Hindawi
Mathematical Problems in Engineering
Volume 2018, Article ID 4397237, 7 pages
https://doi.org/10.1155/2018/4397237

Research Article

Prediction of Coal Mine Gas Emission Quantity Based on Grey-Gas Geologic Method

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Received 10 July 2018; Revised 6 November 2018; Accepted 29 November 2018; Published 23 December 2018

Academic Editor: Alessandro De Luca

To improve the accuracy and reliability of gas emission prediction, the various factors affecting the amount of gas emission were researched and the main factor determining the amount of gas emission was determined by the gas geology theory. In this paper, we adopted grey-gas geologic method and grey relevancy analysis separately to estimate forecast accuracy and to establish the grey systematic forecasting model; meanwhile, two residual tests were carried out. Combined with the concurrent in situ data, the result of the grey systematic prediction model is verified. The later residual test results indicated that the model is of a high accuracy and the prediction result is reliable, manifesting the method of grey-gas geologic method is a better way to forecast the gas emission.

1. Introduction

Gas emission forecast is the important basis for building new mines and new ventilating designs in mining panel and preventing and managing gas; it plays an important role in reducing gas explosion accidents and ensuring the safety in coal mine production [1]. At present, Chinese scholars have done lots of researches on forecasting methods of gas emission such as mine statistical method, plot headstream method, and gas geological map method [2–4]. Based on the quantification theory, gas geological map method takes gas geological condition as a prediction indicator to build mathematical model of gas emission to forecast coal face, coal mines, and gas emission in mines. However, without a long-term datum of gas emission, it is hard to guarantee an accurate forecast. Grey system is a process forecast which changes in certain position and relates to time [5]. The system demands less sample data and, without typical distribution, Chinese scholars have made great researches on the application of grey system to forecast gas emission [6]. But in the forecast process of grey system, the thickness and depth of coal seams and the depth of overlaying rocks are not considered; thus the forecast result is of a low accuracy. To sum up, this article establishes a grey-gas geological forecast method by combining gas geological map forecast method with grey system forecast system to maximize their strengths.

2. Theory Research on Grey-Gas Geology Forecast

Combining grey correlation theory with gas geology theory, the basic idea of grey-gas geological forecast method is to analyze the geological factors such as the depth of overlaying rocks, coal seams, the mud rocks, and the geological structure with the foundation of gas geology theory. Then the grey correlation method is used to make a quantitative description and comparison to analyze the dynamic relation between geology and development of gas emission. By this way, the similarities of curve shapes of gas emission and several influential factors are determined to estimate the correlation degree that the higher the correlation, the closer the curve, and vice versa. When determining the gas emission according to the correlation degree, theories factor is removed. This forecast method can either make a qualitative analysis of different influential factors on the gas emission or make a quantitative analysis of the relations between those factors, reducing workload by avoiding unnecessary calculation. Meanwhile, it can also figure out the regularities between those factors to build a forecast model of gas emission, improve the forecast accuracy, and provide reliable basis for managing gas emission [6].

The calculation procedures of grey-gas geologic method are as follows.

(1) Use the gas geology theory to analyze evolution characteristics of geology structure and mines of different subjects stage by stage, analyze the regularities of gas occurrence and gas emission, and find out the influential factors of gas emission.

(2) Identify the sequence $X_1, X_2, X_3, \ldots, X_m$ are the main influential factors of gas emission and are independent variables. Suppose there are n groups of sample data to compose matrix X:

$$X = (X_1, X_2, X_3, \ldots, X_m) = \begin{Bmatrix} x_1(1) & x_2(1) & \cdots & x_m(1) \\ x_1(2) & x_2(2) & \cdots & x_m(2) \\ \vdots & \vdots & \vdots & \vdots \\ x_1(n) & x_2(n) & \cdots & x_m(n) \end{Bmatrix} \quad (1)$$

Take the amount of gas emission as dependent variables to compose matrix Y:

$$Y = \begin{Bmatrix} y_1(1) \\ y_1(2) \\ \vdots \\ y_1(n) \end{Bmatrix} \quad (2)$$

(3) Pretreatments of primary data: as the dimensions of the above variables are different and the differentials of the data range are quite large, to eliminate the dimension of each variable, the orders of magnitude will be consolidated to have comparability. So the primary data will be pretreated first in the way of equalization shown in the following:

$$x_i'(k) = \frac{x_i(k)}{(1/n)\sum_{k=1}^{n} x_i(k)} \quad (3)$$

$$y_1'(k) = \frac{y_1(k)}{(1/n)\sum_{k=1}^{n} y_1(k)} \quad (4)$$

In the formulas, $i = 1, 2, \ldots, m$, $\mathrm{k} = 1, 2, \ldots, \mathrm{n}$.

