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Study on the Regularity of Surface Collapse in Goaf using UAV Remote Sensing Technology

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Abstract

UAV remote sensing technology is used to analyze the characteristics of surface collapse and evaluate the degree of damage in the mining area, and the regularity of surface collapse in the mining area is studied. The distribution and variation characteristics of surface collapse pits and surface cracks and surface deformation characteristics are obtained from UAV images. Taking the area of collapse pits, the depth of collapse pits, the width of cracks, the drop of cracks, the density of cracks, surface subsidence and surface inclination as the evaluation factors, the fuzzy opinion centralized decision-making of the classical fuzzy comprehensive evaluation method is introduced into the combined weighting method, and the fuzzy comprehensive evaluation model based on AHP-CRITIC method is established. The results show that: (1) From August 2020 to June 2021, 125 surface cracks have increased; Three new collapse pits are generated, with a maximum area of about 323m^2 and a maximum depth of about 21m; The surface deformation in the south of the mining area is obvious, forming a settlement funnel. (2) The severe damage degree of surface collapse is mainly distributed near the surface collapse pits, the moderate damage degree is mainly distributed in the central and southern part of the study area, and the mild and slight damage degree is mainly distributed in the periphery of the ore body.

Keywords: *Analytic Hierarchy Process (AHP), CRITIC Method, Fuzzy Comprehensive Evaluation, Surface collapse, UAV remote sensing, GIS*

1. Introduction

The surface collapse of goaf is the phenomenon of surface collapse after surface bending due to the loss of support conditions of overlying strata and the destruction of original balance after the underground seam is mined (Gao, 2018). The manifestations of surface subsidence are mainly summarized as surface subsidence, surface cracks and collapse pits (He *et al.*, 2016; Husan *et al.*, 2016). In recent years, the development and utilization of Longshou mineral resources in Jinchang City, Gansu Province has played a great role in promoting the development of the national economy. At the same time, the development of mineral resources has also brought severe environmental problems to society and mankind (Su and Zhang, 2013). The long-term exploitation of resources in the mining area leads to the formation of a large-scale collapse area on the surface, which seriously affects the environmental protection and safety production of the mining area. Therefore, it is very necessary to analyze the characteristics of surface collapse in goaf and study the degree of surface collapse damage to guide the safe excavation, surface collapse treatment and sustainable development of mining area.

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With the requirements of strengthening the construction of ecological civilization in China, mine environmental problems have attracted much attention. The problem of surface collapse caused by high-intensity resource mining is particularly prominent. How to obtain the surface collapse information of mining area by efficient, fast and safe means is very important. For traditional manual measurement methods such as GPS measurement, leveling and total station measurement, it is impossible to obtain continuous three-dimensional data in an efficient and large area (Gao *et al.*, 2018). Many scholars began to analyze the surface collapse of the mining area through InSAR, three-dimensional laser scanning and satellite remote sensing technology, but there are limitations in resolution and accuracy (Wang, 2015; Li *et al.*, 2015; Yu *et al.*, 2016). With the development of UAV technology, UAV remote sensing has a series of technical advantages, such as high image resolution, low cost, flexible and not affected by complex terrain. It is widely used in geological work (Hou *et al.*, 2017; Zhang *et al.* 2020). Due to the importance of land reclamation in China, there are more and more studies on the evaluation of surface collapse damage in mining areas. The common evaluation methods include fuzzy comprehensive evaluation method, limit condition method, index method, etc. (Liu and Lv, 2013; Tang and Wei, 2011; Wang and Liu, 2015; Cheng, 2017). These methods can reflect the damage degree of surface subsidence area in mining area to a certain extent, but there is no unified method standard for determining the index weight. For the classical fuzzy comprehensive evaluation methods, most scholars use expert scoring method or analytic hierarchy process to determine the index weight (Zhou, 2019), and the two methods are highly subjective. Aiming at the problem of strong subjectivity, this paper uses the subjective and objective combination weighting of Analytic Hierarchy Process (AHP) and CRITIC method to evaluate the damage degree of surface collapse by fuzzy comprehensive evaluation method.

