Journal of Electronics and Information Science (2024)
Clausius Scientific Press, Canada

DOI: 10.23977/jeis.2024.090115
ISSN 2371-9524 Vol. 9 Num. 1

Statistical analysis of coal mine accidents from 2012 to 2023 and trend prediction in the future in China

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Keywords: Coal mine accident, Statistical analysis, Trend forecast, Grey GM (1, 1) model, The gray Markov prediction model

Abstract: Statistical analysis of coal mine accidents plays an important role in reducing the probability of accidents and promoting coal mine safety management. However, the current research on the year, region, accident type and so on has some emphasis and many cross. In order to comprehensively and systematically master the characteristics and laws of coal mine accidents in China in recent years, this paper analyzes and discusses the number of coal mine accidents and the number of deaths in China based on the statistical data of coal mine accidents from 2012 to 2023, from the six aspects of year, month, period, region, accident grade and accident type. Based on this, the grey Markov model is used to predict and analyze the future trend of coal mine accidents in China. The research shows that the number of coal mine accidents and the number of deaths in China have shown a downward trend in recent years, but with tortuosity and recurrence, and more attention should be paid to general accidents. The high-incidence period of accidents is March, August, November and 10:00-13:59 every day. The incidence and mortality of gas and roof accidents are higher. In the large and above accidents, flood, fire, poisoning, and suffocation accidents account for a large proportion. It is predicted that the number of accidents in China in 2024 and 2025 will be 95 and 64, and the number of deaths will be 133 and 99.

1. Introduction

The “Statistical Bulletin of the National Economic and Social Development of the People’s Republic of China in 2022” pointed out that, China's total energy consumption in 2022 will be 5.41 billion tons of standard coal, of which coal consumption accounts for 56.2 % of total energy consumption; Although the proportion of coal consumption has generally shown a downward trend in recent years, it will still be China's main energy source in the short term. For a long time, roofs, gas, water, fire, mineral dust, etc. have been the main disasters that restrict the safe and efficient production of coal mines, many scientific researchers in China have carried out a lot of fruitful research work on the above-mentioned disasters and achieved a series of remarkable results. The coal mine safety situation is improving year by year, for example, the number of coal mine gas accidents and deaths in 2022 will both decrease by 44 % year-on-year, and there will be no fatal accidents such as rock bursts or fires; the mortality rate per million tons will be 0.054. Despite this, coal mine disaster prevention and control work still has a long way to go.

As one of the effective means of safety management, accident statistical analysis plays an important role in finding the rules of accident occurrence, and then predicting and preventing accidents in future production processes. Jiang Xingxing et al [1], Ning Xiaoliang[2], Zhang Peisen et al[3,4] and Xu Pengfei[5] conducted statistical analyzes on coal mine accidents in different years in China from 2000 to 2021, and proposed corresponding countermeasures. Wang Yungang et al. [6] conducted statistics on major coal mine accidents in China from 2011 to 2020, and used the safety entropy model to analyze typical cases. They believed that the safety of many influencing factors in the production system continues to decrease, resulting in an increasing entropy value, which in turn causes system chaos and ultimately leads to accidents. Zhang Junwen et al. [7] conducted statistics on major coal mine accidents and above in China from 2005 to 2019, and believed that clarifying the subject of local safety supervision is fundamental, and effective prevention and control of power and gas disasters is the focus. Jing Guoxun et al. [8,9] conducted a statistical analysis of coal mine gas accidents in China from 2008 to 2013 and 2015 to 2019, and believed that illegal operations are the cause of the high incidence of coal mine gas accidents, and gas explosions and coal and gas outbursts are the causes of gas accidents, Main types. Xu Tengfei et al. [10] conducted a statistical analysis of gas explosion accidents in low-gas mines in China from 2010 to 2019. They believed that coal mines with an annual output of less than 0.30 Mt/a are prone to gas explosion accidents, and ventilation is the main inducement. Low-gas coal mines are relatively more susceptible to gas explosion accidents. Major accidents are prone to occur. Zhang Peisen et al. [11] used mathematical statistics methods to conduct a statistical analysis of water damage accidents in coal mines in China from 2008 to 2019, and believed that water from the old kiln was the main source of water inrush. Wu Jinsui et al. [12] conducted a statistical analysis of coal mine water damage accidents in China from 2001 to 2020, and believed that the number of major water damage accidents was small and the death toll was high. Although there was an overall downward trend, there were large rebounds and fluctuations in individual years, but their It remains the focus of water damage accident prevention. Zhou Tianmo et al. [13] conducted statistics on coal mine accidents in Inner Mongolia from 2011 to 2018, and used multiple linear regression methods to analyze and discuss accident characteristics, occurrence patterns and internal causes. They believed that transportation and roof accidents are the main factors in the number of coal mine accidents and deaths in Inner Mongolia. The main influencing factor is the number of people. Li Weiguang et al. [14] conducted a statistical analysis of coal mine accidents in Sichuan from 2010 to 2019 and believed that roof, gas, and transportation accidents were the main types of coal mine accidents in Sichuan. Accidents mainly occurred in township coal mines, and the main disaster factors were human unsafe behaviors. The above research results have played a positive role in reducing the probability of accidents and promoting coal mine safety management. However, many researchers have focused on the years, regions, accident types, etc. in statistical analysis of coal mine accidents and often overlap. In order to comprehensively and systematically grasp the characteristics and patterns of coal mine accidents in China from 2012 to 2023, and thereby provide reference for future coal mine safety management, this article uses the gray Markov prediction model to develop coal mine accident statistics based on official published data Analytical and predictive research.

