Suitability evaluation of land reclamation as arable land in coal mining area based on catastrophe theory

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Article

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Abstract

A catastrophe progression model for the suitability evaluation of land reclamation as arable land in coal mining area was put forward based on the catastrophe theory. The suitability classification of land reclamation as arable land in coal mining area was divided into four grades: suitable, moderately suitable, less suitable, and unsuitable. On the basis of comprehensive consideration of three factors including land quality, soil nutrients and engineering suitability in the reclamation area, eleven parameters including terrain slope grade, effective thickness of soil layer, soil parent materials, soil contamination, organic content, alkali hydrolyzable nitrogen (N), available phosphorus (P), available potassium (K), ground collapse, land destruction extent, and conditions of irrigation and drainage were selected as evaluation indicators, and the classification standards of each evaluation indicator was determined. Using MATLAB software to generate 800 total samples (200 samples per level) between the arrays corresponding to each level of standards according to the principle of normal distribution, of which 600 were used as training samples to establish the catastrophe progression criteria, and 200 were used as test samples to verify the reliability of the proposed criteria, and the proposed criteria also were verified by engineering examples. The suitability of land reclamation as arable land in coal mining area in Shaodong county, China, was comprehensively evaluated by using the proposed model. The research results have reference and guiding significance for the comprehensive evaluation of the suitability of land reclamation as arable land in coal mining areas.

Keywords Land reclamation · Suitability · Evaluation · Catastrophe theory · Catastrophe progression method

Introduction

The exploitation of mineral resources not only promotes economic development, but also destroys land resources[1-3], and affects the physical and chemical properties of soil and ecological environment to a certain extent[4-12]. Land reclamation is an effective way to solve these contradictions[13]. The suitability evaluation of land reclamation is a comprehensive assessment of the suitability and utilization degree of a certain use mode after land reclamation according to the natural, economic and social attributes of the land in the land reclamation project area. The purpose is to determine the best scheme of land reclamation and achieve the coordinated development of sustainable land utilization and ecological environment protection. It is also the most effective way to solve the contradiction between the exploitation of resources and land destruction[14]. The suitability evaluation of land reclamation provides a basis for the final determination of land reclamation direction, the formulation of reclamation technology and reclamation standards, so as to avoid blindness and secondary damage in land reclamation and achieve the goal of rational utilization of land to the maximum extent. Therefore, the suitability evaluation of land reclamation is the premise for determining the reclamation planning of damaged land[13], which provides the basis for the direction of reclamation land reuse, the selection of improvement measures and the decision-making of land use planning[13, 15].

Suitability evaluation plays an important role in land reclamation, and the selection of evaluation methods affects the accuracy and objectivity of the suitability evaluation results, and also affects the decision-making related to land reclamation[16]. Therefore, scholars have carried out a lot of effective researches in this field. Chen et al.[17] proposed a method of suitability evaluation of land reclamation based on extension and verified it with an example. The research showed that this method can not only overcome the influence of human factors in the evaluation process, but also quantify the evaluation factors, so as to improve the accuracy of the suitability evaluation of land reclamation. Ma et al.[18] performed an expert system based on C Language Integrated Production System that could provide a reclamation suitability evaluation for opencast mines according to different types of mined sites. Soltanmohammadi et al.[19] developed a fifty-attribute framework for mined land suitability analysis including fifty numbers of economical, social, technical and mine site factors. Wang et al.[20] improved the limit comprehensive conditions method by studying different suitability evaluation methods and applied this method to the comprehensive evaluation of land reclamation of abandoned mines for agricultural land in the Gaoqiao mining area in Mianchi county of Henan province, China. Zhang et al.[21, 22] used Bayes discriminant analysis method and Fisher discriminant analysis method respectively to establish comprehensive evaluation models for the suitability of land reclamation as grassland in coal mining areas of Xinjiang, China. Cheng et al.[15] proposed an improved fuzzy comprehensive evaluation method by improving the division method of evaluation units and the establishment method of membership functions, and applied the proposed method to the comprehensive evaluation of land reclamation of abandoned mines for agricultural land in Mentougou District of Beijing, China. Zhou et al.[23] built an evaluation index system according to the actual situation of land reclamation in surface mines, combined with AHP and entropy weight method to calculate the index weight, and proposed a evaluation method of land reclamation suitability based on multi-attribute decision theory. Moosavirad and Behnia[24] deeply elaborated the goal of land reclamation of Gol-e-Gohar Iron Ore Mine and the suitability evaluation principles, and developed the limit comprehensive conditions method based on the current researches. Cheng and Sun[13] combined the integrated index method and the difference product method to evaluate the reclamation suitability of the damaged land around Longchi coal mine for woodland. they not only gave the results of the suitable reclamation direction, but also pointed out the factors restricting the reclamation suitability, providing theoretical support for the reclamation decision and improvement plan of the damaged land. Amirshenava and Osanloo[25] believed that the suitability evaluation of land reclamation in the mining area was a key step in reclamation planning, which could ensure the sustainability of land use after mining. They proposed a general semi quantitative method for suitability evaluation of land reclamation.