2. Overview and Data Sources of the Study Area

2.1 Overview of the Study Area

Jinchuan nickel sulfide copper deposit is one of the three major metal paragenetic deposits in China. It is located in Jinchang City, Gansu Province, China. The deposit is composed of four mining areas, and Longshou Mine is one of the main mining areas. The study area in this paper is the collapse area of West No. 2 mining area of Longshou Mine. As shown in Figure 1, the original design of this area was to use the natural caving method for mining. In June 2016, the cemented backfill in rows 5 to 7 of West No. 2 mining area unexpectedly collapsed in a large area and penetrated to the surface, and then the mining was stopped. In April 2019, West No. 2 mining area began to adopt sublevel caving mining without bottom pillar. As a kind of caving mining method with simple structure, high efficiency and low cost, it has been rapidly popularized and widely used in underground mining at home and abroad (Hui *et al.*, 2020; Zhou *et al.*, 2006). In order to monitor the safe mining of the mining area, this paper extracts the surface spatial information and studies the law of surface collapse.

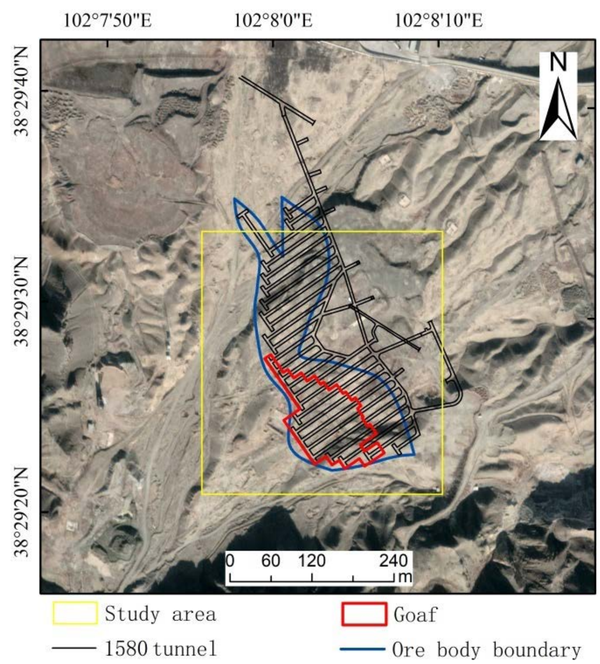

Figure 1. Overview of the study area.

2.2 Data Acquisition and Data Processing

The research data in this paper are the remote sensing images of UAV in August 2020 and June 2021. The flight platform used is Dajiang spirit 4 rtk4 rotor UAV. The data processing system selects context capture image processing professional software, which can quickly make multiple images into accurate two-dimensional images and three-dimensional real scene models. As the surface cracks and collapse pits in the study area are the main types of surface collapse in the mining area, most of the surface cracks are more than 2cm wide. Combined with camera parameters, the ground resolution of UAV image is set as 2cm, and the relative altitude calculated by UAV relative altitude formula (1) is about 73m.

$$H = \frac{f \times GSD}{a} \quad (1)$$

where, GSD is the ground resolution (m); F is the focal length of camera lens (mm); A is the camera pixel size (mm).

Import aerial survey images, coordinate POS and other data into context capture software for image matching, aerial triangulation, triangulation and texture mapping, and finally generate DOM (Digital Orthophoto Image), DEM (digital elevation model) and 3D real scene model. According to the common points obtained from ground control survey, the elevation fitting correction model of four parameter surface fitting is used to fit and correct the three-dimensional coordinate data. Combined with the field investigation, the surface crack with a width of about 2 cm can be accurately identified in the three-dimensional real scene model by setting a relative navigation height of 73 m.

3. Analysis of Surface Subsidence Characteristics in Mining Area

3.1 Change of Surface Crack Activity

With large-scale underground mining, from August 2020 to June 2021, many small new fracture groups have been generated outside the original surface fracture group, and some fractures have expanded from one to multiple (Figure 2).