2. Statistical analysis of coal mine accidents in China from 2012 to 2023

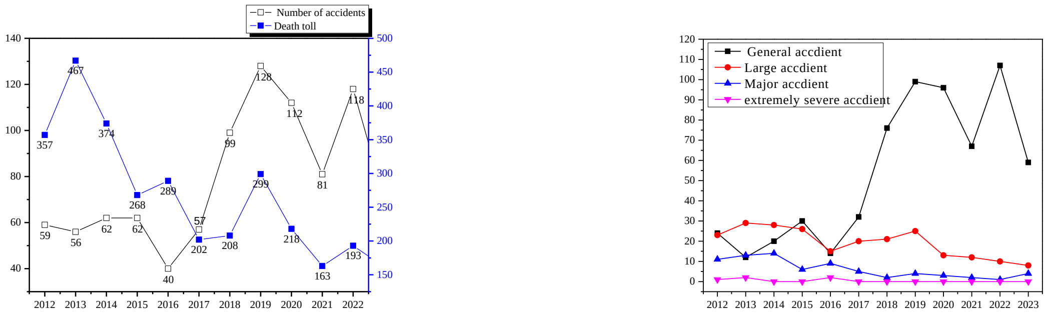
2.1. Year and level of accident

According to statistics, a total of 945 accidents occurred in coal mine accidents from 2012 to 2023, with 3,200 deaths. Among them, according to the “Regulations on Reporting, Investigation and Handling of Production Safety Accidents”, coal mine accidents are divided into four levels based on the number of fatalities. Three or less fatalities are classified as general accidents, and more than three or ten fatalities are classified as relatively serious accidents. A major accident is classified as a major accident if more than ten people are killed but less than 30 people are killed, and as a particularly serious accident if more than 30 people are killed. From 2012 to 2023, a total of 636 general accidents occurred, accounting for 68 %; 230 major accidents, accounting for 24 %; 74 major accidents, accounting for 7 %; 5 particularly major accidents, accounting for 1 %, specific statistics The results are shown in Table 1.

Table 1: The number of accidents in different accident grades from 2012 to 2023.

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	Total
General accident	24	12	20	30	14	32	76	99	96	67	107	59	636
large accident	23	29	28	26	15	20	21	25	13	12	10	8	230
Major accident	11	13	14	6	9	5	2	4	3	2	1	4	74
extremely severe accident	1	2	0	0	2	0	0	0	0	0	0	0	5

Based on the drawing in Table 1, the changing pattern of the number of coal mine accidents and deaths from 2012 to 2023 is obtained, as shown in Figure 1.



(a) Number of accidents and fatalities

(b) Accident level and number of accidents

Figure 1: The number of accidents and deaths in different years from 2012 to 2023.

As can be seen from Figure 1(a), the number of accidents in China shows a downward trend from 2012 to 2023, and the number of fatalities shows a downward trend, but with volatility. The number of accidents from 2016 to 2023 showed fluctuating characteristics. For example, there was an upward trend in 2017, then it began to decline in 2019, and it showed a fluctuating trend from 2020 to 2023. Although there were fewer accidents from 2012 to 2014, the death toll remained high. The number of deaths generally shows a downward trend. There were 4 rising points in the number of deaths in 2013, 2016, 2019 and 2022, which were respectively an increase of 31 % compared with 2012, an increase of 8 % compared with 2015, an increase of 44 % compared with 2018, and an increase of 44 % compared with 2021 up 18 %.

