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Analysis of Mine Water Disaster Based on Fractal Theory

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Abstract: Mine water disaster has characteristics of contingency and randomness which increase the difficulty of predictive models. In the recent ten years, Chinese statistical data of mine water disaster show that the frequency conforms to exponential regression analysis and the time series of death toll accord with fractal time series. Firstly, R/S and Hurst index are used to prove the death toll of mine water disaster to accord with fractal time series. Then, the fractal interpolation theory is used to predict the occurrence rules of mine water disaster. Finally, the fitting curve of fractal interpolation is drawn by use of MATLAB method and compared with the actual curve of statistical data. The results show that fractal theory to predict rule of mine water disaster is feasible. So, this prediction technique can prevent the failure and concealment from reporting mine water disaster.

Key words: Mine water disaster, fractal theory, time series, R/S analysis method, Hurst index

INTRODUCTION

According to the accident inquiry system in SAWS (State Administration of Work Safety), 453 national casualty accidents of mine water disaster have occurred from 2003 to 2012 which have killed 3107 miners. These accidents contained 62 major accidents and 10 particularly serious accidents (SAWS, 2013; PRC State Council, 2007). In 2012, there were nearly 13000 mines nationwide. When those mines produced 3.65 billion tons of coal, correspondingly, mine water discharge is 7.17 billion cubic meters. However, 13 mine water disaster accidents occurred and 99 miners died in 2012. Obviously, the national mine hydrology condition is very complicated and water disaster is very serious. So, it is necessary to study the evolution and establish a scientific prediction model. Judged by appearance, mine water disaster shows characters of contingency time and geographic randomness, whose prediction model aims at frequency or death toll with discrete, irregular and nonlinear. The mine water disaster is similar to weather forecast, flood, earthquake, coast shape and other natural phenomena. But this kind of natural phenomenon which shows correlation and self-similarity, accord with fractal theory and its algorithm to establish a prediction model (Mandelbrot, 1983, 1985, 2002; Wei, 1999; Li *et al*., 2007). Therefore, in this study, the fractal characteristic of time series of mine water disasters is firstly verified. Then, one prediction model of mine water disaster prediction model is established based on the fractal interpolation algorithm. Lastly, it analyzes the development trend and provides technical decision support for risk prediction of mine water disaster.

ANALYSIS OF FRACTAL CHARACTERISTIC

Time series of mine water disaster: Over the past ten years, two complex nonlinear curves which are composed of frequency and death toll of coal mine disaster conform to time series. As shown in the Fig. 1, the trend of frequency broadly in line with exponential regression analysis and $R^2 = 0.9724>0.95$. So, the regression equation is reliable because of significant correlation. Combined with actual accident statistics from the accident inquiry system in SAWS, 120 mine water disasters have occurred in 2002. According to exponential regression curve of frequency in Fig. 1, 123 ($122.97e^{-0.217*0}$) mine water disasters occurred by pushing forward a cycle prediction water disaster in 2002. We predict 12 ($122.97\ e^{-0.217*11}$) mine water disasters, as is similar to actual statistics until November in 2013. Those two predicted data basically verify the exponential prediction model of frequency of mine water disaster.

However, the death toll of mine water disaster mine water does not meet the exponential, logarithmic, polynomial, or power regression forecasting. If we apply fractal theory to analyze time series of mine water disaster, we must prove that this time series has fractal characteristics.

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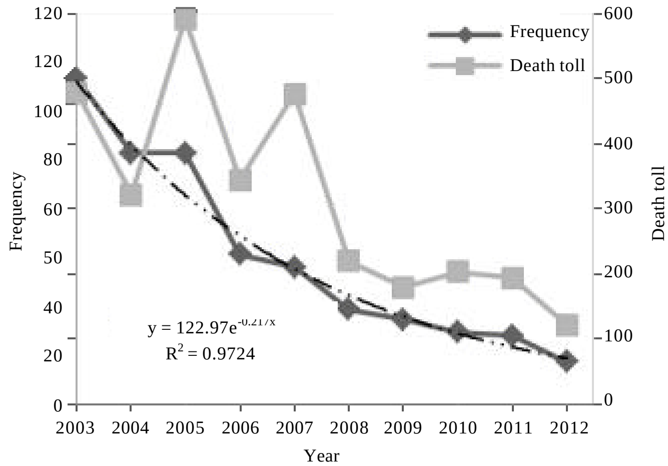