In addition, some scholars have applied the comprehensive deviation rate method[26], FAO method[27], immune clone algorithm[28], niche suitability variable weight method[29], neural network method[30], comprehensive extreme condition method[31], and so on, to comprehensively evaluate the suitability of land reclamation. For the suitability evaluation of land reclamation, different indicators and methods will lead to different evaluation results, which will affect the decision-making work of land reclamation. On the basis of the existing researches, CPM was employed in this paper to evaluate the suitability of land reclamation for arable land in coal mining areas, and verified the feasibility and reliability of this method through engineering examples, which provided a new idea and way for the study of the quantitative method of comprehensive evaluation of land reclamation suitability.

Study area

The study area is Niumasi coal mine, which located in Shaodong county of Hunan Province, China. Its landform is mainly micro hilly area, and the soil is mainly clayey soil. Niumasi mining area situates in the south of the East-West paleouplift from Baima Mountain to Longshan mountain, the north wing of Qiyang arc structure, and the fold group of the NE-SW asymmetric syncline.

Niumasi mining area was an important producing area of high-quality main coking coal in Hunan Province. There were mainly four working areas, including Douxian, Shuijingtou, Mayuan village and Tiejishan. The total area was about 36 km^2, and the coal resources are now nearly exhausted. After the deep and large-scale mining of underground coal seams in this area, the surface subsidence was characterized by large-area, continuous and gentle in space, and the houses in the coal mine living area were cracked and deformed to varying degrees. The site surface settlement was basically stable without obvious collapse. The survey showed that there were nearly 80 small coal mines around this mining area, which have caused great damage to the land resources and environment of the area. This paper comprehensively evaluates the suitability of reclamation for arable land in view of the land damage caused by small coal mines in this mining area.

Evaluating indicator

The land reclamation direction in the coal mining area is mainly arable land, forest land, grassland, garden land, etc[21, 22, 30, 31]. Due to the small per capita arable land area in Shaodong county, when determining the land reclamation direction of the mining area, the land reclamation is mainly considered as arable land. Referring to relevant studies[21, 22, 28, 30-33], three factors used as suitability evaluation index of land reclamation for arable land including land quality, soil nutrients and engineering suitability are taken into account in this mining area. Eleven parameters, including terrain slope grade, effective thickness of soil layer, soil parent materials, soil contamination, organic content, alkali hydrolyzable nitrogen (N), available phosphorus (P), available potassium (K), ground collapse, land destruction extent, and conditions of irrigation and drainage, are selected as the evaluation indicators.

The classification standards for the above eleven indicators are summarized in Table 1.

Table 1 Indices and criterion for suitability evaluation of land reclamation as arable land

Indices		Classification of land reclamation suitability status			
		Suitable	Moderately suitable	Less suitable	Unsuitable
Land quality	Terrain slope grade (°)	＜3	3～7	7～15	＞15
	Effective thickness of soil layer (cm)	≥80	50～80	30～50	≤30
	Soil parent materials	loam assign the value of 8～10	Clay and sandy loam assign the value of 6～8	Sandy soil assign the value of 4～6	Gravel soil assign the value ＜4
	Soil contamination	Non assign the value of 8～10	Slight assign the value of 6～8	Moderate assign the value of 4～6	Heavy assign the value ＜4
Soil nutrients	organic content (g/kg)	＞40	30～40	20～30	＜20
	Alkali hydrolyzable nitrogen (g/kg)	＞150	120～150	90～120	＜90
	Available phosphorus (g/kg)	＞40	20～40	10～20	＜10
	Available potassium (g/kg)	＞200	150～200	100～150	＜100