As can be seen from Figure 1(b) that from 2012 to 2023, the number of larger and larger accidents in China has shown a downward trend, while general accidents have shown an upward trend, and there are certain fluctuation characteristics. For example, there will be three rising points in general accidents in 2015, 2019 and 2022, which are 50 % higher than 2014, 30 % higher than 2018 and 60 % higher than 2021 respectively.

The above analysis results show that the technical specifications of coal mines have not been developed in the early years, and 2012 is also at the end of the "golden decade" of coal. The sharp drop in coal prices has forced many coal mines to increase mining productivity to protect corporate expenses, thus it caused many safety accidents and led to an increase in the death toll. With the country attaching great importance to and guiding the coal mining industry and the development of science and technology, the safety situation in coal mines is improving, and the number of larger and larger accidents has shown a downward trend. There have been no particularly major accidents from 2017 to 2023, but generally Accidents have fluctuating characteristics and show an upward trend. Therefore, China's coal mine safety is still facing a severe situation, and the prevention and control of accidents is still the top priority of China's safety production work.

2.2. Month of accident

According to statistics, the statistical results of monthly coal mine accidents from 2012 to 2023 are shown in Table 2.

Table 2: The number of accidents and deaths in different months from 2012 to 2023.

Month	1	2	3	4	5	6	7	8	9	10	11	12	Total
Number of accidents	61	47	93	85	96	82	100	82	78	84	74	63	945
Death toll	185	168	362	304	276	221	220	324	248	263	320	309	3200

According to the drawing in Table 2, the change pattern of the number of accidents and the number of fatalities in different months is obtained, as shown in Figure 2.

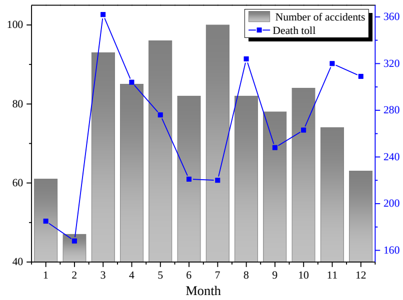


Figure 2: The number of accidents and deaths in different months from 2012 to 2023.

As can be seen from Figure 2, there are more accidents in March, May and July every year from 2012 to 2023; the number of fatalities is distributed in a "W" shape, reaching its peak in March, August and November every year. Among them, 93 accidents occurred in March, accounting for 10 %, 96 accidents occurred in May, accounting for 10 %, July had the largest number of accidents, 100, accounting for 11 %; March had the largest number of fatalities, accounting for 11 %. 362 people died, accounting for 11 %, a month-on-month increase of 115 %; 324 people died in August, accounting for 10 %, a month-on-month increase of 47 %; 320 people died in November, accounting for 10 %, a month-on-month increase of 22 %.

2.3. Accident time period

The statistical results of coal mine accidents in different periods from 2012 to 2023 (taking 2 hours as a period) are shown in Table 3.

Table 3: The number of accidents and deaths in different time per day from 2012 to 2023.

time period/2h	00:00-01:59	02:00-03:59	04:00-05:59	06:00-07:59	08:00-09:59	10:00-11:59	12:00-13:59	14:00-15:59	16:00-17:59	18:00-19:59	20:00-21:59	22:00-23:59
Number of accidents	71	70	60	47	81	113	87	79	95	75	93	74
Death toll	274	257	167	244	203	372	309	290	240	272	277	295

According to the drawing in Table 3, the changing patterns of the number of accidents and fatalities in different periods of time are obtained, as shown in Figure 3.

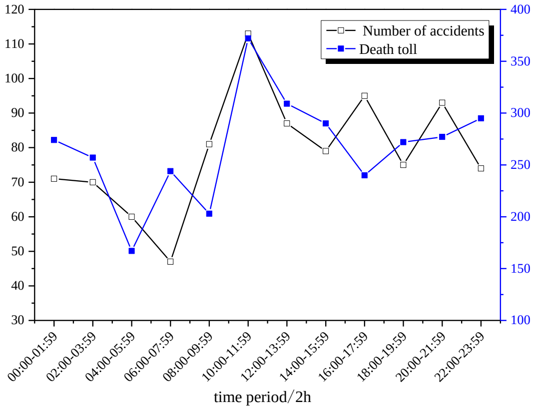


Figure 3: The number of accidents and deaths in different time per day from 2012 to 2023.

