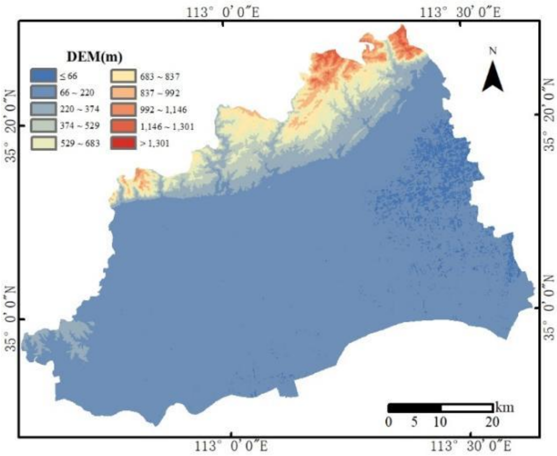
3.1. Data sources

The study area was selected to use Sentinel-2 remote sensing image data on July 31, 2021 after the occurrence of the concentrated rainfall event and ASTER GDEM 30m elevation data, Sentinel-2 data from the official website of the ESA (https://www.esa.int), the image cloudiness are less than 5%, ASTER GDEM data from the Geo ASTER GDEM data from Geospatial Data Cloud (https://www.gscloud.cn/). The imaging process of the images is affected by atmospheric interaction and random noise, and the actual image gray scale value cannot fully reflect the actual size of electromagnetic waves radiated by the features, therefore, it is necessary to make radiometric and atmospheric corrections to the remote sensing data to obtain the actual reflectivity of the features.

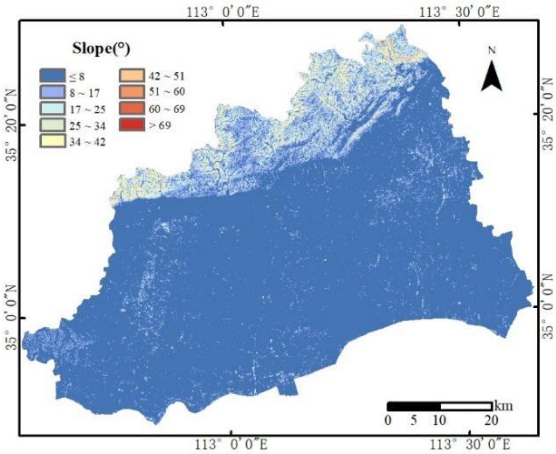
The occurrence of landslides along the highway is not only related to the topography and geological structure, but also closely related to external factors such as human activities and meteorological rainfall. The data sources and accuracy of the selected evaluation factors are shown in Table 1, and the influence factors and their grading diagrams are shown in Figure 3.

Table 1 Data sources and precision

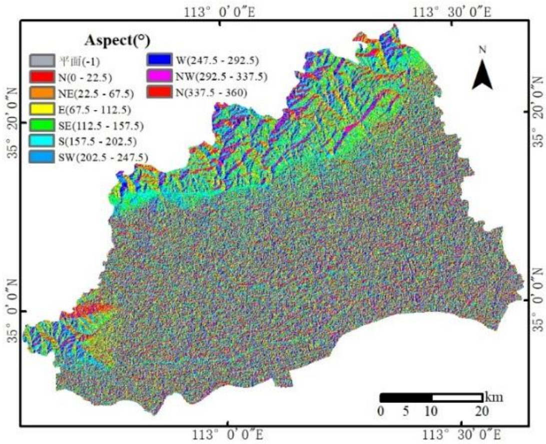
Data classification	data name	Data sources	resolution (of a photo)
Historical remote sensing images	Sentinel-2B	ESA official website (https://www.esa.int)	10m
Historical Slippage Point	Historical landslide hazard sites	Center for Resource and Environmental Sciences and Data, Chinese Academy of Sciences (https://www.resdc.cn/)	//
topography	altitude (e.g. above street level)	Geospatial Data Cloud (https://www.gscloud.cn/)	30m×30m
	Slope direction, slope gradient, degree of terrain relief	Obtained from DEM using ArcGIS software using spatial analysis.	30m×30m
geological element	Lithology, faults	1:2500000 geological map (vectorized)	//
meteorology and hydrology	linear water system	Center for Resource and Environmental Sciences and Data, Chinese Academy of Sciences (https://www.resdc.cn/)	//
	Average annual rainfall	WorldClim(https: //www.worldclim.org/)	30 s x 30 s (≈900 m)
Impact of human activities	linear road	Center for Resource and Environmental Sciences and Data, Chinese Academy of Sciences (https://www.resdc.cn/)	//
	Human impact index	Center for Socioeconomic Data and Applications (https://sedac.ciesin.columbia.edu/)	1km x 1km
	Land use type	Institute of Space and Astronautical Information Innovation, Chinese Academy of Sciences (http://www.aircas.ac.cn/)	30m×30m



