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Prediction of the maximum water inflow in Pingdingshan No.8 mine based on grey system theory

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Abstract In order to prevent and control the water inflow of mines, this paper built a new initial GM(1, 1) model to forecast the maximum water inflow according to the principle of new information. The effect of the new initial GM(1, 1) model is not ideal by the concrete example. Then according to the principle of making the sum of the squares of the difference between the calculated sequences and the original sequences, an optimized GM(1, 1) model was established. The result shows that this method is a new prediction method which can predict the maximum water inflow accurately. It not only conforms to the guideline of prevention primarily, but also provides reference standards to managers on making prevention measures.

Keywords prediction, maximum water inflow, grey system theory, GM(1, 1) model

Introduction

The disaster of water inrush is one of the most serious coal mine disasters, and it is important to forecast the water inflow in mines. On October 17, 1971, the east cross cut of Dongfeng Mine was opened at −275 m level in Pingdingshan No.8 mine, where it had floor water-inrush accident. The recovery time lasted up to 7.5 years. Therefore, it is significant to forecast the water inflow of coal mines accurately which can help to prevent coal mine accidents and ensure the safety of coal mine production (Xiao et al., 2008).

The main aquifers of Pingdingshan No.8 mine related to deposit water filling are middle Cambrian period limestone and upper Cambrian period limestone which have the thickness of 300 m. Combined with tertiary marlite scattered near the east wing which communicates with the old and new hydraulic aquifer, the hydro-geological conditions become increasingly complex. Mine discharge is determined by a number of factors (such as geology, exploration status, etc.) and uncertainty factors (such as weather, etc.) and other complex factors. With these factors interacted, the water inflow shows great randomness and chances, so it has distinct grey characteristics (Xu, 2008; Li, 2009; Wen et al., 2010). Therefore, it is feasible to forecast water inflow by using grey system theory. In this paper, combined with the maximum historical water inflow data of Pingdingshan No.8 mine, the grey prediction model, a new initial GM(1, 1) model, was put forward. Under the prediction, results are not ideal circumstances, and we then proposed the optimized GM(1, 1) model, of which prediction accuracy is significantly improved. so this is a new method to forecast the water inflow.

1 The establishment of grey forecasting model

1.1 Grey forecasting model theory

Grey system theory is a random variable as a grey variable in a certain range of changes and the random process as the grey process associated with time in a certain range of changes. With the method of data processing, the chaotic raw data were processed into more regular generation data for research (Li et al., 1999). The grey theory avoids the inherent defects of conventional statistical methods and only requires a limited amount of data to estimate the behavior of an uncertain system.

Grey system prediction finds and masters the evolution laws of system to make quantitative predictions of science by processing the original data and establishing gray model, and process a range of observed data which reflect the characteristics of predicted object.

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Then we established the appropriate differential equation model to predict future development trends (Liu et al., 2004). So the grey prediction model contains two processes. One is establishing the GM model and the other is extrapolation forecast using the GM models. Generally, the gray prediction model is GM(1, 1) model. In order to improve accuracy, there are many improvements based on the GM(1, 1) model.

1.2 The establishment of GM(1, 1) model

The idiographic arithmetic of GM(1, 1) model is described as follows (Xiao et al., 2004; Zheng et al., 2009; Bao and Liu, 2010):

Step 1: Accumulated generating data sequence $X^{(1)}$. Assume the original sequence $X^{(0)}$ is non-negative and has n observations.

$$X^{(0)} = \{x_1^{(0)}, x_2^{(0)}, \cdots, x_n^{(0)}\}$$

$$x_k^{(0)} \geq 0 \quad (k = 1, 2, 3, \cdots, n)$$

Input $X^{(0)}$, accumulating generation operators, and obtain a sequence as:

$$X^{(1)} = \{x_1^{(1)}, x_2^{(1)}, \cdots, x_n^{(1)}\}$$

$$X^{(1)} = AGO(X^{(0)})$$

Step 2: Generate mean generation with consecutive neighbour sequence $Z^{(1)}$.

$$Z^{(1)} = \{z_2^{(1)}, z_3^{(1)}, \cdots, z_n^{(1)}\}$$

of which, $z_k^{(1)} = 0.5(x_k^{(1)} + x_{k-1}^{(1)})$.

It can be written $Z^{(1)} = \mathrm{MEAN}(X^{(1)})$.

Step 3: Get the parameters a and u by the last squares method.