As can be seen from Figure 3, 10:00-11:59 every day is the period of high accident incidence. During this period, 113 accidents occurred, accounting for 12 %, and 372 people died, accounting for 12 %. The accident rate is higher and the number of fatalities is higher at noon and nighttime, both of which are higher than in the morning period. Among them, the number of accidents is lower during 00:00-03:59 and 06:00-07:59, but the number of fatalities is higher. The larger number indicates that larger and larger accidents are prone to occur during this period.

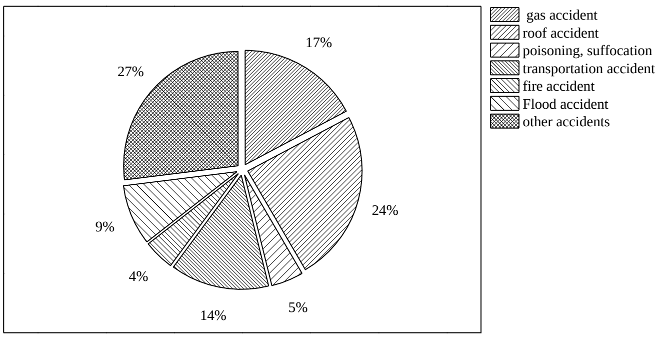
2.4. Accident type

The statistical results of coal mine accident types in China from 2012 to 2023 are shown in Table 4.

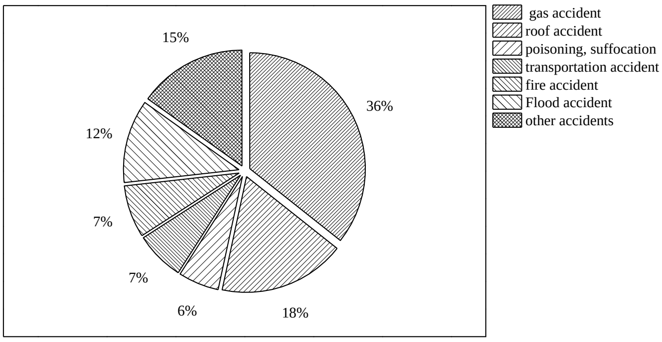
Table 4: The number of accidents and deaths in different accident types from 2012 to 2023.

Accident type	gas accident	roof accident	poisoning, suffocation	transportation accident	fire accident	Flood accident	other accidents	total
Number of accidents	163	230	43	132	41	81	255	874
Death toll	1141	567	182	219	234	372	485	3038

According to the drawing in Table 4, the changing patterns of the number of different types of accidents and the number of fatalities are obtained, as shown in Figure 4.



(a)Number of accidents



(b) Death toll

Figure 4: The number of different types of accidents and death toll from 2012 to 2023.

As can be seen from Figure 4, other accidents occurred the most from 2012 to 2023, with 255 accidents, accounting for 27 %, but the number of fatalities was 485, accounting for 15 %, indicating that the main accident level of this type of accident is general accidents; while gas the number of accidents was relatively small, 163, accounting for 17 %, but the number of fatalities was 1,141, accounting for 36 %, indicating that this type of accident is more serious. Roof accidents were the second largest accident type in terms of number of occurrences and fatalities, with 230 accidents occurring, accounting for 24 %, and 567 fatalities, accounting for 18 %. The number of fire, flood, poisoning, and suffocation accidents accounted for 4 %, 9 %, and 4 % respectively, but the average fatality rate per accident was about 6 people/case, 5 people/case, and 4 people/case.

2.5. Accident area

The statistical results of coal mine accidents in different regions of China from 2012 to 2023 are shown in Table 5.

Table 5: The number of accidents and deaths in different regions from 2012 to 2023.

province	Shanxi	Shaanxi	Inner Mongolia	Sichuan	Yunnan
Number of accidents	165	77	67	61	59
Death toll	392	190	152	218	190
	Guizhou	Gansu	Hunan	Heilongjiang	Henan
Number of accidents	65	44	45	37	41
Death toll	354	104	180	236	124
	Liaoning	Jiangxi	Anhui	Chongqing	Shandong
Number of accidents	38	38	37	27	27
Death toll	144	103	82	149	88
	Jilin	Ningxia	Autonomous Region	Hubei	Hebei
Number of accidents	20	22	18	17	15
Death toll	150	42	122	67	47
	Fujian	Guangxi	Qinghai	Jiangsu	Beijing
Number of accidents	11	9	3	1	1
Death toll	30	14	21	0	1

As can be seen from Table 5, between 2012 and 2023, 165 coal mine accidents occurred in Shanxi Province, accounting for 17 %, and 392 people died, accounting for 12 %; Guizhou Province had 354 coal mine accident deaths, accounting for 11 %, and the accidents. The number of accidents was 65, accounting for 7 %. Like Heilongjiang, Chongqing, Jilin, Autonomous Region, Qinghai and other provinces, they all showed the characteristics of fewer accidents and higher death tolls.