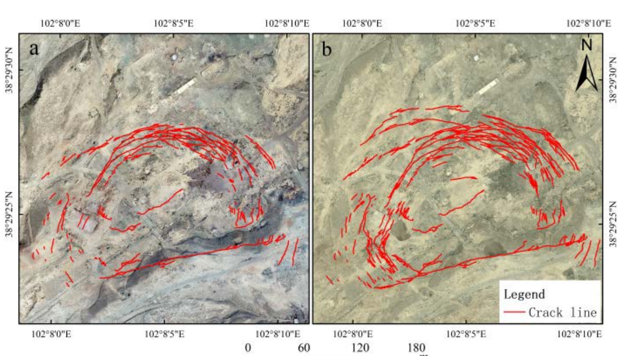

Figure 2. Distribution of surface cracks in 2020 (left) and 2021 (right).

3.1.1 Length Change

The number of surface cracks in June 2021 increased by 125 compared with August 2020, and the cracks were further developed. The change of surface crack length in the mining area can directly reflect the change trend of the surface. In order to facilitate comparison, five length intervals are set: 0 ~ 5m, 5 ~ 15m, 15 ~ 30m, 30 ~ 60m and more than 60m. The distribution of surface crack length is shown in Figure 3. In August 2020 (Figure 2a), the number of surface cracks is 220, of which the maximum number of cracks within 0 ~ 5m is 98, accounting for 45%; In June 2021 (Figure 2b), the number of surface cracks is 345 respectively, of which the maximum number of cracks within 5 ~ 15m is 140, accounting for 41%. According to the UAV images, 2020.08–2021.06 is an intense period of fracture activity. Not only the number of cracks increases significantly, but also the length of each range section increases to varying degrees. Gradually, small cracks transition to medium cracks, and medium cracks transition to large cracks. At the same time, due to continuous underground mining, many new cracks of different sizes and lengths have been generated along the mining direction.

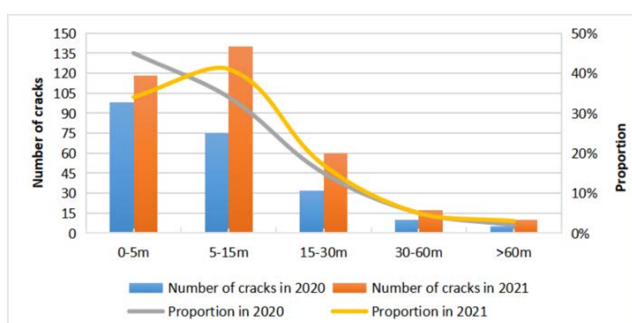

Figure 3. Distribution of surface cracks length range.

3.1.2 Density Analysis

In this study, the density analysis of surface cracks is carried out with the reference of water system density analysis. The sum of all crack lengths per unit area is expressed as follows:

$$p = \sum_{i=1}^{n} \frac{Li}{s} \quad (2)$$

where, n is the number of cracks; S is the cell grid area (㎡); Li is the total length of cracks in the element grid (m); P is the crack density (m/ ㎡).

According to the size test of the study area, the unit grid size of 5m×5m is determined. ArcGIS is used to establish the grid, calculate the area of each grid unit and the length of surface cracks, calculate the surface crack density through intersection, connection and fusion, interpolate with Kriging interpolation method, and draw the surface crack density distribution map of the study area in two phases (Figure 4).

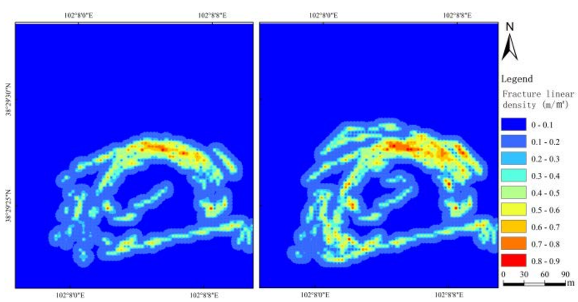

Figure 4. Distribution map of surface crack density in 2020 (left) and 2021 (right).

According to statistics, the cell of surface crack density has been growing, indicating that the range of surface cracks has been expanding and the cracks are expanding. It can be seen from the density distribution map of surface cracks in the two phases: with the expansion of mining area, the corresponding surface cracks will gradually expand, gradually showing local high values, and there will be no initial regional aggregation, which is in line with the change law of mining cracks.