	Ground collapse	Non assign the value of 8～10	Small amount of uneven settlement on the ground assign the value of 6～8	Small amount of collapse on the ground assign the value of 4～6	Many ground collapses assign the value ＜4
Engineering suitability	Land destruction extent	Non assign the value of 8～10	Damage but not too serious assign the value of 6～8	Serious damage assign the value of 4～6	Extremely damage assign the value ＜4
	Conditions of irrigation and drainage	The water source is very close, the water quality is good, and the irrigation and drainage conditions are good assign the value of 8～10	The water source is close, the water quality is general, and the conditions for establishing irrigation and drainage are general assign the value of 6～8	The water source is far away, and the establishment of irrigation and drainage conditions is not guaranteed assign the value of 4～6	No water sources assign the value ＜4

Survey items and results in the study area

Two parameters in land quality factor, including the terrain slope grade, effective thickness of soil layer, are quantitative indicators, which can be determined by engineering technicians on the spot. Two parameters in land quality factor including soil parent materials and soil contamination are determined by the specific situations on the spot, and the values are assigned according to Table 1 respectively.

Four parameters in soil nutrients factor, including organic content, alkali hydrolyzable nitrogen (N), available phosphorus (P), available potassium (K), are quantitative indicators, which can be measured through field soil sampling. During soil sampling, the plot that can fully reflect the soil characteristics shall be selected first, and the sampling depth is generally within 20 cm. Organic matter in soils is determined by potassium dichromate volumetric method heated in oil bath. Alkali hydrolyzed nitrogen (N) in soils is determined by Kanghui dish method. Available phosphorus (P) in soils is extracted by sodium bicarbonate and determined by molybdenum antimony colorimetry. The content of available potassium (K) in soils is extracted with ammonium acetate and then determined by flame photometry.

Three parameters in engineering suitability, including ground collapse, land destruction extent, and conditions of irrigation and drainage, are determined accoding to the specific situations on the spot by engineering technicians and the values are assigned according to Table 1 respectively.

According to the above eleven indicators and corresponding measurement methods, four pieces of lands with a total area of about 1.3 km^2 in Shuijingtou work area were investigated. The results are listed in Table 2.

Table 2 Evaluation results of Shuijingtou work area

Indices	Sample No.			
	1	2	3	4
Terrain slope grade (°)	4	3	7	10
Effective thickness of soil layer (cm)	26	35	82	45
Soil parent materials	Clay soil	Clay soil	Sandy and clay soil	Sandy loam and sand

Soil contamination	There are pesticide pollution sources and no heavy metal pollution sources	There are pesticide pollution sources and no heavy metal pollution sources	There are pesticide pollution sources and no heavy metal pollution sources	There are pesticide pollution sources and no heavy metal pollution sources
organic content (g/kg)	46.2	38.7	40.1	36.9
Alkali hydrolyzable nitrogen (g/kg)	94.1	92.0	97.8	89.3
Available phosphorus (g/kg)	33.0	28.8	25.1	23.8
Available potassium (g/kg)	104.4	126.8	135.6	142.1
Ground collapse	Serious uneven settlement	Serious uneven settlement	Serious uneven settlement	Serious uneven settlement
Land destruction extent	Serious damage	Serious damage	Serious damage	Serious damage
Conditions of irrigation and drainage	The water source is far away but the conditions are good	The water source is far away but the conditions are good	The water source is far away but the conditions are good	The water source is far away but the conditions are good

Catastrophe progression method (CPM)

In this paper, CPM is utilized to evaluate the four land samples in Table 2. CPM is a comprehensive evaluation method based on catastrophe theory and fuzzy mathematics theory, its basic idea[34-41] is to first determine the overall evaluation objective of the evaluation object, and then decompose it layer by layer to form an evaluation index system with a hierarchical structure.