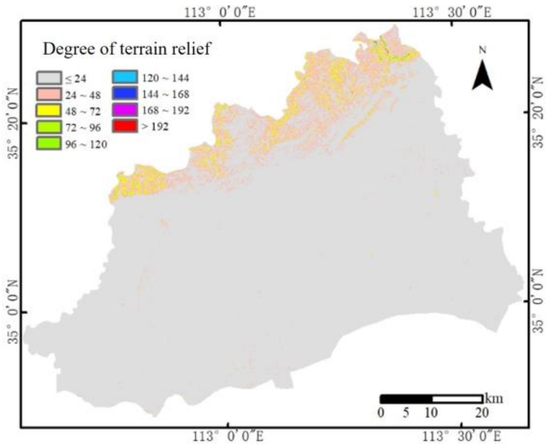
(a) Elevation



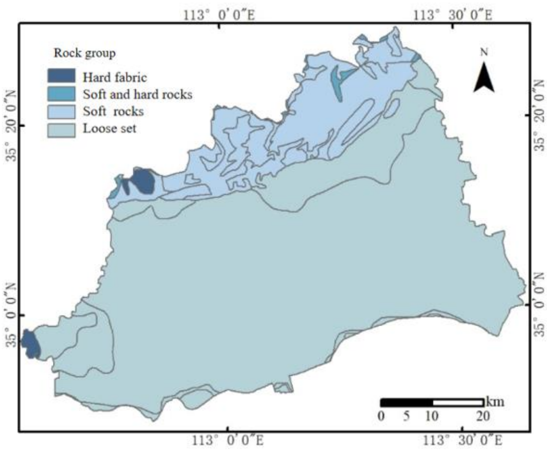
(b) Slope



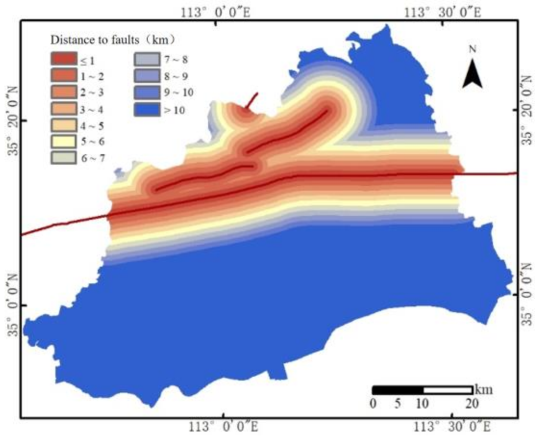
(c) Slope direction



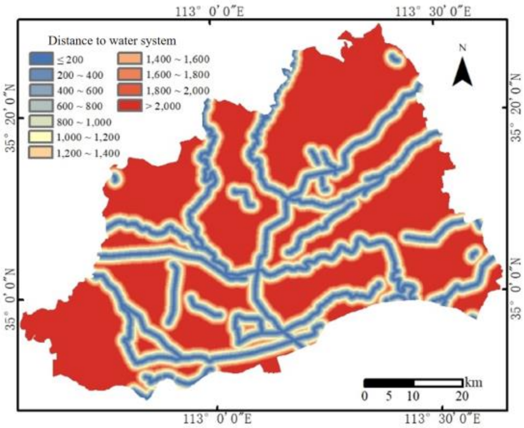
(d) Degree of terrain relief



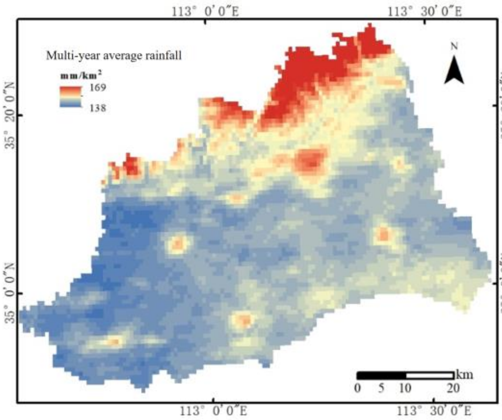
(e) Rock group



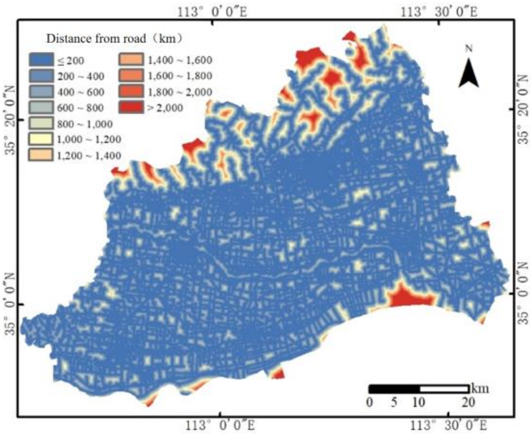
(f) Distance to faults



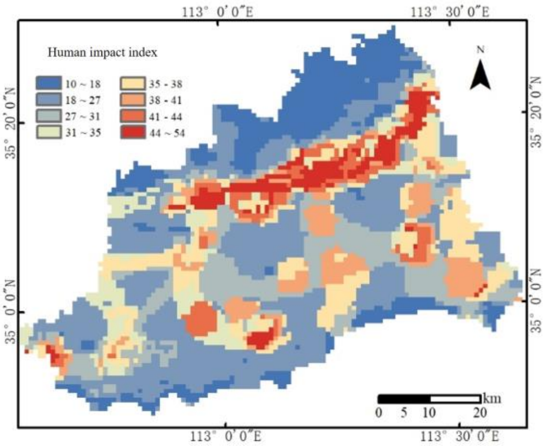
(g) Distance to water system



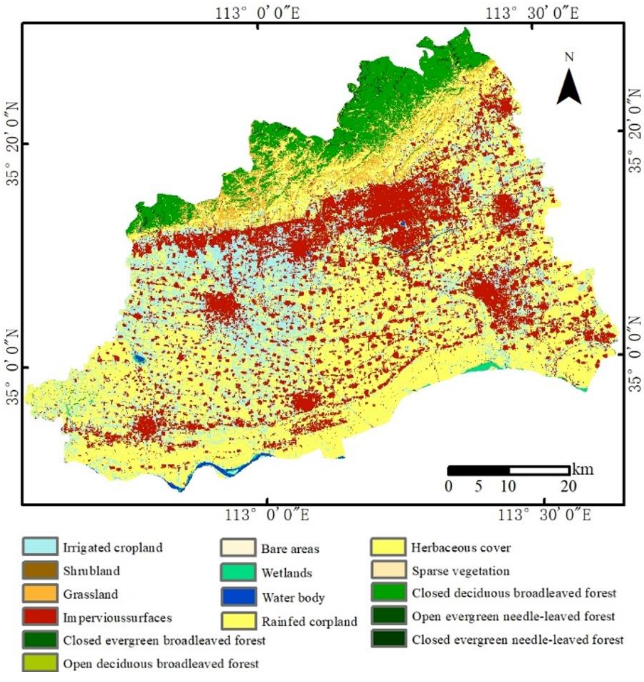
(h) Multi-year average rainfall



(i) Distance from road



(j) Human impact index



(k) Land use types

Figure 2 Schematic diagram of the impact elements and their classification

3.2. Research methodology

3.2.1. Landslide identification based on spectral features

Landslide refers to the role and phenomenon that rocks, soil, and debris on a mountain slope move down the slope as a whole by producing shear displacement along a certain weak structural surface under the action of gravity, and it shows differences in optical remote sensing images[18] with its surrounding features, i.e., it has differences in spectral response feature information. According to the previous research results[19] , based on the field investigation, combined with remote sensing image features, the landslide and its surrounding features are sampled, the spectral curves of the