(4) Take formula (5) to calculate the dependable variables at each node and the absolute value $\Delta_i(k)$ of each independent variable; then the maximum Δ_{imax} and minimum Δ_{imin} of the absolute value of difference are [7]

$$\Delta_{\mathrm{i}}(\mathrm{k}) = \left| x_{\mathrm{i}}'(\mathrm{k}) - y_1'(k) \right| \quad (5)$$

(5) Calculate the correlation coefficient of dependent variables and independent variables shown in

$$\rho \in (0, 1) \quad (6)$$

In this formula, $\rho \in (0, 1)$, $\rho = 0.5$.

(6) Calculate the relevancy between independent variables and each variable, that is, calculate the mean value of correlation coefficient as in the following:

$$R_{\mathrm{i}} = \frac{1}{\mathrm{n}} \sum_{k=1}^{n} L_i(k) \quad (7)$$

(7) Make a comparative analysis to determine weights of each variable calculated result of relevancy and build a gas emission forecasting model by using grey system theory.

3. Grey System Modeling

Due to multiple factors affecting gas emission, the correlation degree is large, so this paper takes GM(1, N) model.

3.1. GM(1, N) *Model.* Raw data series are

$$X_i^{(\mathbf{0})} = \left(x_i^{(\mathbf{0})}(1), x_i^{(\mathbf{0})}(2), x_i^{(\mathbf{0})}(3), \ldots, x_i^{(\mathbf{0})}(n) \right), \quad i = 1, 2, \ldots, N \quad (8)$$

Raw data are irregular, random series with obvious swing. Accumulate $X_i^{(\mathbf{0})}$ to produce new series.

$$x_i^{(1)}(k) = \sum_{j=1}^{k} x_i^{(0)}(j) \quad (9)$$

$$X_i^{(1)} = \left(x_i^{(1)}(1), x_i^{(1)}(2), x_i^{(1)}(3), \ldots, x_i^{(1)}(n) \right) = \left\{ \sum_{j=1}^{1} x_i^0(\mathrm{j}), \sum_{j=1}^{2} x_i^0(\mathrm{j}), \sum_{j=1}^{3} x_i^0(\mathrm{j}), \ldots, \sum_{j=1}^{j} x_i^0(\mathrm{j}), \ldots \right\}, \quad i = 1, 2, \ldots, N \quad (10)$$

Build differential equation:

$$\frac{dx_1^{(1)}}{dt} + ax_1^{(1)} = b_1 x_2^{(1)} + b_2 x_3^{(1)} + \cdots + b_{N-1} x_N^{(1)} \quad (11)$$

This model is GM (1, N) and is a differential equation with N Variables in one order.

In formula (8), coefficient vector is marked as $\widehat{a}$: $\widehat{a} = [a, b_1, b_2, \ldots, b_{N-1}]$; then calculate $\widehat{a}$ by using least-square theory. $\widehat{a} = (B^T B)^{-1} B^T Y_N$.

In the following formulas, B is Class matrix and Y_N is constant term vector:

$$B = \begin{bmatrix} \frac{-\left[x_1^{(1)}(1)+x_1^{(1)}(2)\right]}{2} & x_2^{(1)}(2) & \cdots & x_N^{(1)}(2) \\ \frac{-\left[x_1^{(1)}(2)+x_1^{(1)}(3)\right]}{2} & x_2^{(1)}(3) & \cdots & x_N^{(1)}(3) \\ \vdots & \vdots & \vdots & \vdots \\ \frac{-\left[x_1^{(1)}(n-1)+x_1^{(1)}(n)\right]}{2} & x_2^{(1)}(n) & \cdots & x_N^{(1)}(N) \end{bmatrix} \quad (12)$$

$$Y_N = \left[x_1^{(0)}(2) \;\; x_1^{(0)}(3) \;\; \cdots \;\; x_1^{(0)}(n)\right]^T \quad (13)$$