Fig. 1: National decade occurrence of mine water disaster

Mathematical model description: On the one hand, the Poincare mapping and Lyapunov index are usually used to judge whether the time series is fractal in known dynamical systems. On the other hand, the power spectrum and Hurst index may be better in unknown dynamical systems. Currently, the R/S analysis method and Hurst index are often used to determine the correlation of time series (Liao *et al*., 1998). When Hurst, one British hydrology expert, did research on the relationship between water flow and reservoir storage capacity in Nile River, he proposed R/S (Rescaled Range Analysis) method. Then, Benoit B. Mandelbrot, the father of fractal geometry, proposed the fractal time series or fractional Brownian motion and improved R/S method (Hurst *et al.*, 1965; Mandelbrot, 1983; Huang and Li, 1990). The principle and method are as follows.

It is assumed that the death toll sets of mine water disaster is x_i (i = 1, 2, 3..N). Take any positive integer, the mean sequence is following:

$$\bar{x}(n) = \frac{1}{n}\sum_{i=1}^{n} X_1 \quad (1)$$

The cumulative deviation sequence as follows:

$$X(i,n) = \sum_{i=1}^{n} X_1\left[x_t - \bar{x}(n)\right] = \sum_{i=1}^{n} X_t - i\bar{x}(n) \quad (2)$$

The difference sequence between the smallest and largest values in a frequency distribution is following:

$$R(n) = \max_{1\le i\le n}(X(i,n)) - \min_{1\le i\le n}(X(i,n)) \quad (3)$$

Standard deviation sequence is:

$$S(n) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x}(n))^2} \quad (4)$$

Defining the following equality relation, α is a constant:

$$R/S = (\alpha n)^H \quad (5)$$

The natural logarithm of both sides of Eq. 5:

$$\ln(R/S) = H\ln n + H\ln n\alpha \quad (6)$$

Hurst index has three forms. The first, H = 0.5, the time series belongs to standard Brownian motion and means an independent random series. That is, the correlation coefficient of time series is 0. It is shown that the future development trend isn't affected by past. The second, 0 = H<0.5, the time series belongs to fractal Brownian motion. That is, the past and future have negative correlation. It is shown that the increasing or decreasing of the past will cause the decreasing or increasing of the future. Moreover, the closer to 0 H is, the stronger the negative correlation is. The third, 0.5<H = 1, the past and future have positive correlation. Similarly, it is shown that the increasing or decreasing of the past will cause the increasing or decreasing of the future. Moreover, the closer to 1 H is, the stronger the positive correlation is and the more self-similarity the time series is. This is the key characteristic of fractal time series.

Fractal analysis: Hurst index represent whether the time series of death toll of mine water disaster possess fractal

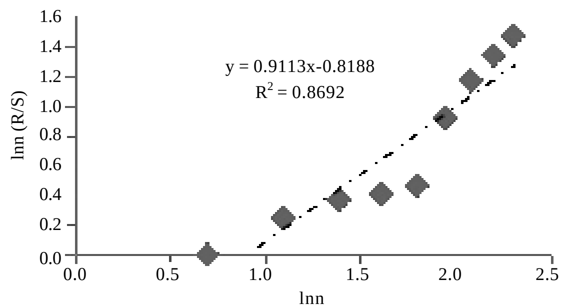

Fig. 2: ln (R/S) -lnn figure of mine water disasters death toll

Table 1: Death toll and R/S

Year	Time series$_n$	Death toll x_i	R (n)	S (n)	R/S
2003	1	478	-	-	-
2004	2	322	78.00	78.00	1.0
2005	3	592	142.00	110.67	1.3
2006	4	344	158.00	109.02	1.4
2007	5	476	149.60	98.95	1.5
2008	6	220	196.00	122.59	1.6
2009	7	179	347.00	138.40	2.5
2010	8	203	453.25	141.14	3.2
2011	9	194	540.89	142.01	3.8
2012	10	122	647.00	149.00	4.3

self-similarity or not. If $H\neq 0.5$, it means that the time series belongs to fractal Brownian motion. Decade death toll of mine water disaster and R(n)/S(n) are listed in Table 1. 2002 as the statistical origin (i>0).

As is shown in Eq. 6, if ln (R/S) and lnn are given data, the graph is draw in rectangular coordinate system. Then we make ln (R/S) on lnn linear regression and obtain the linear equation which is y = 0.9113x-0.8188 by using of the least square method. Therefore, slope is Hurst index, as shown in Fig. 2. Hurst index is 0.9113 and greater than 0.5. It is illustrated that the time series of death toll is provided with enduring relevance, self-similarity and fractal. It is a fractal time series (Falconer, 2003).