features are drawn, the spectral features of each feature are analyzed, and the rapid identification rules of loess landslide along the highway are proposed. The sampling area of the landslide is the main body of the landslide, and the highway and water bodies near the landslide are sampled. The area with NDVI greater than 0.7 on the hillside around the landslide is selected for sampling the vegetation. Optical remote sensing image imaging due to the sun irradiation angle, there are mountain shadows on the image, which may affect the accuracy of landslide extraction, for which samples were collected. Jiaozuo City is a new tourist city, and there are artificially developed tourist sites in the peripheral mountainous areas of the city, according to the comparison of multi-period remote sensing images, stable building information is selected for sample collection. The sample collection point information is shown in Figure 1. The folding diagram of spectral features of various features is shown in Fig. 4.

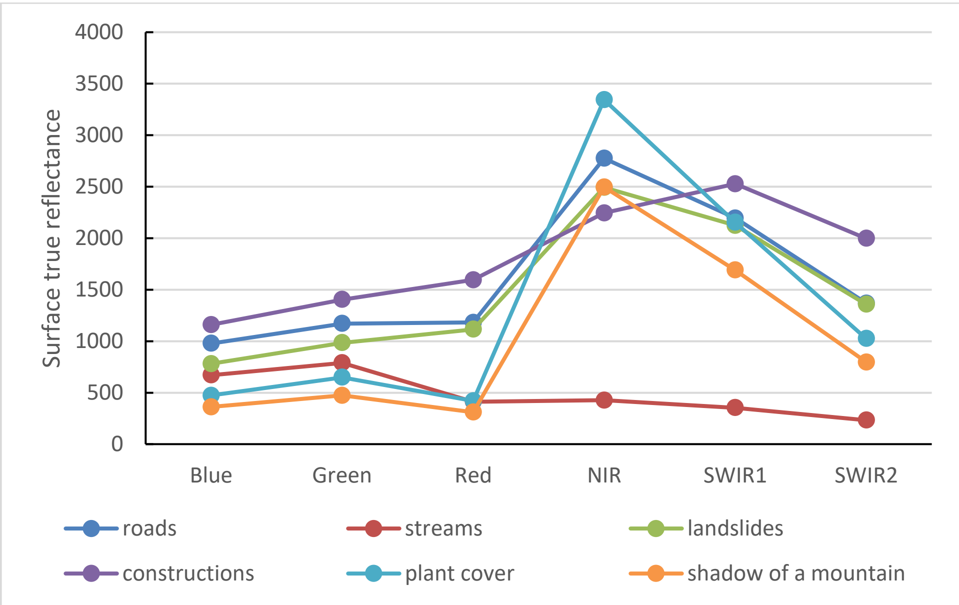


Fig. 3 Spectral characterization curves for each type of feature

Comprehensive analysis of the spectral information of each place in the study area shows that the spectral reflectance value of the landslide area is increasing in the green band to the red band, while the vegetation, shadow of the mountain, and the river are reflected as decreasing, and the "slope" of the man-made structures in the green band to the red band is greater than that of the landslide, and that of the landslide is greater than that of the road. "The "slope" of landslides is greater than that of roads. Therefore, the red light band (Band4) and the green light band (Band3) are selected to separate the landslide from other surrounding features by threshold segmentation through band operation. Jiaozuo city presents the topographic and geomorphic characteristics of high north and low south, the middle and southern part of the city is the impact plain of the Huangqin River, mostly farmland, with small elevation differences and slopes less than 15°, which does not have the conditions for the development of landslides, and the centralized rainfall event occurs before and after the ripening and harvesting period of winter wheat, in order to eliminate the influence of the changes in crop growth on the results of the identification of landslides, the difference of slope characteristics between the middle and south of Jiaozuo city and the northern mountainous hills is used to eliminate this effect. According to the spectral characteristics of landslides and topographic features, the extraction rules for rainfall-induced landslides in Jiaozuo City are as follows:

