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Research Article

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Dynamic simulation for the process of mining subsidence based on cellular automata model

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Abstract: Under the background of the ecological civilization era, rapidly obtaining coal mining information, timely assessing the ecological environmental impacts, and drafting different management and protection measures in advance to enhance the capacity of green mine construction have become the urgent technical problems to be solved at present. Simulating and analyzing mining subsidence is the foundation for a land reclamation plan. The Cellular Automata (CA) model provides a new tool for simulating the evolution of mining subsidence. This paper takes a mine in East China as a research area, analyses the methods and measures for developing a model of mining subsidence based on the theories of CA and mining technology, then discusses the results of simulation from different aspects. Through comparative analysis, it can be found that the predicted result is well consonant with the observation data. The CA model can simulate complex systems. The system of mining subsidence evolution CA is developed with the support of ArcGIS and Python, which can help to realize data management, visualization, and spatial analysis. The dynamic evolution of subsidence provides a basis for constructing a reclamation program. The research results show that the research methods and techniques adopted in this paper are feasible for the dynamic mining subsidence, and the work will continue to do in the future to help the construction of ecological civilization in mining areas.

Keywords: mining subsidence, cellular automata, dynamic reclamation, geographic information system

1 Introduction

Surface subsidence caused by the exploitation of coal resources has led to the devastation of the environment and has affected regular land use. Currently, the main modes of mining reclamation are not performed until subsidence entirely ceased. This could potentially take three or more years before reclamation processed, resulting in an extended period without the use of the land and extended damage to the surface. To shorten the time of reclamation, dynamic reclamation for subsidence land is becoming a trend of ecological restoration in the mining area, because it encourages timely and appropriate measures to control ecosystem degradation and accelerate ecological restoration. It is based on the principle of early intervention. Dynamic reclamation is still in the early stage of wide-spread implementation, mostly because the dynamic prediction theory of mining subsidence is still immature. Mining subsidence dynamics prediction can show the evolution process of surface subsidence and fully reflect the damage of the ecological environment. These aspects will dictate which methods need to be implemented during the reclamation process. Therefore, mining subsidence dynamics prediction has become the technical key for wide-spread dynamic reclamation implementation. Currently, the main research results focus on the construction of a time function, such as the Knothe function, normal distribution function, and the Willbull function [1–6]. Due to a large number of calculations that are needed for these methods, the implementation is mainly performed in professional software such as MATLAB or ABAQUS [7]. The cellular automata (CA) model provides a new tool for simulating the evolution of mining subsidence. Although some studies have been conducted in on CA [8–10], dynamic simulation for mining subsidence is a complex system problem, the results are largely affected by the model choice and setting [11–13], and different conditions need different methods. Especially when taking into consideration three-dimensional space, there still are many challenges before full implementation of...
CA modeling for subsidence simulation. For example, how to setup the CA model according to the coal mining technology and integrate the CA model with Geographic information system (GIS) tools to facilitate the ecological restoration.

This paper takes a mine in East China as a research area, analyses the methods and measures for developing a model of mining subsidence based on the theories of CA and mining technology, then discusses the results of simulation from different aspects. The purpose of this study is to (1) establish a mining subsidence CA model under a three-dimensional framework; (2) create a mining subsidence CA model with the support of GIS and Python; and (3) simulate the process of mining subsidence by combining the spatial analysis and three-dimensional visualization functions of GIS.

With the help of CA, the result of the temporal and spatial evolution of subsidence can facilitate the assessment of environmental impact and the optimization of the mining plan. The work can promote the ecological civilization in mining areas and has a wide application prospect in the field of coal mining and land reclamation.

2 Study methodology

2.1 CA

CA is a nonlinear system model with a complete discrete space, time, and state. It can be defined as the following quadruple [14–17]:

\[ A = (L_d, S, N, f) \]

where \( A \) is the CA system, \( L_d \) is a d-dimensional cellular space, \( d \) is a positive integer; \( S \) is a discrete finite set of cellular states; \( N \) is a combination of cellular states in the neighborhood; and \( f \) is a local conversion function.