The reason for this serious regional difference is the uneven distribution of coal resources, and the existence of differentiating factors in different regions, such as different coal seam occurrence conditions, different coalfield geology, and underground gas content. The existence of these differentiating factors makes it difficult to mine coal resources in different provinces, resulting in different number of accidents and different severity of accidents.

3. Research on forecasting trend of coal mine accidents in China

Accident prediction methods mainly include 6 types: regression prediction method, time prediction method, Bayesian network prediction method, neural network prediction method, gray prediction method and Markov chain prediction method [15]. Among them, due to the random nature of accidents, regression prediction methods and time prediction methods are prone to large errors and poor prediction accuracy; Bayesian network prediction methods require knowledge of prior probabilities, and prior probabilities often depend on assumptions, but There can be many kinds of hypothetical models, so the prediction effect will be poor due to the hypothetical a priori model; the neural network prediction method does not have a good explanation for the reasoning process and reasoning basis, and the method is not mature yet. It needs further improvement and improvement; the gray prediction method is usually suitable for short-term prediction, and the prediction accuracy is poor for data with large data fluctuations and long-time spans; the Markov chain prediction method is usually suitable for the prediction of data with large random volatility. In order to overcome the above shortcomings, some scholars combined the Markov chain prediction method and the gray prediction method to construct a gray Markov prediction model, and carried out accident prediction research in the fields of energy, climate, underground engineering and other fields [16-22], and achieved good results. To this end, this article uses the gray Markov model to conduct research on coal mine accident prediction.

3.1. Gray Markov prediction model

(1) Gray GM (1,1) prediction model

The gray prediction model uses the original data series for generation processing to establish differential equations. It is a theory created to overcome the problems in time series prediction.

The original data is $x^{(0)}=\{x_1^{(0)},x_2^{(0)},\cdots,x_N^{(0)}\}$, Among them, N is the length of the sequence, which is accumulated and generated once.

$$x_k^{(0)}=\sum_{j=1}^{k}x_j^{(0)}\ (k=1,2,\cdots,N) \tag{1}$$

Generate the cumulative sequence $x^{(1)}=\{x_1^{(0)},x_2^{(0)},\cdots,x_N^{(0)}\}$ as the basis to establish a gray generative model.

$$\frac{dx^{(1)}}{dt}+ax^{(1)}=u \tag{2}$$

It is called the first-order gray differential equation, denoted as GM (1, 1). In the formula, a and u are the parameters to be identified.

Let the parameter vector be $\hat{a}=[au]^{\mathrm{T}}$, $y_N=\left[x_2^{(0)},x_3^{(0)},\cdots,x_N^{(0)}\right]^{\mathrm{T}}$

$$B=\begin{bmatrix} -\dfrac{\left(x_2^{(1)}+x_1^{(1)}\right)}{2} & 1 \\ \vdots & \vdots \\ -\dfrac{\left(x_N^{(1)}+x_{N-1}^{(1)}\right)}{2} & 1 \end{bmatrix}$$

The least squares solution is obtained from the following formula:

$$\hat{a}=\left(B^{\mathrm{T}}B\right)^{-1}B^{\mathrm{T}}y_N \tag{3}$$

The response equation is obtained:

$$\hat{x}_{k+1}^{(1)}=\left(x_1^{(1)}-\frac{u}{a}\right)e^{-ak}+\frac{u}{a} \tag{4}$$

In the formula, $x_1^{(1)}=x_1^{(0)}$.

The calculated value of $\hat{x}_{k+1}^{(1)}$ is reduced and restored to obtain the estimated value of the original data:

$$\hat{x}_{k+1}^{(0)}=\hat{x}_{k+1}^{(1)}-\hat{x}_k^{(1)} \tag{5}$$

(2) Gray Markov model

The gray Markov model is based on the predicted value of the gray GM (1, 1) model. The predicted value is compared with the actual value. The relative error obtained by dividing the residual by the true value is used as the basis to divide the predicted value into different states. This results in a correction value. This model is based on the gray GM (1, 1) model. In order to solve the problem of the low accuracy of the prediction value of the gray GM (1, 1) model, the prediction value of the gray GM (1, 1) model is corrected.