Assume the parameter vector

$$\hat{\boldsymbol{a}} = [au]^{\mathrm{T}}, \boldsymbol{y}_N = [x_2^{(0)}, x_3^{(0)}, \cdots, x_N^{(0)}]^{\mathrm{T}}$$

$$\boldsymbol{B} = \begin{bmatrix} -(x_2^{(1)} + x_1^{(1)})/2 & 1 \\ \vdots & \vdots \\ -(x_n^{(1)} + x_{n-1}^{(1)})/2 & 1 \end{bmatrix}$$

where, a is evolution parameter, which reflects the trend; u is grey action, its size reflects the variation of the data.

Step 4: Compute the expression of $\hat{x}_{k+1}^{(1)}$. Compute the parameter vector $\hat{\boldsymbol{a}}$ by Matlab,

$$\hat{\boldsymbol{a}} = (\boldsymbol{B}^{\mathrm{T}}\boldsymbol{B})^{-1}\boldsymbol{B}^{\mathrm{T}}\boldsymbol{y}_N$$

Step 5: Compute the albinism differential equation,

$$x_k^{(0)} + az_k^{(1)} = u$$

It can be called the GM(1, 1) model.

Then, the albinism differential equation of GM(1, 1) model can be written as:

$$\frac{\mathrm{d}x^{(1)}}{\mathrm{d}t} + ax^{(1)} = u$$

The time responsible function $\frac{\mathrm{d}x^{(1)}}{\mathrm{d}t} + ax^{(1)} = u$ on the parameter vector is:

$$\hat{x}_{k+1}^{(1)} = \left(x_1^{(0)} - \frac{u}{a}\right)\mathrm{e}^{-ak} + \frac{u}{a} \quad (k = 1, 2, 3, \cdots, n)$$

where, $x_1^{(1)} = x_1^{(0)}$.

Step 6: Compute the expression of $\hat{x}_{k+1}^{(0)}$.

Get the prediction sequences $\hat{x}_{k+1}^{(0)}$ according to the $\hat{x}_{k+1}^{(1)}$ restore.

$$\hat{x}_{k+1}^{(0)} = \hat{x}_{k+1}^{(1)} - \hat{x}_k^{(1)} = \left[x_1^{(0)} - \frac{b}{a}\right](1 - \mathrm{e}^{a})\mathrm{e}^{-ak}$$

$$(k = 1, 2, 3, \cdots, n)$$

1.3 The establishment of the new initial GM(1, 1) model

Although the grey forecasting model has been successfully utilized in many fields and demonstrated promising results, literatures show its performance still could be improved. For this purpose, this paper proposes a novel forecasting model termed the new initial GM(l, l). The new initial GM(l, l) regard the $x_n^{(1)}$ as the initial conditions of the grey prediction model, according to the new information on the role of cognitive theory of information than the old. In the modeling process, putting greater weight on the new information can improve the prediction accuracy. At the same time, this novel model can be referred to GM_n (1, 1), too (Zheng et al., 2009).

The difference between new initial GM(l, l) model and GM(l, l) model is the time responsible function:

$$\hat{x}_{k+1}^{(1)} = \left(X_n^{(1)} - \frac{u}{a}\right)\mathrm{e}^{-a(k-n+1)} + \frac{u}{a} \qquad (k = 1, 2, 3, \cdots, n)$$

$$\hat{X}_n^{(1)} = X_n^{(1)}$$

In the new initial GM (1,1) model, the expression of $\hat{x}_{k+1}^{(0)}$ is :

$$\hat{x}_{k+1}^{(0)} = \hat{x}_{k+1}^{(1)} - \hat{x}_k^{(1)} = \left[X_n^{(1)} - \frac{u}{a}\right](1 - \mathrm{e}^{a})\mathrm{e}^{-a(k+1-n)}$$

$$(k = 1, 2, 3, \cdots, n)$$

At the same time, $k \leq n$, the $x_k^{(0)}$ are fitted values, while $k \geq n$, $x_k^{(0)}$ are prediction values (Dang et al., 2005; Lin and Lee, 2007; Shang and Fang, 2010).

1.4 Compute the precision of the model

There are three test methods to test the precision of the gray prediction model. That is, residual error examination, posterior difference examination and relative degree examination. In this paper, we take the residual test.