$$\begin{cases} \frac{R-G}{R+G} \in (0,0.3) \\ slope > 15° \end{cases} \tag{1}$$

3.2.2. Geoprobes

Geoprobe is a statistical analysis method proposed by Wang Jinfeng's team[20] for detecting the spatial dissimilarity of the research object and revealing its intrinsic driving force, based on the lattice model to analyze the geographic problems, and identifying and evaluating the factors and spatial relationships affecting the geographic phenomena by calculating the correlation, G-value, and cross-checking between the different factors. Compared with traditional statistical models, it can realize the simultaneous detection of quantitative and qualitative data, and can be used in the field of geohazards for the evaluation of driver selection and help researchers to determine the main factors affecting the occurrence of geohazards and the spatial distribution pattern. In this study, the factor detector function of geodetector was used to determine whether the two factors interact and the strength of the interaction by calculating and comparing the q value of a single factor and the q value of the superposition of the two factors, respectively. q value is the explanatory power of the influencing factors on landslides, and its value ranges between 0 and 1, and the larger the q value indicates the higher the degree of explanation[21,22].

$$q = 1 - \frac{1}{N\sigma^2}\sum_{h=1}^{L} N_h\sigma_h^2 \tag{2}$$

In Eq. (1): N is the number of units in the whole study area, i.e., the sample size; N_h is the number of cells in stratum h; h is the number of strata for the continuity factor; σ_h^2 is the variance value of stratum h; σ^2 is the factor variance for the entire study area.

In this study, we used the point density of landslide identification points as the dependent variable, and selected topographic elements: slope, slope direction, elevation, and degree of terrain undulation; geologic elements: rock quality, geological structure; human influence elements: land use type, distance from roads at all levels, and Human Influence Index (HII, Human Influence Index); and meteorological and hydrological elements: average annual rainfall (multi-year average annual rainfall) and distance from linear water system, etc. Combined with mathematical statistics and GIS spatial analysis, the driving factors of landslides along highways in Jiaozuo City were analyzed using the factor detector function of Geodetector.

4. RESULTS AND ANALYSIS

4.1. Landslide identification

A total of 256 rainfall-induced landslides of various sizes along the highway in Jiaozuo City were identified by applying Eq. (1) (shown in Fig. 6). After the "7-20" rainfall event, the authors conducted a field investigation of landslides along the Beishan Highway in Jiaozuo City in October, which included the following: field identification of landslide locations, time of occurrence of landslides, slope gradient, slope direction, morphological characteristics, water table depth, slope humidity, and hazards caused by landslides, etc. The field investigation revealed that the main body of rainfall-induced landslides was mostly Quaternary loess. During the field investigation, it was found that the main body of rainfall-induced landslides is mostly loess cover layer of the fourth system, the land cover type is mostly shrubs, and bedrock outcrops are seldom seen, most of them are small landslides, and the foot of the original slopes of landslides along the highway are excavated, and sliding occurs under the influence of centralized rainfall, and the accumulation of bodies destroys the normal operation of the highway. A total of 179 landslides triggered by concentrated rainfall in Jiaozuo City can be obtained through field investigation and visual interpretation, with an overall recognition accuracy of 69.9% and a Kappa coefficient of 90.5%.

Landslide identification sites in the spatial location is mainly distributed in the northeastern part of Qinyang City, Boai County and the northern part of Xiuwu County and the junction of Zhongzhan District and Jiefang District, concentrated in the Jinxin Expressway and the provincial highway S238, S237 and S233 on both sides of the road, and 83.7% of the landslides fall into the scope of the buffer zone of 500m on both sides of the roads of all levels in Jiaozuo City; in the topography and geomorphology of the zoning, the landslides are located in the low elevation, small undulating mountains, and 82% of the original slope is 15°~25°. Among them, 82% of the landslide identification points have original slopes of 15°~25°, and are mostly distributed in the southeast, east, and southwest of the three slope directions with long sunshine time and stronger weathering.

(a) (b)