Finally, calculate the differential equation with N Variables in one order by $X_1, X_2, \ldots, X_n$:

$$\hat{x}_1^{(1)}(t+1) = \left[x_1^{(0)}(1) - \sum_{i=1}^{n}\frac{b_{i-1}}{a}x_i^{(1)}(t+1)\right]e^{-at} + \sum_{i=2}^{n}\frac{b_{i-1}}{a}x_i^{(1)}(t+1) \quad (14)$$

3.2. Residual Test. Residual test is to test model precision and it is a direct arithmetic checking [8].

The original sequence is

$$X_i^{(0)} = \left(x_i^{(0)}(1), x_i^{(0)}(2), x_i^{(0)}(3), \ldots, x_i^{(0)}(n)\right) \quad (15)$$

The simulated sequence is

$$\hat{X}_i^{(0)} = \left(\hat{x}_i^{(0)}(1), \hat{x}_i^{(0)}(2), \hat{x}_i^{(0)}(3), \ldots, \hat{x}_i^{(0)}(n)\right) \quad (16)$$

The residual sequence is

$$\begin{aligned} \varepsilon^{(0)} &= (\varepsilon(1), \varepsilon(2), \varepsilon(3), \ldots, \varepsilon(n)) = X^{(0)} - \hat{X}^{(0)} \\ &= \left[x^{(0)}(1) - \hat{X}^{(0)}(1), x^{(0)}(1)\right. \\ &\quad \left. - \hat{X}^{(0)}(1), \ldots, x^{(0)}(n) - \hat{X}^{(0)}(n)\right] \end{aligned} \quad (17)$$

The compared residual sequence is

$$\Delta = \left(\left|\frac{\varepsilon(1)}{x^{(0)}(1)}\right|, \left|\frac{\varepsilon(2)}{x^{(0)}(2)}\right|, \ldots, \left|\frac{\varepsilon(n)}{x^{(0)}(n)}\right|\right) = \{\Delta_t\}_1^n \quad (18)$$

The mean relative error is

$$\overline{\Delta} = \frac{1}{n}\sum_{t=1}^{n}\Delta_t \quad (19)$$

The precision can be presented as

$$p = \left(1 - \overline{\Delta}\right) \times 100\% \quad (20)$$

Given the value of α, when $\overline{\Delta} < \alpha$ and $\Delta_k < \alpha$, the model is residual qualified. The posterior residual test is based on the probability distribution of the residual error. It belongs to a kind of statistical tests.

The mean and variance of the original sequence $X^{(0)}$ are, respectively,

$$\overline{x} = \frac{1}{n}\sum_{t=1}^{n}x^{(0)}(t) \quad (21)$$

$$S_1^2 = \frac{1}{n}\sum_{t=1}^{n}\left(x^{(0)}(t) - \overline{x}\right)^2 \quad (22)$$

The mean and variance of the residual $\varepsilon^{(0)}$ are, respectively,

$$\overline{\varepsilon} = \frac{1}{n}\sum_{t=1}^{n}\varepsilon(t) \quad (23)$$

$$S_2^2 = \frac{1}{n}\sum_{t=1}^{n}\left(\varepsilon(t) - \overline{\varepsilon}\right)^2 \quad (24)$$

$C = S_2/S_1$ is called the mean square error ratio. For the given $C < C_0$, when $C < C_0$, it is called the mean square error ratio qualified model [9].

If $= P(|\varepsilon(t) - \overline{\varepsilon}|)$, when $(p/S_1)\langle\mathbf{0.6745}$, it is called the small error probability. For the given $P_0 > 0$, when $P > P_0$ it is called the small error probability qualified model.

According to the above two testing model methods, the ratio of the mean simulation relative error and mean square error should be as small as possible, and the error probability should be as large as possible.

4. Prediction Case of Grey-Gas Geological Method

The coal face of the twelfth coal mine JI 15-17200 of Ping Mine is used as the experimental area to predict gas emission by computer programming.