3.2 Surface Collapse Pit Distribution and Surface Deformation Characteristics

From the UAV images, the distribution of surface collapse pits in June 2021 (as shown in Figure 5) and surface settlement from August 2020 to June 2021 (Figure 6) were obtained. According to the field survey, it is found that there are three collapse pits from August 2020 to June 2021, which are all distributed in the goaf. The maximum area of the three collapse pits is about 323㎡; The depth is up to 21m. Two collapse pits B and C occur about 30m parallel to fault F8, and the collapse pit A occurs at the boundary of the ore body. Under the joint influence of underground mining and faults, it has a great impact on the ground. The surface subsidence map better reflects the surface deformation of the surface subsidence area in recent one year. The study area tends to be in a relatively stable state around the goaf, and the subsidence in the south of the study area is obvious, forming a settlement funnel, in which there are three small regional settlement variation anomalies. These areas are new collapse pits in 2021. It can be seen that the surface deformation in the study area is affected by underground mining, and there is a trend of movement to the mining center around the mining area.

Table 1. Classification scope and criteria of evaluation index system

Target layer A	Criterion layer B	Index layer C	slight	mild	moderate	severe
Evaluation of surface collapse damage degree	Surface collapse pit B_1	Collapse pit area C_1	<10m^2	10~50m^2	50~100m^2	≥100m^2
		Depth of Collapse pit C_2	<0.2m	0.2~0.5m	0.5~2m	≥2m
	Surface crack B_2	Crack width C_3	<0.05m	0.05~0.15m	0.15~0.25m	≥0.25m
		Crack drop C_4	<0.05m	0.05~0.10m	0.10~0.25m	≥0.25m
		Crack density C_5	<0.2(m/m^2)	0.2~0.4(m/m^2)	0.4~0.6(m/m^2)	≥0.6(m/m^2)
	Surface deformation B_3	Surface subsidence C_6	<0.1m	0.1~0.5m	0.5~2m	≥2m
		Surface tilt C_7	<1(°)	1~3(°)	3~7(°)	≥7(°)

4. Evaluation Model of Surface Collapse Damage Degree

4.1 Construction of Evaluation Index System

The factors reflecting the characteristics of surface damage shall be selected as the evaluation indexes. In order to make the selection of indexes as scientific and reasonable as possible, eight evaluation indexes including collapse pit area, collapse pit depth, crack width, crack drop, crack density, surface settlement and surface inclination shall be finally determined by referring to relevant literature and combined with the actual environmental situation of West No. 2 mining area, UAV images and three-dimensional models are used for measurement and statistics. ArcGIS software is used to visualize the indicators and convert them into grid data. Each factor is divided into four categories: slight, mild, moderate and severe damage (Table 1).

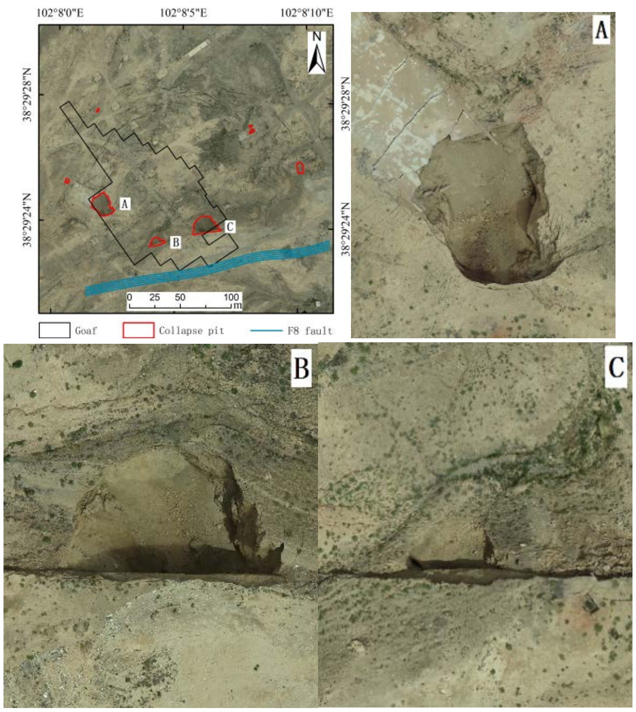

Figure 5. Distribution of surface collapse pits.