1) Status division

Use the gray GM (1, 1) model to obtain the predicted values of the number of general accidents, the number of larger and larger accidents, and the number of casualties. Difference them from the actual values to get the residuals. Divide the residuals by the real values to get the relative error of is used as the benchmark to divide the sequence into states, recorded as E_1, E_2, …, E_n. E_i = (φ_1, φ_2), Among them, *Ei is the i state of the system*, φ_1 and φ_2 are the upper and lower limits of the state interval respectively.

2) state transition probability

$$p_{ij(k)}=p_i\rightarrow p_j=\frac{E_{ij}}{E_i} \tag{6}$$

In the formula, E_{ij} is the number of one-step transitions from state *i* to *j*, and *Ei* is the number of states *i*.

According to the state division data, an $N\times N$ order state transition matrix is obtained:

$$p=p_{ij(k)}=\begin{bmatrix} p_{11} & \cdots & p_{1n} \\ \vdots & \ddots & \vdots \\ p_{n1} & \cdots & p_{nn} \end{bmatrix} \tag{7}$$

In the formula, p_{11} refers to the probability of data transitioning from state 1 to state 1 in one step.

3) Predicted value calculation

If the state of the initial value $x_N^{(0)}$ is E_i, and the element in the transition matrix p has the maximum probability value p_{in}, then the predicted value $x_{n+1}^{(0)}$ will likely transition to the state E_n, and the change interval of the predicted value (φ_1, φ_2) is determined, then it is obtained by the correction value of the gray prediction The gray Markov prediction value is:

$$Y_k = \frac{X^{(0)}}{1 \pm 0.5|\varphi_{1n} + \varphi_{2n}|} \tag{8}$$

In the formula, $X^{(0)}$ is the predicted value of the gray model, and $\varphi_{1n}, \varphi_{2n}$ is the boundary value of the state interval. When the predicted value is greater than the actual value, it takes a positive sign, and when it is less than the actual value, it takes a negative sign.

3.2. Research on coal mine accident prediction based on gray Markov model

As can be seen from Figure 1, the total number of accidents in China from 2012 to 2023 fluctuates greatly, and the prediction accuracy is low. In order to solve this problem, this article builds a model to predict general accidents and larger and larger accidents based on the statistical data in Table 1. The specific data is shown in Table 6.

Table 6: The number of general accidents and major and above accidents in coal mines from 2012 to 2023.

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
General accident	24	12	20	30	14	32	76	99	96	67	107	59
Number of major and above accidents	35	44	42	32	26	25	23	29	16	14	11	12

(1) Forecast of the number of coal mine safety accidents

1) Coal mine general accident prediction

Substituting the original number $x^0 = [24, 12, 20, 30, 32, 76, 99, 96, 67, 107, 59]$ into equations (1), (2), (3), and (4), the discrete response equation is obtained:

$$x_{k+1}^{(1)} = \left(24 + \frac{25.4063}{0.1229}\right) e^{0.1229k} - \frac{25.4063}{0.1229}$$

According to the cumulative reduction of equation (5), the predicted value of general accidents in coal mines is obtained, as shown in Table 7.

It can be seen from Table 7 that the relative error range between the gray prediction value and the actual value of general accidents in coal mines from 2012 to 2023 is (-2.07, 0.36), which is divided into 3 states: E_1= (-2.07, -0.70), E_2= (-0.70,0), E_3= (0,0.36).

Table 7: Grey Markov prediction results of coal mine accidents.

Year	Actual number of accidents	forecast result				Gray Markov prediction results
		Predict the number of accidents	error	Relative error	state	
2012	24	24	0	0.00	E2	24
2013	12	30	-18	-1.50	E1	13

2014	20	34	-14	-0.70	E1	25
2015	30	38	-8	-0.26	E2	28
2016	14	43	-29	-2.07	E1	18
2017	32	49	-17	-0.53	E2	36
2018	76	56	20	0.26	E3	68
2019	99	63	36	0.36	E3	77
2020	96	71	25	0.26	E3	87
2021	67	81	-14	-0.21	E2	68
2022	107	91	16	0.15	E3	110
2023	59	103	-44	-0.75	E1	76
2024		116				85
2025		132				55

According to the state of each year, it can be seen from equation (6) and equation (7) that the one-step transition probability matrix is:

$$p = \begin{bmatrix} \frac{1}{3} & \frac{2}{3} & 0 \\ \frac{1}{2} & 0 & \frac{1}{2} \\ \frac{1}{4} & \frac{1}{4} & \frac{1}{2} \end{bmatrix}$$

The predicted value of the number of general accidents in coal mines in 2012 is in E_2, and the predicted value of the number of general accidents in 2013 is most likely to be in the state of E_1. From equation (8), the number of general accidents in coal mines in 2013 Y (2013) = 13. In the same way, the gray prediction values in other years are corrected based on the one-step transition probability matrix, and the gray Markov model is used to predict general coal mine accidents in the future in 2024 and 2025. The final revised prediction results are shown in Table 7.