Fractal simulation: As the foregoing has proved, the death toll of mine water disaster has a character of fractal. Accordingly, the occurrence regularity of mine water disasters can be predicted by using of fractal interpolation theory and methods.

Fractal interpolation theory: Interpolation is an important method of discrete function approximation. A continuous function is interpolated into the discrete data and makes the continuous curve pass all discrete data points. The discrete data is $\{(x_i, y_i)|x_{i-1}<x_i, i = 0, 1, 2,...N\}$ and the continuous function is $y_i = f(x_i)$, i = 1, 2, …N. After the emergence of fractal geometry, curve fitting functions like the traditional interpolation function cannot explain fractal curves, when fractal interpolation function emerged as the times require. Fractal interpolation which is proposed by M.F. Barnsley on the basis of IFS (Iterated Function System) is a method to generate fractal curve (Barnsley, 1986). The principle is constructing corresponding IFS on a group of given interpolation points and making the attractor of IFS to be a graph through this group of interpolation points.

$\{(x_i, y_i)|_I = 0, 1, 2...N\}$ are given data points, IFS $\{R^2, wi, I = 0, 1, 2...N\}$ is constructed as follows:

$$w_i\begin{bmatrix}x\\y\end{bmatrix}=\begin{bmatrix}a_i & 0\\c_i & d_i\end{bmatrix}\begin{bmatrix}x\\y\end{bmatrix}+\begin{bmatrix}e_i\\f_i\end{bmatrix} \tag{7}$$

In the formula, where, (xi, yi) is the coordinate of a point. wi is defined to affine transformation and calculated from this formula. Where ai, ci, di are transformation matrix elements, ei, fi are the constant component after the conversion of (xi, yi).

If we request this attractor of IFS through the given interpolation points $\{(x_i, y_i)|i = 0, 1, 2...N\}$, each transformation must satisfy the conditions of the following two end-points x0, xN in that way:

$$w_i\begin{bmatrix}x_0\\y_0\end{bmatrix}=\begin{bmatrix}x_{i-1}\\y_{i-1}\end{bmatrix},\ w_i\begin{bmatrix}x_N\\y_N\end{bmatrix}=\begin{bmatrix}x_i\\y_i\end{bmatrix} \tag{8}$$

Then Eq. 7 is substituted in Eq. 8, other parameters are determined. There into, d_i is called vertical scaling factor as free parameters. Also, $0\leq d_i<1$ and i = 1, 2, …N:

$$\begin{cases}a_i=\dfrac{x_i-x_{i-1}}{x_N-x_0}\\ e_i=\dfrac{x_Nx_{i-1}-x_0x_i}{x_N-x_0}\\ c_i=\dfrac{y_i-y_{i-1}}{x_N-x_0}-d_i\dfrac{y_N-y_0}{x_N-x_0}\\ f_i=\dfrac{x_Ny_{i-1}-x_0y_i}{x_N-x_0}-d_i\dfrac{x_Ny_0-x_0y_N}{x_N-x_0}\end{cases} \tag{9}$$

According to related researches, fitting accuracy of fractal interpolation is inversely proportional to the vertical scaling factor (Li *et al*., 2007; Sun, 2011). Where:

$$d_i=\frac{y_i-y_{i-1}}{y_{max}-y_{min}}$$

and y_{max}, y_{min} are the maximum and minimum within [x1, xN].

MATLAB simulation: Statistics of death toll of mine water disaster are less by year than by month and not suitable for fractal interpolation. In order to increase