4.2 Combination Weighting

4.2.1 AHP Method to Determine Subjective Weight

Analytic Hierarchy Process (AHP) is a commonly used method of subjective weight determination. It can combine human experience and corresponding mathematical methods to obtain decision results.

1) The evaluation indexes are layered and a hierarchical structure is established, including target layer, criterion layer and index layer.

2) The scale of 1-9 is used to represent the importance of the index, and the factors at the same level are compared and assigned to obtain the comparison matrix D at each level.

3) The maximum eigen value and eigen vector are obtained by the square root method:

$$\overline{w_i} = \sqrt[n]{\prod_{j=1}^{n} a_{ij}} \left(i, j = 1, 2, \ldots, n\right) \quad (3)$$

where, a_{ij} is the proportional scale; $\overline{w_i}$ is the n root after its multiplication.

4.) Normalization:

$$w_i = \frac{\overline{w_i}}{\sum_{i=1}^{n} \overline{w_i}} \left(i = 1,2,\ldots,n\right) \quad (3)$$

$$W_i = \left(w_1, w_2, \ldots, w_n,\right)^T \quad (4)$$

Where: W_i is the calculated eigen vector.

5) The consistency of the judgment matrix is tested with the corresponding indexes, and the subjective weight of each evaluation index is obtained through the test.

$$\begin{cases} \lambda_{\max} = \dfrac{1}{n} \sum_{i=1}^{n} \dfrac{(AW_i^T)_i}{w_i} \\ CI = \dfrac{\lambda_{\max} - n}{n-1} \\ CR = \dfrac{CI}{RI} \end{cases} \quad (6)$$

where, λ Max is the maximum eigen value of the judgment matrix; CI is the consistency index; RI is the average random consistency index. When CR < 0.1, the judgment matrix A has satisfactory consistency, otherwise the judgment matrix needs to be adjusted until the consistency is met.

Table 2. Objective weight calculation results of CRITIC

Evaluating indicator	Index conflict	Index variability	Information content	Weight
Collapse pit area	3.838	0.081	0.312	0.1428
Depth of Collapse pit	3.782	0.074	0.278	0.1271
Crack width	4.094	0.039	0.162	0.0739
Crack drop	4.178	0.029	0.122	0.0557
Crack density	5.088	0.094	0.479	0.2188
Surface subsidence	4.610	0.054	0.247	0.1131
Surface tilt	4.571	0.129	0.588	0.2688

Table 3. Evaluation index and combination weight value

Evaluating indicator	AHP weight	CRITIC weight	Combined weight
Collapse pit area	0.2774	0.1428	0.2101
Depth of Collapse pit	0.1387	0.1271	0.1329
Crack width	0.2862	0.0739	0.1801
Crack drop	0.0625	0.0557	0.0591
Crack density	0.1092	0.2188	0.1640
Surface subsidence	0.0840	0.1131	0.0986
Surface tilt	0.0420	0.2688	0.1554

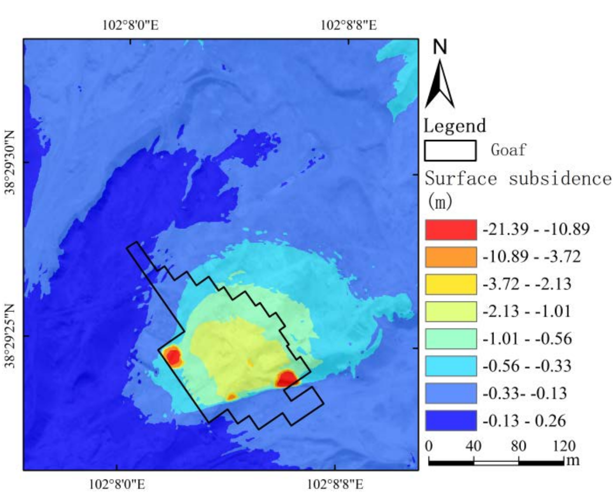

Figure 6. Surface settlement.