2) Prediction of larger and larger accidents in coal mines

Substituting the original data $x^0 = [35, 44, 42, 32, 26, 25, 23, 29, 16, 14, 11, 12]$ into equations (1), (2), (3), and (4), the discrete response equation is obtained:

$$x_{k+1}^{(1)} = \left(35 - \frac{51.8882}{0.1321}\right) e^{-0.1321k} + \frac{51.8882}{0.1321}$$

Table 8: Grey Markov prediction results of large coal mine accidents and above.

Year	Actual number of accidents	forecast result				Gray Markov prediction results
		Predict the number of accidents	error	Relative error	state	
2012	35	35	0	0.00	E2	35
2013	44	44	0	0.00	E2	44
2014	42	39	3	0.07	E3	39
2015	32	34	-2	-0.06	E1	30
2016	26	30	-4	-0.15	E1	27
2017	25	26	-1	-0.04	E2	23
2018	23	23	0	0.00	E2	23
2019	29	20	9	0.31	E3	24
2020	16	18	-2	-0.13	E1	16
2021	14	15	-1	-0.07	E1	13

2022	11	13	-2	-0.19	E1	12
2023	12	12	0	0.00	E2	11
2024		10				10
2025		9				9

According to the cumulative reduction of equation (5), the predicted values of larger and larger accidents in coal mines are obtained, as shown in Table 8.

It can be seen from Table 8 that the relative error range between the gray prediction value and the actual value of major and above accidents in coal mines from 2012 to 2023 is (-0.19, 0.31), which is divided into 3 states: E_1= (-0.19, -0.05), E_2= (-0.05,0.05), E_3= (0.05,0.31).

According to the state of each year, it can be seen from equation (6) and equation (7) that the one-step transition probability matrix is:

$$p = \begin{bmatrix} \frac{3}{5} & \frac{2}{5} & 0 \\ 0 & \frac{1}{2} & \frac{1}{2} \\ 1 & 0 & 0 \end{bmatrix}$$

Table 9: Coal mine accidents; the actual value and the predicted value.

Year	actual value	gray predicted value	Gray Markov prediction value
2012	59	59	59
2013	56	68	55
2014	62	67	61
2015	62	68	45
2016	40	71	46
2017	57	74	61
2018	99	81	102
2019	128	90	104
2020	112	102	111
2021	81	116	103
2022	118	134	107
2023	71	115	87
2024	-	126	95
2025	-	141	64

The predicted value of the number of major and higher accidents in coal mines in 2012 is in E_2, and the predicted value of the number of major and higher accidents in 2013 is most likely to be in the E_2 state. Therefore, the number of general accidents in coal mines in 2013 is Y (2013) = 44. In the same way, the gray prediction values of other years are revised according to the one-step transition probability matrix, and the gray Markov model is used to predict the number of major and above accidents in coal mines in the future in 2024 and 2025.

From Table 7 and Table 8, the predicted number of coal mine accidents from 2012 to 2025 can be seen in Table 9.

(2) Coal mine fatality forecast

Substituting the original number $x^0 = [357, 467, 374, 268, 289, 202, 208, 299, 218, 163, 193, 162]$ into equations (1), (2), (3), and (4), the discrete response equation is obtained:

$$x_{k+1}^{(1)} = \left(357 - \frac{460.3169}{0.1001}\right)e^{-0.1001k} + \frac{460.3169}{0.1001}$$

According to the cumulative reduction of equation (5), the predicted value of the number of fatalities in coal mines is obtained, as shown in Table 10.

Table 10: Grey Markov prediction results of death toll in coal mines.