Note residuals and the percentage of residuals respectively as $e_k^{(0)}$ and $\delta_k^{(0)}$. Then

$$e_k^{(0)} = x_k^{(0)} - \hat{x}_k^{(0)}$$

$$\delta_k^{(0)} = \left| \frac{e_k^{(0)}}{x_k^{(0)}} \right| \times 100$$

The average relative error is $\bar{\delta} = \frac{1}{n}\sum_{k=1}^{n} \delta_k^{(0)}$.

If $\bar{\delta} \le 20\%$, then the model is known as residuals qualified model. However, if $\bar{\delta} \ge 20\%$, the model must be fixed firstly so as to meet the accuracy requirements. Simultaneously, the smaller the average relative error is, the more accurate the precision is, and the better the fitting is (Liu et al., 2004).

2 Application of the grey system theory on the prediction of the water inflow

We establish the GM(1, 1) model and the new initial GM(1, 1) model using the maximum water inflow data of Pingdingshan No.8 mine from 2000 to 2007. Then we can compare the precision of the GM(1, 1) model and the new initial GM(1, 1) model. As is shown in the Table 1, there are the maximum water inflow data of Pingdingshan No.8 mine from 2000 to 2007.

Inputting the raw data, we can get the GM(1, 1) prediction model by the least square method which is computed by the Matlab. The time responsible function of GM(1, 1) prediction model is:

$$\hat{x}_k^{(1)} = -16\ 079.547\ 31\mathrm{e}^{-0.046\,5(k+1)} + 16\ 800.047\ 31$$
$$(k = 1, 2, 3, \cdots, n)$$

At the same time, the time responsible function of the new initial GM(1, 1) prediction model is:

$$\hat{x}_k^{(1)} = -11\ 610.347\ 31\mathrm{e}^{-0.046\ 5(k-8)} + 16\ 800.047\ 31$$
$$(k = 1, 2, 3, \cdots, n)$$

With the prediction model, the maximum water inflow amount from 2000 to 2007 is calculated. The results are shown in Table 2.

Table 1 The maximum water inflow data of Pingdingshan No.8 mine from 2000 to 2007

Year	2000	2001	2002	2003	2004	2005	2006	2007
The number	1	2	3	4	5	6	7	8
The maximum water inflow (m^3/h)	720.5	749.0	671.9	680.7	626.0	604.5	564.8	572.3

Table 2 The real and simulation data of comparison between GM(1, 1) model and new initial GM(1, 1) model

Year	Real value $x_k^{(0)}$ (m^3/h)	Simulation value $\hat{x}_k^{(0)}$ (m^3/h)		Remnant error $e_k^{(0)}$		Relative error $\delta_k^{(0)}$	
		GM(1, 1) model	New initial GM(1, 1)	GM(1, 1) model	New initial GM(1, 1)	GM(1, 1) model	New initial GM(1, 1)
2001	749.0	730.581 3	730.470 7	18.418 7	18.529 3	2.46	2.47
2002	671.9	697.387 0	697.281 4	−25.487 0	−25.381 4	3.79	3.78
2003	680.9	665.700 9	665.600 2	14.999 1	15.099 9	2.20	2.22
2004	626.0	635.454 5	635.358 3	−9.454 5	−9.358 3	1.51	1.49
2005	604.5	606.582 4	606.490 5	−2.082 4	−1.990 5	0.34	0.33
2006	564.8	579.022 0	578.934 4	−14.222 0	−14.134 4	2.52	2.50
2007	572.3	552.713 9	552.630 2	19.586 1	19.669 8	3.42	3.44

The average relative error of the GM(1, 1) model is $\varDelta = \frac{1}{n}\sum_{k=2}^{8} \delta_k^{(0)} = 2.32\%$,while that of the new initial GM(1, 1) model is $\varDelta = \frac{1}{n}\sum_{k=2}^{8} \delta_k^{(0)} = 2.32\%$. The precision testing results suggest that the precision of the prediction models are unsatisfactory. It shows that when a component of the original sequence as initial conditions, we can not guarantee the original and simulate sequence getting best fitting by optimizing the time responsible function in the process of grey system modeling (Tian and Zhao, 2007).

3 The establishment of the optimized GM(1, 1) model

The establishment of the optimized GM(1, 1) model is based on the GM(1, 1) model which is difficult to find the initial value. After determining the evolution parameter *a* and grey action *b*, in accordance with the principle of making the sum of the squares of the difference between the calculated sequences and the raw sequences, we make sure the constant number *c* of the whitening weight function in order to create the optimum time response sequence (Tian and Zhao, 2007).