4.2.2 CRITIC Method to Determine Objective Weight

CRITIC method is an objective evaluation method using the attributes of data itself. It has better objectivity than standard deviation method and entropy weight method. This method uses the conflict and standard deviation between indicators to evaluate. The conflict is expressed by correlation coefficient. If the positive correlation between the two indicators is stronger, the conflict is smaller, and the weight will be lower; The contrast intensity is expressed by standard deviation. The larger the standard deviation, the greater the fluctuation, and the higher the weight. Main steps of CRITIC method:

1.) Normalization of raw data:

$$X = \frac{x_j - x_{\min}}{x_{\max} - x_{\min}} \quad (7)$$

where, X is the normalized value; X_j is the value before normalization; $x_{\min}$ and $x_{\max}$ are the minimum and maximum values of each index respectively.

2). Calculate the standard deviation of each indicator:

$$\begin{cases} \overline{x_j} = \frac{1}{n}\sum_{j=1}^{n} X \\ \sigma_j = \sqrt{\frac{\sum_{j=1}^{n}(X - \overline{x_j})^2}{n-1}} \end{cases} \quad (8)$$

Where: σ_j is the standard deviation of the j-th index.

3). The linear correlation coefficient between indexes is calculated to obtain the correlation matrix r

4). Calculate the amount of information:.

$$I_j = \sigma_j \times r \quad (9)$$

Where: I_j is the information quantity of the j-th index.

5). Objective weight:

$$W_j = \frac{I_j}{\sum_{j=1}^{n} I_j} \quad (10)$$

Where: W_j is the objective weight of the j-th index.

4.2.3 Combination Weight

The objective weight calculation results of CRITIC method are shown in Table 2. Average the AHP weight and CRITIC weight to obtain the combined weight. The evaluation indicators and combined weight values are shown in Table 3.

4.3 Fuzzy Comprehensive Evaluation Based on Combination Weight

Considering the fuzziness in the classification of various factors, the evaluation model is established by using the fuzzy comprehensive evaluation method based on combination weight. According to the influencing factors of surface collapse damage, the evaluation system factor set U={C1,C2,C3,C4,C5,C6,C7} and the comment set V = {slight, mild, moderate and severe}. For the evaluation indexes in this paper, the classification standard is divided by interval, which conforms to the characteristics of trapezoidal distribution membership function. Therefore, the membership function and membership degree of each comment are determined by formula method (Yang, 2000), and the trapezoidal distribution membership function is as follows:

$$U_1(x) = \begin{cases} 1 & (x < a) \\ \frac{(a+b)-2x}{b-a} & (a \le x < \frac{a+b}{2}) \\ 0 & (\frac{a+b}{2} \le x) \end{cases} \quad (11)$$

$$U_2(x) = \begin{cases} 1 - \frac{(a+b)-2x}{b-a} & (a \le x < \frac{a+b}{2}) \\ 1 & (\frac{a+b}{2} \le x < b) \\ \frac{(b+c)-2x}{c-b} & (b \le x < \frac{b+c}{2}) \end{cases} \quad (12)$$

$$U_3(x) = \begin{cases} \frac{2x-(a+b)}{b-a} & (\frac{a+b}{2} \le x < b) \\ 1 & (b \le x < \frac{b+c}{2}) \\ 1 - \frac{2x-(b+c)}{c-b} & (\frac{b+c}{2} \le x < c) \end{cases} \quad (13)$$

$$U_4(x) = \begin{cases} 0 & (x < \frac{b+c}{2}) \\ \frac{2x-(b+c)}{c-b} & (\frac{b+c}{2} \le x < c) \\ 1 & (c \le x) \end{cases} \quad (14)$$

In equations (11) – (14), U_i (x) is the membership function of each evaluation index; a,b and c are the benchmark limit value of the evaluation factor level, and x is the measured value of the evaluation factor.