4.1. Gas Geology Analysis. (1) Coal seam gas content: the gas content of raw coal of the working face is the decisive factor to influence the gas emission in the exploration of the face in coal seams. When the gas content in coal face is high, the gas will flow into the exploration space, which tremendously increases the gas emission quantity of the coal face of coal seam. In a word, gas content in coal seam is an important basis to predict the gas emission. The average gas content of the coal face of Ji15-17200 is 5.76m^3/t, which is comparatively high. Despite little change of absolute gas emission quantity with the fluctuation of gas content, there still exists positive relevance: the absolute gas emission quantity will increase with the increase of gas content. Moreover, the relative gas emission quantity in coal face is more than gas content in coal seam, proving that the source of gas emission quantity is not just from current seam but also from surrounding rocks of coal seam.

(2) Embedding depth of coal seam: the influence of embedding depth of coal seam on gas emission quantity is mining depth of coal seam, and the increase of mining

Table 1: The calculation results of correlation degree.

	R_1	R_2	R_3	R_4	R_5
correlation degree	0.70	0.75	0.73	0.65	0.69

depth will lead to an increase of gas content of coal seam which will further cause an increase of gas emission quantity. The thickness of overlying rock of coal seam is mainly represented by the embedding depth of coal seam because the former equals the later minuses the thickness of the quaternary sedimentary rock. The quaternary is mainly loess layer and is generally distributed on the earth surface. It has poor cementation, large porosity, and good connectivity, facilitating the release of gas. Meanwhile, as the quaternary unconsolidated sediment is easy to move and has a large variation in thickness, it causes the large vertical variation in the overlying strata in coal seam. The increase of thickness of overlying rock will cause the increase of the absolute gas emission quantity, making a positive relevance.

(3) Thickness of coal seam: the thicker the coal seam is, the larger the gas quantity is and so is gas occurrence quantity; then it will cause an increase of the gas emission quantity.

Being a single coal seam of Ji 15, the coal face of 17200 has a whole occurrence and the fissure develops well with a partial dirt band. Influenced by the structure, the thickness of regional coal seam and dig angle changes greatly.

According to the geophysical analysis results and downhole data, there are three areas that the thickness of coal seam changes: the first area is 360m to 450m up the terminal mining line of intake airflow roadway, 215m to 300m of which is a coal seam thickness abnormal area; the second is 60m-75m down to the terminal mining line of intake airflow roadway which is a coal seam thinning abnormal area; then around the mining line of intake airflow roadway is a thin coal abnormal area [10].

According to the data of gas emission quantity, the coal seam thickness abnormal area was mined from May to July, 2012, the coal seam thinning abnormal area was mined from March to July, 2013, and the thinning coal seam area was mined from October to November, 2013. In thickness abnormal area, especially in thinning area, the gas emission quantity became great. Meanwhile, in thickness abnormal area, the stability of coal seam is weak and the variation coefficients of coal seam are great which may cause coal and gas outburst. So it is also important to manage and prevent outburst while managing the gas emission quantity.

(4) The quantity of the coal face: the daily output of the coal face reflects the condition of coal seam occurrence of the coal face; that is, the better the coal seam occurrence is, the easier the mining is, the bigger the output is, and the more the gas emission quantity of coal face is. Adapting comprehensive mechanical mining technology, the coal face of 17200 realizes the mechanization of coal loading and shipping with an expected mining cycle of 19 months but a real cycle of 21 months and the average daily output is about 1175t and the maximum daily output reach 1529t. Then with the increase of the output, the gas emission quantity fluctuates. It represents the daily output has certain influence on the gas emission quantity, so the more the daily output is, the more the gas emission quantity is [11].

(5) Geographic structure: closed geographic structure helps to seal gas such as compressive fault while open geographic structure is conductive to gas emission such as tensional normal fault. It is common to see fault structure in the mining process of coal face which influences much on gas emission quantity. According to the geographic analysis, the geographic structure of the coal face is complex with minor normal faults developing and a synclinal structure developing in coal seam thinning area. The synclinal structure is formed by compression, leading to the thinness of this current coal seam and the abnormal of coal seam which further influence the gas emission quantity. The development of normal faults will cause the development of coal seam and fissures of surrounding rock leading to the emission of gas and then the decrease of gas emission quantity.

According to the comprehensive geographic analysis, there emerges a normal fault (1#) in the intake airflow roadway of the coal face, 11m back of Jin 6; there emerges a thrust fault (6#) in return airway, 22m back of Jin 4; there emerge four normal faults (2#, 3#, 4#, 5#) with 2#, respectively, 330m being away from terminal mining line, 3# 270m away from terminal mining line, 4# away from terminal mining line and 5# away from terminal mining line. Those faults of coal face all belong to minor faults and distribute loosely, influencing little on gas emission quantity.