The time responsible function of the optimized GM(1, 1) prediction model is:

$$\hat{x}_k^{(1)} = \frac{u}{a} + c\mathrm{e}^{-ak}$$

where, $c = (D^{\mathrm{T}} D)^{-1} D^{\mathrm{T}} A$, $A = \left(x_1^{(1)} - \frac{u}{a}, x_2^{(1)} - \frac{u}{a}, \cdots, x_n^{(1)} - \frac{u}{a} \right)$, $D = (\mathrm{e}^{-a}, \mathrm{e}^{-2a}, \cdots, \mathrm{e}^{-na})$.

Get the prediction sequences $\hat{x}_{k+1}^{(0)}$ according to the $\hat{x}_{k+1}^{(1)}$ restorage (Liu et al., 2004).

$$\hat{x}_1^{(0)} = \hat{x}_1^{(1)}$$

$$\hat{x}_{k+1}^{(0)} = \hat{x}_{k+1}^{(1)} - \hat{x}_k^{(1)} \quad (k = 1, 2, 3, \cdots, n)$$

The time responsible function of the optimized GM(1, 1) prediction model by calculating is:

$$\hat{x}_k^{(1)} = -16\ 845\mathrm{e}^{-0.046\ 5k} + 16\ 800.047\ 31 \quad (k = 1, 2, 3, \cdots, n)$$

With the prediction model, the maximum water inflow from 2000 to 2007 is calculated; and the results are shown in Table 3.

Table 3 The real & simulation data of comparison about the optimized GM(1, 1) model

Year	Real value $x_k^{(0)}$ (m^3/h)	Simulation value $\hat{x}_k^{(0)}$ (m^3/h)	Remnant error $e_k^{(0)}$	Relative error $\delta_k^{(0)}$
2000	720.5	720.407 3	0.092 7	0.01
2001	749.0	730.585 5	18.414 5	2.46
2002	671.9	697.391 0	−25.491 0	3.79
2003	680.9	665.704 8	14.992 5	2.21
2004	626	635.458 2	−9.458 2	1.51
2005	604.5	606.585 9	−2.085 9	0.35
2006	564.8	579.025 4	−14.225 4	2.52
2007	572.3	552.717 1	19.582 9	3.42

From Table 3 and Fig.1, we can see the precision of the prediction model is very high; meanwhile, the original and simulate sequence get the best fitting. The average relative error of the optimized GM(1, 1) model is 2.03% by accuracy test. The calculation precision testing results suggest that the prediction precision not only meets all the requirements, but also reach 97.97%. Therefore, we can predict the water inflow using the optimized GM(1, 1) model. With the prediction model, the maximum water inflow from 2008 to 2010 are calculated; the results are shown in Table 4.

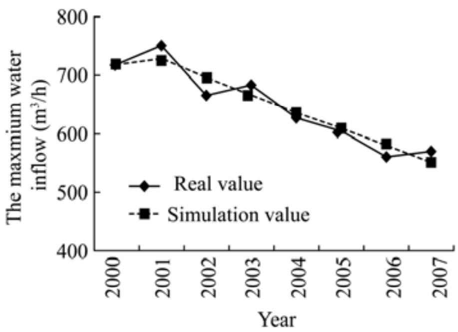

Fig.1 The real and simulation value of the maximum water inflow of Pingdingshan No.8 mine from 2000 to 2007

4 Conclusions

(1) The prediction precision of the new initial GM(1, 1) model can not achieve the desired results with some limits. The precision of the improved GM(1, 1) model does not necessarily improve some concrete grey problems. So it is essential to select the suitable prediction model based on the qualitative analysis.

Table 4 The simulation data of Pingdingshan No.8 mine from 2008 to 2011

Number	Year	Simulation value (m^3/h)
9	2008	527.604 1
10	2009	503.632 2
11	2010	480.749 5
12	2011	458.906 4

(2) The application of grey prediction model can solve the randomness and chance of the maximum water inflow. Especially, according to the range of the water inflow by years or days, it not only designs the discharged water from coal mine project properly, but also reduces the damage of mine accident.

(3) A method to predict the water inflow is provided. The key of this method which has a higher prediction accuracy is to calculate c. At the same time, we should adopt the scientific and appropriate pretreatment when we apply the maximum water inflow based on the grey system theory.

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