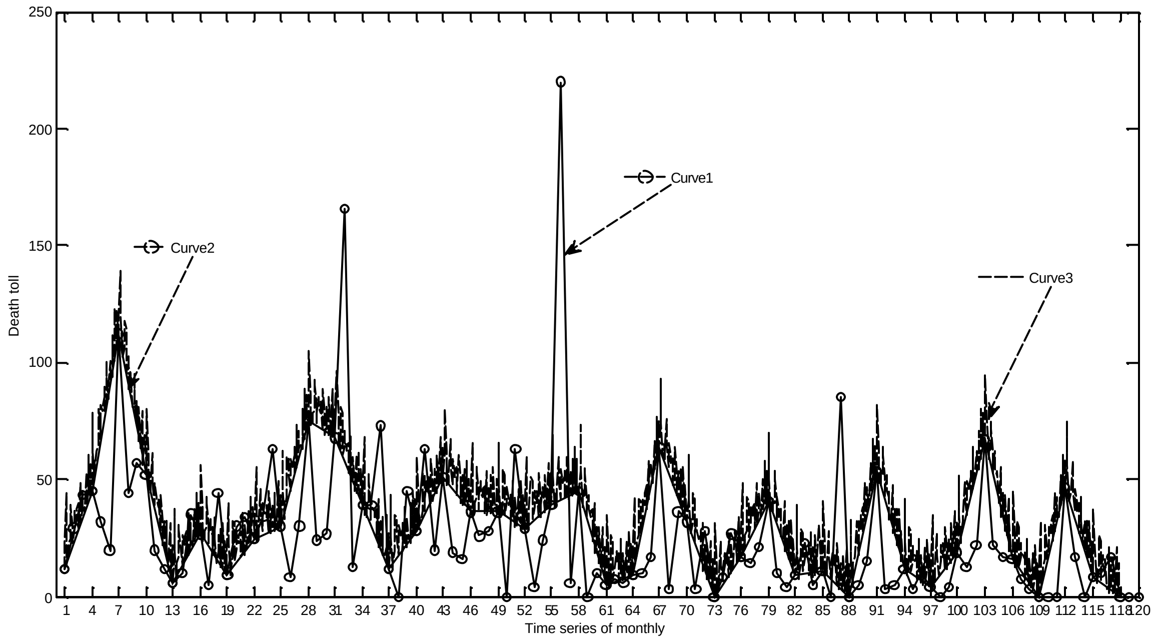

Fig. 3: Statistical data and fractal interpolation data of death toll

sample capacity, we count the death toll by month. There are 120 statistical data in total from 2003 to 2012, as is shown from curve 1 in Fig. 3. We choose the data of first month of each quarter as interpolation interval. Two data point are interpolated between two adjacent points by use of fractal interpolation method. 120 simulated data are regained. The fitting curve of fractal interpolation is drawn in MATLAB, as is shown from curve 3 in Fig.3.

Where curve 1, 2, 3 represent the statistical data, the data of first month of each quarter, the fractal interpolation data in this figure.

RESULTS AND DISCUSSION

In Fig. 3, there are three large deviations by comparing statistical data to fractal interpolation data.

Firstly, in the 32th month, namely in August 2005, 166 miners died. Among which includes 121 people who died in a particularly serious mine water disaster occurred in Daxing coal mine. Daxing coal mine is located in Wanghuai town, Meizhou city, Guangdong province. At 13:30 on August 7, mine excavation face in the 420 meters underground was flooded owing to summer heavy rainfall and mine exhaustive exploitation.

Secondly, in the 56th month, namely in August 2007, 220 miners died. Among which includes 172 people who died in a particularly serious mine water disaster occurred in Xinwen coal mine. Xinwen coal mine is located in Xintai city, Shandong province. On August 17, Chaiwen River, is adjacent to Xinwen coal mine, burst its banks. The river flooded the entire Xinwen coal mine.

Thirdly, in the 87th month, namely in March 2010, 85 miners died. Among which includes 32 and 38 people who died in two particularly serious mine water disaster. One is Luotuoshan coal mine which belongs to Shenhua Wuhai Coal Group Corporation Limited, in the Inner Mongolia Autonomous Region. At 7:29 on March 1, 16 layer mine excavation face in the underground was flooded owing to thrilling the underground water of Ordovician limestone. This disaster caused the death of 32 people. The other is Wangjialing coal mine which belongs to Huajin Coking Coal Corporation Limited, in Xiangning county, Shanxi province. At 13:40 on March 28, mine excavation face in the underground was flooded owing to thrilling the goaf. This disaster caused the death of 38 people.

Obviously, the departure of these three months' statistical data from the fitting curve of fractal interpolation was brought about by two reasons which caused death toll to sharply increase. For one thing, summer rainfall was heavy and surface water flooded coal mine. For another thing, several particularly serious accidents were grouped in one month. These statistical data does not have reference and representativeness.

CONCLUSION

Therefore, the fractal interpolation iterative curve of death toll of mine water disaster basically fits the statistical data. It has been proved that the method, by means of selecting key points on the curve of death toll time series as the interpolation points, iterating by using the fractal interpolation function and recovering key points into the time sequence curve with same time interval, is feasible. In actual production, there are many phenomena of the failure and concealment to report mine water disaster. This prediction method can estimate and complement frequency or death toll of mine water disaster. Likewise, it can verify authenticity and reliability of the statistical data.

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