After normalizing the control variables at each level according to the mathematical model of the corresponding catastrophe system, the values of catastrophe subordinate functions are calculated layer by layer according to the principle of 'non complementarity' or 'complementarity', until the value of catastrophe subordinate function of the evaluation object, that is, the catastrophe progression criterion, Thereby determining the state category of the evaluation object.

According to the basic idea of CPM, a catastrophe progression model for comprehensive evaluation of the suitability of land reclamation as arable land in coal mining areas is established, which includes the following aspects: (1) Evaluation object; (2) Evaluation index system with a hierarchical structure; (3) Normalization; (4) Training samples; (5) Catastrophe progression criteria.

Evaluation object and Evaluation index system with a hierarchical structure

The evaluation object is the general objective of the evaluation. The evaluation object of land reclamation is the suitability of land reclamation. In this paper, it is the suitability of land reclamation as arable land in the coal mining area. The overall objective of this evaluation is set as 'A'. The first-class evaluation indexes are: land quality, soil nutrients and engineering suitability, set as 'B1', 'B2' and 'B3' respectively. Decompose the first-class indicators to form a secondary indicator system. The secondary index system of 'B1' are: terrain slope grade, effective thickness of soil layer, soil parent materials, and soil contamination, which are set as 'C1', 'C2', 'C3' and 'C4' respectively. The secondary index system of 'B2' are: organic content, alkali hydrolyzable nitrogen (N), available phosphorus (P), and available potassium (K), set as 'C5', 'C6', 'C7' and 'C8' respectively. The secondary index system of 'B3' is: ground collapse, land destruction extent, and conditions of irrigation and drainage, set as 'C9', 'C10' and 'C11' respectively. 'C1' to 'C11' are also called the control variables.

Normalization

Normalization processing includes two aspects: one is dimensionless processing of original data; the second is to normalize the control variables at each level according to the mathematical model of the corresponding catastrophe system, and then calculate the values of catastrophe subordinate functions. The method by Cao et al.[42], Cheng et al.[36], Xu et al.[43] is used for dimensionless processing of the original data.

The above hierarchical index system constitutes the following catastrophe system: (i) C1 to C4 and C5 to C8 are constituted the butterfly catastrophe models B1 and B2 respectively; (ii) C9, C10, and C11 are formed as a swallowtail catastrophe model B3 (iii) B1, B2, and B3 constitute a swallowtail catastrophe model A. The control variable normalization formulas of swallow tail catastrophe system are: $x_a = \sqrt{|a|}$ 、 $x_b = \sqrt[3]{|b|}$ 、 $x_c = \sqrt[4]{|c|}$; The control variable normalization formulas of butterfly catastrophe system are: $x_a = \sqrt{|a|}$ 、 $x_b = \sqrt[3]{|b|}$ 、 $x_c = \sqrt[4]{|c|}$ 、 $x_d = \sqrt[5]{|d|}$. Where x is the state variable in the catastrophe system; a, b, c, and d are the control variables; x_a, x_b, x_c, and x_d are values of x corresponding to a, b, c, and d in the above expressions.

Training samples and Test samples

The evaluation of land reclamation suitability is essentially a pattern recognition problem, that is, the actual evaluation results of the evaluation index system used in land reclamation suitability are compared with the classification standards of the evaluation indexes, and the level corresponding to the standard value array closest to the array formed by the actual evaluation results is the level of land reclamation suitability, that is, the identification result of CPM in this paper. According to the grading standards of evaluation indicators in Table 1, MATLAB software is utilized to generate 800 total samples (200 samples per grade) between the arrays corresponding to each level of standards according to the principle of normal distribution, of which 600 are training samples and 200 are test samples.

Catastrophe progression criteria

By dimensionless evaluation indexes of training samples and normalizing control variables, the values of catastrophe subordinate functions and the catastrophe progression values of each hierarchical level are solved, and finally the catastrophe progression values of each training samples are obtained. Thus, the ranges of the catastrophe progression values of each state level are obtained, that is, the catastrophe progression criteria of suitability for land reclamation as arable land in the coal mining areas: (i) 'Suitable' when $x \geqslant 0.9600$; (ii) 'Moderately suitable' when $0.8800 \leqslant x < 0.9600$; (iii) 'Less suitable' when $0.7900 \leqslant x < 0.8800$; (iv) 'Unsuitable' when $x < 0.7900$. These criteria are used to identify the test samples, and it is found that the evaluation results are completely consistent with the expected results, which indicates that the criteria can be used for the suitability evaluation of land reclamation in this paper.