Figure 4 Example of a landslide explored in the field

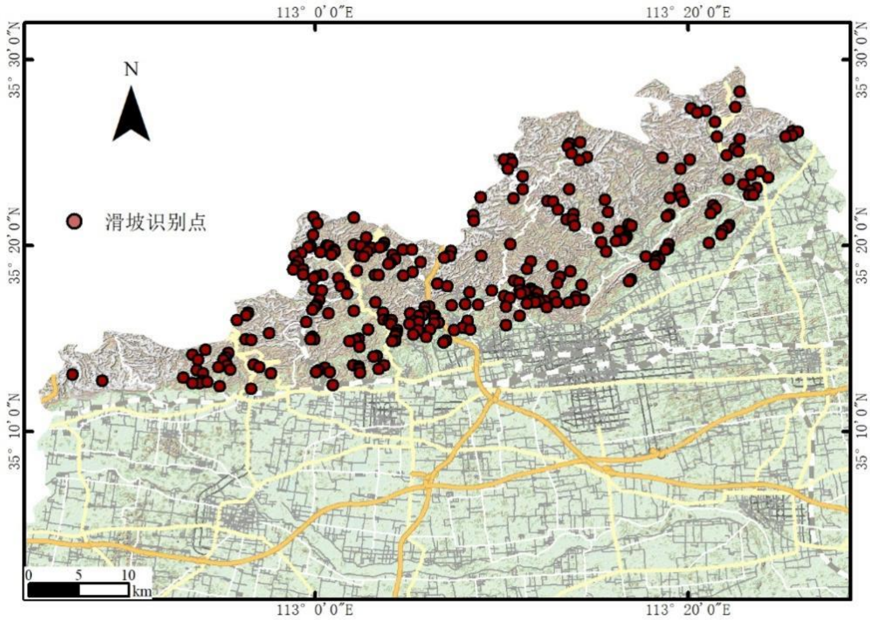


Fig. 5 Map of landslide identification results

4.2. Driver analysis

The q-value of each influencing factor was calculated by the factor analysis tool of Geodetector, and the factors were ranked according to their q-values: human activities > elevation > distance from road > distance from fault > slope direction > average annual rainfall > rock quality > land use type > slope > topographic undulation > distance from linear water system. The q-values of human activities, elevation and distance from road were 0.8057, 0.5129 and 0.5092, respectively, which were the three influencing elements with the highest q-values and had the highest intensity of explaining the landslides along the Jiaozuo highway, i.e., topography and human activities were the important influencing factors for the landslides along the Jiaozuo highway.

According to the distribution data of historical landslide disaster points in Jiaozuo area, it can be seen that the disaster points are all distributed in the mountainous areas in the north of Jiaozuo city, mostly developed in the low rolling low hills area, with the slope direction in the south direction, and 64.7% of the points fall within 200m along the highway, which shows that the topography and human activities have a greater impact on the occurrence of landslides in Jiaozuo area. The results of post-disaster landslide identification show that 83.7% of the landslide points fall within the range of 500m on both sides of the road, indicating that the excavation and filling during the construction of roads in mountainous areas destroys the original structural soil structure characteristics of the slope, and ultimately sliding occurs under the influence of concentrated rainfall, which is in line with the results of the driving factor analysis showing that human activities have the greatest influence on landslides. The central and southern part of Jiaozuo area is alluvial flood plain, the slope is mostly less than 15°, which is not in line with the conditions of landslide development, and the northern part is mountainous hills, and the surface layer is mostly loess overlay of the fourth system, which is in line with the basic conditions of landslide development.

5. CONCLUSION

(1) This paper uses spectral analysis to analyze the spectral characteristics of landslides along the highway in Jiaozuo City on Sentinel-2 remote sensing images, and fuses the slope based on the ratio of the true reflectance of the red and green surface to obtain the landslide identification rules, extracting a total of 256 landslides along the highway after the disaster, and obtaining the overall accuracy of the landslide identification results through the visual deciphering and on-site research;

(2) Factors that are strong drivers of landslides along the highway are human activities and topography, which are consistent with the basic conditions for landslide development;

(3) In the field of post-disaster landslides in the Jiaozuo area, it was found that most of the slopes along the highway were not protected, or loose shrubs were planted to protect the slopes, and the foot of the slopes were excavated and the slopes were loose, which made it very easy to form a washout gully, and then form landslides, in order to reduce the occurrence of landslides along the highway in loess-covered areas, it is necessary to reinforce the highway side slopes or to construct protective walls, or plants adapted to the characteristics of loess can be planted to enhance soil resistance strength, and also to set drainage ditches or drainpipes on the slope. Plants can be planted to strengthen the shear strength of the soil, and drainage ditches or drainpipes can be set up on the slopes, while the joint group prevention and monitoring officers carry out regular inspections of unstable slopes or historical landslides to strengthen the maintenance and management.

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