Evolution can be expressed as the following formula:

\[ S_{i,j}^{t+1} = f(S_{i,j}^t) \quad r \in (i - n, i + n); t \in (j - n, j + n) \]

where \( S_{i,j}^{t+1} \) is the state of the cellular unit \((i,j)\) at time \( t + 1 \); \( S_{i,j}^t \) is the set of all neighbors at time \( t \), and \( n \) represents the distance of the neighborhood.

Compared with the traditional equation-based geographic model, the CA model has better spatio-temporal dynamics and can simulate the emergence, chaos, evolution, and other characteristics of complex nonlinear systems. This tool is commonly used in ecology, environmental, natural disasters, risk predictions, etc. As a powerful tool for highly complex geographical phenomena, many have continued to expand the standard CA model by combining it with fractal theory, the multi-factor evaluation model, artificial neural networks, Markov chain, and multi-agent, etc. [18–20].

2.2 Mining subsidence CA model

2.2.1 Establishment of cellular space

Mining subsidence prediction of the CA model relates to the surface cellular space and underground coal cellular space. These two types of cellular space are constructed based on the unified spatial reference, and the evolution of the underground cellular space drives the change of the surface cellular space.

2.2.1.1 Choice of cellular size

A smaller cellular size results in a higher calculation accuracy. However, the calculation time increases rapidly. According to regulations and previous research, suitable size can be chosen according to the mining conditions (Table 1).

2.2.1.2 Work face cellular space

According to the mining plan, the cellular space of the mining working face is expressed as the following formula:

\[ \Omega = \{C_{i,j}\} \]

where \( \Omega \) is the mining work face cellular space set and \( C_{i,j} \) is the cellular unit of the mining work face. The length of the mining work face is \( L \), width is \( D \), and the size of cellular is \( d \), then, \( i \in (i_0, i_0 + L/d), j \in (j_0, j_0 + D/d) \), where \( i_0, j_0 \) is the origin of the work face cellular code.

Table 1: Size of cellular for prediction

<table>
<thead>
<tr>
<th>Mining depth/m</th>
<th>Size of cellular/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;100</td>
<td>≤2</td>
</tr>
<tr>
<td>100–300</td>
<td>≤4</td>
</tr>
<tr>
<td>300–500</td>
<td>≤8</td>
</tr>
<tr>
<td>&gt;500</td>
<td>≤16</td>
</tr>
</tbody>
</table>
2.2.1.3 Surface cellular space

According to mining subsidence theory, the influence of subsidence is in a specific area, and the distance to the boundary of the working face is the radius of influence of mining subsidence \( r \). Based on this, the surface cellular space range can be described with the following formula:

\[
\Phi = \{S_{m,n}\}
\]

where \( \Phi \) is surface cellular space set and \( S_{m,n} \) is a surface cellular unit, among which:

\[
m \in (i_0 - 2r/d, i_0 + (L + 2r)/d),
\]

\[
n \in (j_0 - 2r/d, j_0 + (D + 2r)/d).
\]

2.2.2 Cellular neighborhoods

Neighborhoods play essential roles in CA models. The evolution of the surface cellular state depends on the change of the cellular state of underground coal seams. Therefore, the neighbor space of the surface cells is defined in the underground coal cellular space as well. The distance of the neighborhood is determined according to the main influencing radius \( r \), that is, the neighborhood order \( k = \text{int}\left(\frac{r}{d} + 1\right) \). So, for a given surface cellular unit \( S_{m,n} \), its neighbor cellular units are \( C_{i,j} \), where

\[
j \in (n - k), \quad (n + k), \quad i \in ((m - k), \quad (m + k).
\]

2.2.3 Evolutionary rule construction

The evolution rule reflects the interaction between the neighboring cellular units and the central cellular unit and is the basis for the automatic evolution of the system.