Verification of catastrophe progression criteria

In order to verify the effectiveness of the above criteria, an example of land reclamation suitability evaluation was analyzed, and the evaluation results were compared with that by Neural Network method and the actual situations provided by Wu et al.[30]

Wu et al.[30] provided a total of 20 soil samples. The catastrophe progression values of soil samples were calculated to identify its suitability level in this paper. The evaluation results are consistent with that of the Neural Network method and the actual situations.

Suitability evaluation results in study area

According to the above catastrophe progression model, the suitability status of the four land samples in Table 2 are identified. First, assigning values to the qualitative indicators in Table 2, and the results are listed in Table 3. Then, computing the catastrophe progression values of four samples, and the results are listed in Table 3.

According to the catastrophe progression values, the identification results of the four land samples are as follows: the suitability level of 1# - 3# lands are all 'Moderately suitable', and that of 4# land is 'Unsuitable'. In addition, by analyzing the catastrophe progression values of the four land samples, we can obtain: The catastrophe progression values of 1# and and 3# land samples are approximately the same, indicating that their suitability levels are approximately the same, while the catastrophe progression value of 2# are larger than those of 1# and 3# indicating that its suitability is better. 4# land sample is not suitable for reclamation as arable land, so it can be reclaimed as forest land or used for other purposes. These results indicate that CPM can not only evaluate the suitability of land reclamation, but also comprehensively compare the suitability degrees.

Table 3 Suitability evaluation results of land reclamation as arable land in Shuijingtou work area

Indexes	Samples			
	1	2	3	4
Terrain slope grade (°)	4	3	7	10
Effective thickness of soil layer (cm)	26	35	82	45
Soil parent materials	8	8	6	6
Soil contamination	7	7	7	7
organic content (g/kg)	46.2	38.7	40.1	36.9
Alkali hydrolyzable nitrogen (g/kg)	94.1	92.0	97.8	89.3

Available phosphorus (g/kg)	33.0	28.8	25.1	23.8
Available potassium (g/kg)	104.4	126.8	135.6	142.1
Ground collapse	6	6	6	6
Land destruction extent	5	5	5	5
Conditions of irrigation and drainage	6	6	6	6
Catastrophe progression value	0.8878	0.9190	0.8853	0.7309
Suitability	Moderately suitable	Moderately suitable	Moderately suitable	Unsuitable

Conclusions

In this paper, the suitability of land reclamation as arable land in Niumasi coal mine of Shaodong county in Hunan Province, China, is evaluated by CPM. On the basis of considering three factors of land quality, soil nutrients and engineering suitability in the reclamation area, a catastrophe progression model is established by selecting evaluation indicators and determining their grading standards. This model are suitable for the suitability evaluation of land reclamation as arable land in Niumasi coal mine, and can be applied to land reclamation projects in other mining areas.

1. CPM can better evaluate the suitability of the land to be reclaimed, which is conducive to further understanding and mastery of the land quality, soil nutrients and the suitability of reclamation projects of the land to be reclaimed. The theoretical basis of CPM is catastrophe theory and fuzzy mathematics theory. CPM has no special requirements for the distribution of sample data, and does not need to give weight to evaluation indicators, avoiding the subjectivity brought by artificially determining the weight of each evaluation indicator, and making the classification results of different algorithms comparable.

2. The computed method and process of the catastrophe progression values of samples are simple, easy to understand and master. In the suitability evaluation of land reclamation in mining areas, the catastrophe progression value can be combined with qualitative analysis, which can more accurately and quantitatively describe the level attribute of the characteristic value of the evaluation index, and can better quantitatively and comprehensively evaluate the suitability of land reclamation.
3. The main disadvantage of the catastrophe progression model of land reclamation established in this paper is that the classification grade of suitability and the classification standard corresponding to the evaluation index are subjective. Although the calculation results of the catastrophe progression values are objective, the number of suitability classification groups and the corresponding grading standards of evaluation indicators are artificially given. In addition, up to now, there are no unified evaluation index system and classification standards for land reclamation suitability.

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