(6) The thickness of the overlying roof clay rock of coal seam: the existence of clay rock around the coal roof can also influence the occurrence of gas on the seal of gas. The thicker the clay rock is, the more the gas content is and so is the gas emission quantity. The fine sandstorm on the main roof of coal face of Ji 15-17200 is developed with an average thickness of 10.09m in a belt shape of the middle and below part. A few plaques and sandy mudstone are seen in the grey sandstorms and mica plate is also included. The immediate roof of coal face is mudstone of an ash black color and a dense structure and with an average thickness of 4.01m and some mica chips.

4.2. Grey Relational Calculation. The coal face of 12th Ping Mine 17200 is taken for example to make grey relational analysis. The factor influencing the gas emission quantity is independent variable X, gas content is X_1, the thickness of overlying rock is X_2, the thickness of coal is X_3, the output of coal face is X_4, the thickness of overlying mudstone is X_5, and gas emission quantity is dependent variable Y.

According to the gas emission quantity data of coal face of 17200 after selection, the above grey relational analysis method is adapted to calculate the correlation of gas emission quantity to gas content, the thickness of overlying rock, the thickness of coal seam, the output of coal face, the process of mining, and the thickness of overlying mudstone. The result is shown in Table 1.

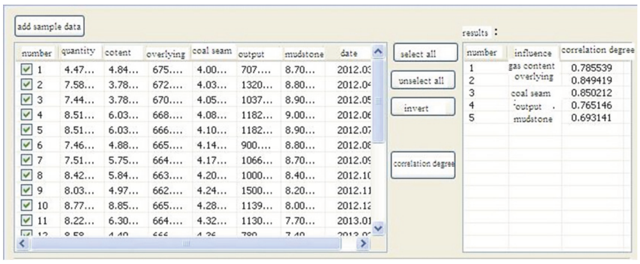

FIGURE 1: The grey relation calculation.

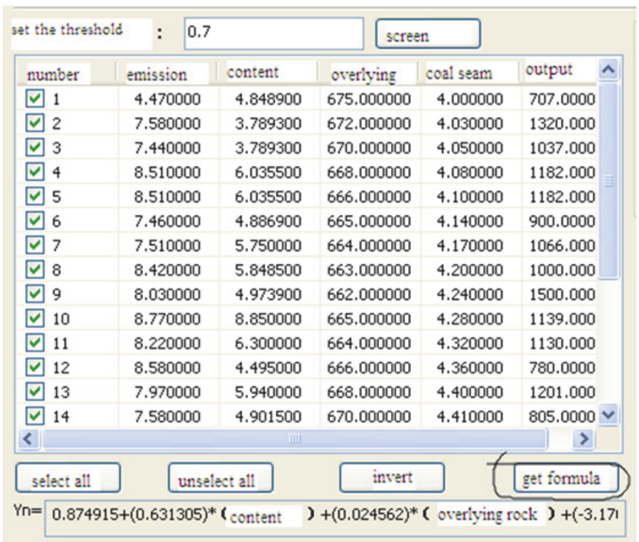

FIGURE 2: Acquired prediction formula.

According to the calculation result, the correlation of gas emission quantity to those influencing factor above 0.6 represents a strong relation. Those factors are main factors influencing the gas emission quantity of coal face and the thickness of overlying rock of coal seam is the dominant factor. Meanwhile, the gas content, the thickness of coal seam, the output of coal face, and the thickness of mudstone all play an important part to gas emission quantity which deserves necessary consideration when building gas emission quantity prediction model [12].

4.3. Model Application. C language programming is adapted to realize the grey-gas geographic method to predict gas emission quantity.

Choose the factors to do the grey relation calculation to get the grey correlation degree of each influencing factor. After calculation, select the dominant factor according to the grey correlation degree. Then analyze the gas emission quantity of coal face of 12th mine 17200, followed by analysis of the thickness of coal seam, the thickness of overlying rock, the gas content, the average of daily output, and the thickness of mudstone, shown in Figure 1.

The mathematical model is based on the result from the grey relational calculation as shown in Figure 2.