For a given surface cellular unit \( S_{m,n} \), its state \( S_{m,n}^{t+1} \) at the time \( t + 1 \) depends on the state of the neighbor cellular units \( C_{i,j} \) at a time \( t \). The transition is defined as the following formula:

\[
S_{m,n}^{t+1} = f(C_{i,j}^t) = \sum_{i=m-k}^{m+k} \sum_{j=n-k}^{n+k} (C_{i,j}^t + R_{i,j}^{m,n})
\]

where \( R_{i,j}^{m,n} \) is the influence function of the neighbor units, which can be described with the following formula:

\[
R_{i,j}^{m,n} = w_0 \frac{1}{r^2} e^{-\frac{d}{r^2}} \frac{d^2}{\pi^2} \chi_{(m-j)^2 + (n-i)^2}
\]

where \( w_0 \) is the maximum subsidence value (unit: mm). It can be calculated with the following formula:

\[
w_0 = mq \cos(a)
\]

where \( m \) is the thickness of the coal seam, \( q \) is the subsidence coefficient, and \( a \) is the angle of dip.

The state of the work face cellular unit at a given time \( t \) can be described with the following formula:

\[
C_{i,j}^t = \frac{2}{\sqrt{\pi}} \int_0^x e^{-u^2} du
\]

where \( x \) is the time distance, which is dimensionless and can be calculated with the following formula:

\[
x = (t - t_c)/t_0
\]

where \( t_c \) is the mining moment of the coal cellular unit. If the coal cellular unit is not mined at time \( t \), then \( x \) is set to 0. \( t_0 \) indicates the time-effect distance and can be calculated with the following formula:

\[
t_0 = r/v
\]

where \( v \) is the advancing speed of the working face and \( r \) is the main radius of influence.

2.3 Accuracy testing

To verify whether this method is viable, the predicted values are compared with in situ measured data (Figure 1). The value of subsidence is surveyed with the instrument of electronic level according to third class level requirements. The standard deviation for in situ measured data is \( \pm 6 \) mm/km, so, it can be regarded as the actual value to evaluate the accuracy of prediction. Through correlation

![Figure 1: Distribution of predicted value and in situ measured value.](image-url)
analysis, the correlation coefficient between the predicted value and the in situ measured value is 0.99. So, the accuracy of the CA method meets the requirements for dynamic land reclamation planning.
3 Application

3.1 Overview of case study

The study area locates in the in Shandong Province, China. The average thickness of the coal seam is 8.0 m. The burial depth is 320 m. The terrain is overall flat, with an average elevation of 44 m. The simulated working face has a length of 1,580 m along strike and a width of 350 m along dip. It will be exploited with a fully mechanized mining method, and the working face will advance at a speed of 4 m/day. Combined with the rock movement observation data of the surrounding mines, the main influence angle tangent is 2 and the maximum subsidence coefficient is 0.84.

3.2 Implementation of the model

Python and ArcGIS are integrated into the model to implement the mining subsidence CA. Python is an object-oriented, interpreted computer programming language with a rich and powerful library for rapid development and efficient integration with other tools. ArcGIS 10 provides a Python site package (ArcPy), where GIS users can quickly create simple or complex workflows with the help of ArcPy in Python and develop utilities that can be used to process geoscience data [21]. The implementation process of the system is shown in Figure 2.

3.3 Results analysis

3.3.1 The evolution of specific points with mining

In this case, five points (A, B, C, D, E) on the main section of the surface deformation are selected, which are shown in Figure 3. Mining started on the first day, and the values of cellular units are analyzed within 500 days, and the processes of subsidence with time are shown in Figure 4.

Initially, for a given cellular unit, the rate of subsidence is slow, yet increases quickly when the position of the working face moves to directly underneath the surface cellular unit. After the working face has passed the cellular unit, the subsidence rate then slowly decreases until the end. The start of subsidence at each point varies with time, as the distance to mining the working face directly affects the state. Therefore, treatment for land reclamation can be selected based on the predicted value. For example, the subsidence at point A approaches an end on the 90th day, at a total depth of 3,300 mm. This location can then be treated with a terrace after that day rather than waiting until the end of all mining.