According to the membership function and measured value of each evaluation index, the single evaluation result of each evaluation index of the evaluation unit in the study area corresponding to the comment set can be calculated, and then the membership degree of each single evaluation can be combined in turn to obtain a fuzzy relationship matrix R. The weights of each evaluation index are combined to form the fuzzy weight coefficient vector W for the evaluation of surface collapse damage degree. The comprehensive membership of each comment is:

$$B = W \times R \quad (15)$$

The evaluation structure model in this study has four levels. Combined with the mathematical principles analyzed above, the fuzzy comprehensive evaluation model is established by using the Model Builder tool with the support of ArcGIS. Four evaluation result layers are obtained by fuzzy calculation based on function operation, that is, the factor grid images belonging to different evaluation levels. According to the principle of maximum membership, Use the highest position command to input the four layers in turn, and take the comment with the largest membership in the evaluation results as the final evaluation result of the evaluation unit to obtain the final classification (Figure 7).

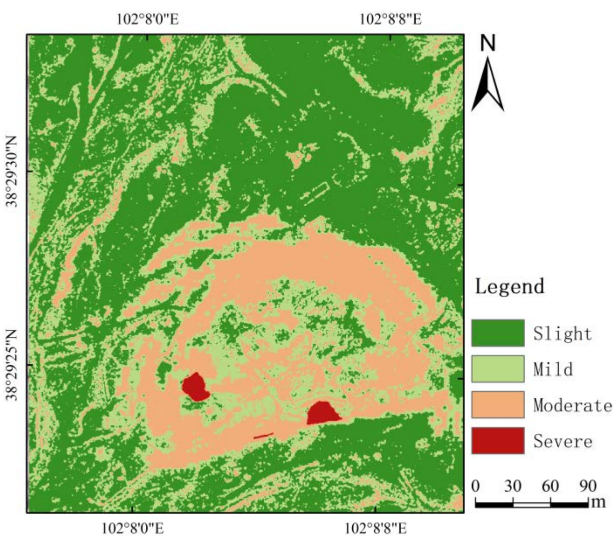

Figure 7. Evaluation grade distribution of surface collapse damage degree.

4.4 Evaluation Results and Analysis of Surface Collapse Damage Degree

The severe surface collapse damage of the west second coal mining area is mainly distributed near the three collapse pits, with an area of about 695.11 ㎡, accounting for 1% of the total area of the study area; Moderate damage is mainly distributed in the central and southern part of the study area, that is, the area with dense surface cracks, with an area of about 24902.84 ㎡, accounting for 18% of the total area of the study area; Mild and minor damages are mainly distributed around the ore body, covering an area of about 36946.53 ㎡ and 72207.1㎡, accounting for 27% and 54% of the total area of the study area. According to the evaluation results, the formation of surface collapse pit is the most intuitive and most destructive form of surface collapse. It is worth noting that after surface deformation, surface cracks and collapse pits are easy to occur around the subsidence basin. With the progress of mining, it may develop into a new medium and heavy collapse area.

5. Conclusion

Because the surface of the study area is loose sand and soil, the surface collapse area is deformed rapidly under the action of natural force and dynamic compression deformation. For the safety and efficiency of data acquisition, UAV remote sensing technology can be used to quickly obtain the two-dimensional image and three-dimensional real model of the surface collapse area. By setting reasonable aerial parameters, the three-dimensional information with high spatial-temporal resolution can be obtained. Under the test conditions, the ground resolution of UAV image can reach 2cm, which meets the basic requirements of fine extraction of mining surface collapse in mining area. Comparing the surface collapse information extracted from the image and model with the field survey results, the reliability of UAV remote sensing technology to obtain the spatio-temporal information of surface collapse is verified.

In this paper, the determination method of classical index weight is improved, combined with AHP method and CRITIC method, and the fuzzy comprehensive evaluation model is established by GIS to realize the visualization of evaluation results. The combination of qualitative and quantitative analysis of the degree of surface collapse damage in the mining area is more accurate and reference. From the evaluation results, the moderate and severe damage areas are above the goaf, and the damage area has reached 19%. In order to ensure safe underground excavation and environmental protection in the mining area, protective landfill and other means should be taken to ensure that economic development and ecological remediation go hand in hand.

This paper analyzes the characteristics of surface collapse and evaluates the degree of damage in the second mining area of West Jinchuan, effectively shows the situation and law of surface collapse in the mining area, which can provide reliable surface collapse data for safe mining and ecological protection in the mining area, and provide technical support for subsidence early warning in the mining area.

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