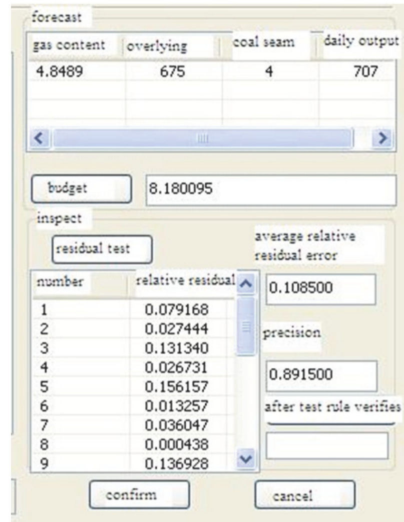

FIGURE 3: Model predicted results.

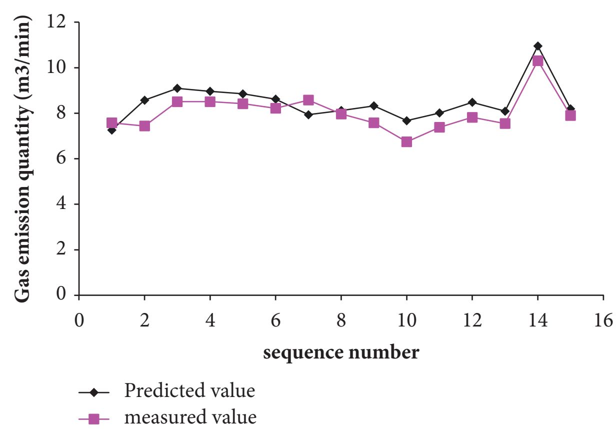

FIGURE 4: The analysis of predicted results of gas emission quantity in coal face.

The residual test result by grey-gas geographic model and predicted result of gas emission quantity are shown in Figure 3.

Based on the comparison between the predicting result of gas emission quantity and measured value shown in Table 2 and Figure 4, it can be concluded that the predicting result and the developing tendency of gas emission quantity by system are almost the same as that by actual measurement with an average error of 0.57 and a maximum error of 0.9, which proves the accuracy of predicting model built by system and the reliability of the predicting result, providing reliable basis for gas emission quantity prediction under the mine.

5. Conclusion

(1) Combining the advantages of gas geological map method and grey system, the grey-gas geologic method overcomes the problem of low accuracy of grey prediction and meets

Table 2: Contrast and statistics of the predicted result of gas emission quantity in coal face.

Number	Gas content/m^3/t	The thickness of overlying rock/m	The thickness of coal seam/m	The average of daily output	The thickness of mudstone/m	Gas emission quantity predicted value/m^3/t	Gas emission quantity measured value/m^3/min
1	3.79	672.00	4.03	1320.00	8.80	7.26	7.58
2	4.74	670.00	4.05	1037.00	8.90	8.58	7.44
3	6.04	668.00	4.08	1182.00	9.00	9.09	8.51
4	6.04	666.00	4.10	1182.00	8.90	8.97	8.51
5	5.85	663.00	4.20	1000.00	8.40	8.85	8.42
6	6.30	664.00	4.32	1130.00	7.70	8.62	8.22
7	4.50	666.00	4.36	780.00	7.40	7.94	8.58
8	5.94	668.00	4.40	1201.00	7.00	8.12	7.97
9	4.90	670.00	4.41	805.00	6.60	8.33	7.58
10	5.95	674.00	4.42	1529.00	6.00	7.68	6.75
11	6.05	678.00	4.45	1476.00	5.50	8.01	7.39
12	6.36	680.00	4.42	1529.00	4.80	8.48	7.82
13	4.39	687.00	4.50	1052.00	4.00	8.09	7.55
14	8.29	695.00	4.40	1523.00	3.70	10.95	10.31
15	4.08	702.00	4.32	1474.00	3.30	8.20	7.90

the need of large amounts of data of gas geographic method, making the prediction result more practical.

(2) Building a system to realize grey-gas geographic method is to predict gas emission quantity and this method is proved to be reliable by taking the 12th of Ping Mine as experimental area to contrast the predicted result with the test result in which the predicted result almost matches the test result.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This study is financially supported by the National Coal Field Engineering Research Center for Gas Geology and Gas Control, the Collaborative Innovation Center of Coal Safety Production of Henan Province, the Collaborative Innovation Center of the Central Plains Economic Zone CBM (Shale Gas) of Henan Province, the Key Science and Technology Program of Henan Province (152102210105), the Foundation of Henan Educational Committee (2010B440004), the Program for Innovative Research Team in University of Ministry of Education of China (IRT_16R22), and the project funded by China Postdoctoral Science Foundation (2017M622343), and this project is supported by Henan Postdoctoral Foundation.