Figure 4: Changes in surface cells with mining.

Figure 5: Changes in the amount of subsidence of the surface along the main section with the advancement of the working face.
3.3.2 Subsidence evolution along the main mining section

Changes in subsidence along the main section at five-time points (100th, 200th, 300th, 400th, and 500th day) were selected to analyze the process of subsidence with working face advancement. The amount of subsidence and change in values along the main section during the mining process is shown in Figure 5. During the advancement of the working face, subsidence occurs ahead of the working face, and the subsidence curve continues to progress forward with the advancement of the working face. Subsidence continues to develop even after mining has ended. This figure also shows where the basin and slope are distributed which can aid in the proper selection of treatments as different regions require different methods. Finally, the curve also shows when subsidence ends (Figure 5); therefore, timely reclamation can be implemented to minimize the ecological degradation, or before the start of subsidence, some measures, such as planting or drainage, can be applied to the region.

3.3.3 Changes in subsidence in the total surface

As the analysis of the above, 5-time points were selected (100th, 200th, 300th, 400th, and 500th day) to analyze the changes in subsidence of the surface across the entire region. The calculation results are shown in Figure 6 and provide an overall perspective of subsidence throughout the mining process. The CA model provides the area and depth of subsidence at various times so that a plan for land use can be made in advance. Based on the results, the quantities of earthwork for land reclamation can also be calculated.

4 Discussion

(1) From the result of accuracy testing, it can be found that the predicted result is well consonant with the observation data. This indicates that the CA model is in capacity to reveal the mechanism of mining subsidence progress because the model is constructed based on the theory of non-continuous media mechanics. The advantages of the CA model for mining subsidence are that it is easy to calculate and can integrate the process with time.

(2) From the view of point change with mining, the evolution of subsidence on a detailed location can be found. The function is to predict and assess the impact on the place needed to pay attention. Based on the result, it can be determined when to take measures to control the damage and restore the land use; from the view of line change with mining, the shape and scope of subsidence with time can be

Figure 6: Changes in subsidence of the surface over time across the entire region: (a) 100th surface subsidence simulation, (b) 200th surface subsidence simulation, (c) 300th surface subsidence simulation, (d) 400th surface subsidence simulation, (e) 500th surface subsidence simulation.
found which can facilitate the farmland and structure lays out. Through compared with relevant research findings [22,23], the spatial scope and shape of the CA method are consistent with other methods; from the view of area change with mining, the overall perspective of the surface subsidence evolution can be obtained, which can help to fully understand and master the impact of subsidence.

3) The CA model can integrate with the software of GIS which provides many useful tools for data management and visualization. Moreover, it is simple to conduct a correlation analysis between other spatial data by GIS tools.

5 Conclusions

This paper discusses simulating the process of surface subsidence based on the CA model, which provides a powerful tool and theoretical basis for dynamic reclamation. The main innovations achieved are as follows:

1) The mining subsidence is affected by many factors and it is a complex progress. The CA model has the ability to simulate complex systems. The CA model of mining subsidence evolution in three-dimensional space is constructed based on mining subsidence theories. The cellular space division, neighborhood definition, evolution rules, and other aspects of the model are defined according to the condition of coal characteristics and mining technology. The result is tested with in situ measured value and has high accuracy. The evolution results reflect the process of surface subsidence and provide a basis for preparing reclamation measures before the initiation of mining.

2) The system of mining subsidence evolution CA is developed with the support of ArcGIS and Python, which can help to realize data management, visualization, and spatial analysis. The process of mining subsidence is demonstrated from three levels, point, line, and surface by combining the model with a case study of a mine in eastern China. The spatial scope and shape of the CA method are consistent with other methods. The dynamic evolution of subsidence provides a basis for constructing a reclamation program.

3) The precision of the simulation could be improved by decreasing the cell size. For a mine area with a large space, this would significantly increase the amount of data and dramatically increase the amount of calculation time. The CA model provides a new idea for subsidence simulation, but the subsidence evolution model under complex geological mining conditions still needs further study.

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References