Year	Actual number of accidents	forecast result				Gray Markov prediction results
		Predict the number of accidents	error	Relative error	state	
2012	357	357	0	0.00	E2	357
2013	467	404	63	0.13	E3	462
2014	374	366	8	0.02	E2	367
2015	268	331	-63	-0.24	E1	270
2016	289	299	-10	-0.03	E2	256
2017	202	271	-69	-0.34	E1	221
2018	208	245	-37	-0.18	E1	209
2019	299	222	77	0.26	E3	268
2020	218	200	18	0.08	E2	201
2021	163	181	-18	-0.11	E1	148
2022	193	164	29	0.15	E3	197
2023	162	148	14	0.09	E3	149
2024		134				133
2025		121				99

It can be seen from Table 10 that the relative error range between the gray prediction value and the actual value of coal mine fatalities from 2012 to 2023 is (-0.34, 0.26), which is divided into 3 states: E_1=(-0.34,-0.11), E_2=(-0.11,0.08), E_3=(0.08,0.26).

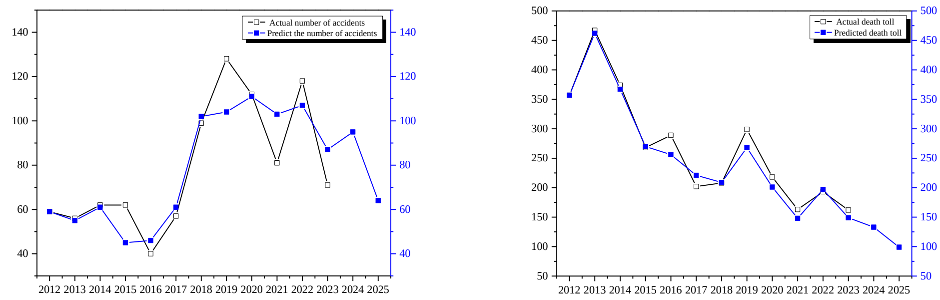
According to the state of each year, it can be seen from equation (6) and equation (7) that the one-step transition probability matrix is:

$$p = \begin{bmatrix} \frac{1}{4} & \frac{1}{4} & \frac{1}{2} \\ \frac{3}{4} & 0 & \frac{1}{4} \\ 0 & \frac{2}{3} & \frac{1}{3} \end{bmatrix}$$

The predicted value of coal mine fatalities in 2012 is in the E_2 state, and the predicted value of fatalities in 2013 is most likely to be in the E_1 state. Therefore, the number of coal mine fatalities in 2013 Y (2013) = 462. In the same way, according to the one-step transition probability matrix the gray prediction values in other years are revised, and the gray Markov model is used to predict the number of coal mine deaths in the future in 2024 and 2025. The final revised prediction results are shown in Table 10.

(3) Data inspection

From Table 9 and Table 10, we can obtain the curve characteristics of the actual number of accidents and fatalities and the predicted number of accidents and fatalities in China from 2012 to 2023, as shown in Figure 5.



(a) Actual vs. predicted number of accidents (b) Actual vs. predicted deaths

Figure 5: Changes in the actual and predicted number of accidents and fatalities in coal mines from 2012 to 2023.

As can be seen from Figure 5, China's actual and predicted accident number and fatality curves from 2012 to 2023 are generally consistent, but there are some fluctuation points, such as 2019 and 2021. This is because the occurrence of accidents is random and may rise or fall significantly at a certain point in time. The gray Markov prediction model mainly calculates based on the one-step transition probability of the data in the time span, so it will there are data discrepancies, but the bending trend of the predicted curve and the actual curve are almost consistent. The gray Markov model is used to predict the number of general accidents, the number of larger and larger accidents, and the number of fatalities in 2024 and 2025. The prediction results are in line with the downward trend in the number of general accidents, the downward trend in the number of larger and larger accidents, the overall downward trend in the number of accidents, and the downward trend in the number of fatalities.

4. Conclusion

(1) The country attaches great importance to coal mine safety. Due to the improvement of regulations, production safety management and technological development, the safety situation has improved, but general accidents still occur frequently and there is volatility.

(2) Production needs to focus on the months and periods with high accident incidence, such as March, July, August, November and the 10:00-13:59 period. Supervision needs to be strengthened and plans formulated in advance.

(3) The incidence and fatality rates of gas and roof accidents are high, and mine floods, fires, poisoning, and suffocation accidents are very harmful.

(4) There are significant differences in the number and grade of accidents in different regions. For example, Guizhou Province has fewer accidents, but the local geological conditions are more complex and the accidents are more harmful, so management needs to be managed in a manner adapted to local conditions.

(5) Through accident trend prediction research, the occurrence of accidents and deaths in coal mines in China is on a downward trend, but with volatility and twists and turns. In 2024, it is predicted that 95 accidents will occur and 133 people will die. General accidents may occur at a high rate, and precautions need to be taken.

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