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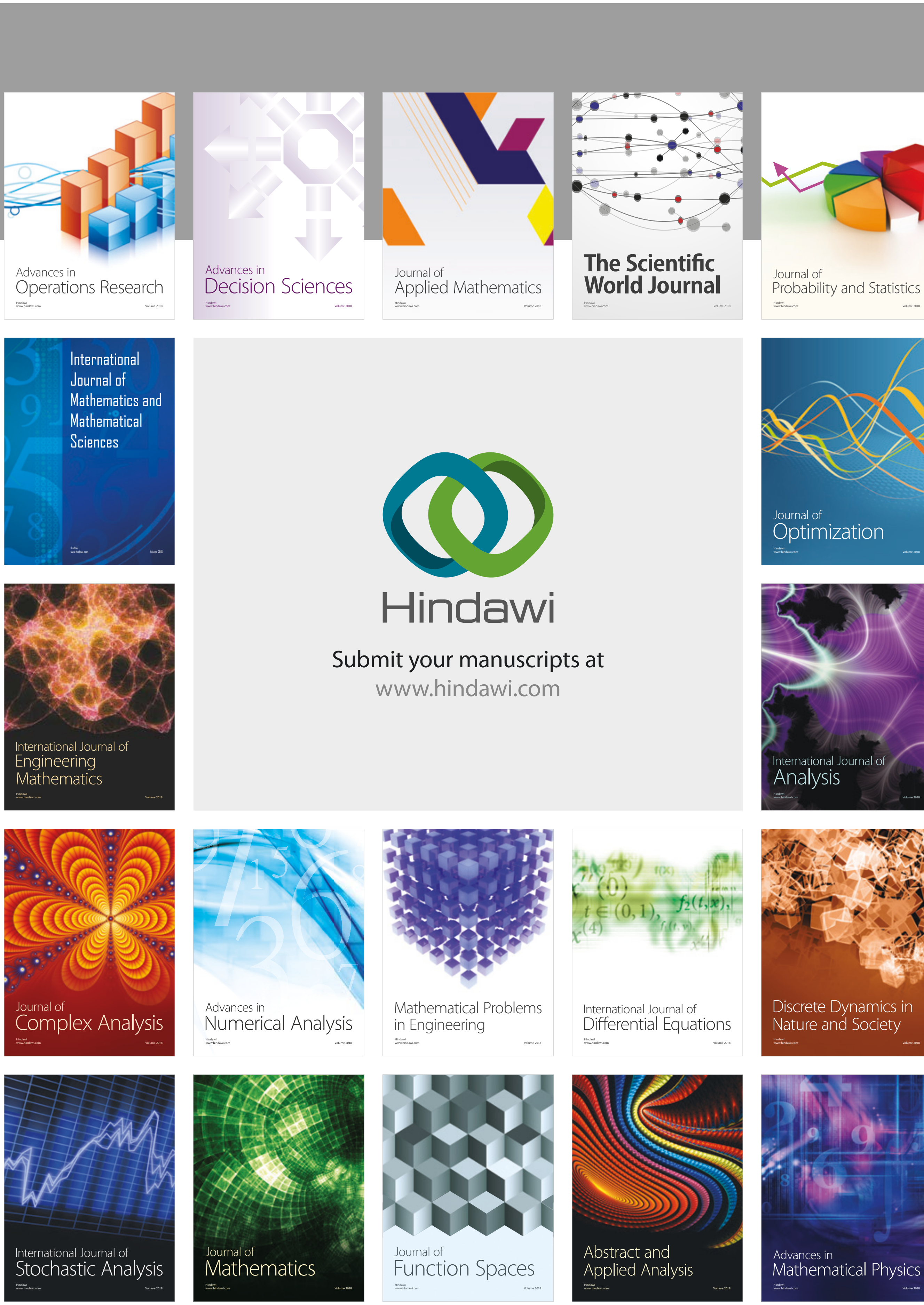
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