Study on hidden danger investigation and impact assessment method for earthquake-induced secondary disasters in coal mines

QI Qingjie\textsuperscript{1}, LIU Wengang\textsuperscript{1}, WANG Anhu\textsuperscript{1}, SUN Zuo\textsuperscript{1}, YANG Jinghu\textsuperscript{1}, LIU Siyun\textsuperscript{1}, LIU Yingjie\textsuperscript{1}

(1. Emergency science research institute, China Coal Research Institute, Beijing 100013, China;)

Correspondence should be addressed to WANG Anhu; E-mail: qiulm@ustb.edu.cn

ORCID ID: https://orcid.org/0000-0002-1950-7835

Abstract: Mining is one of the key production industries that involves hazardous operations and various safety risks, and is prone to being seriously affected by earthquake disasters and secondary disasters. Indeed, following a number of earthquakes, including the Tangshan and Wenchuan earthquakes, serious secondary disasters, such as tunnel engineering damage and the rapid increase of water inflow, occurred, resulting in varying degrees of casualties and economic losses. In this study, with the problem of the lack of investigation and impact assessment methods for earthquake-induced secondary disasters in coal mines, an appropriate investigation system was designed based on the theories of earthquake disaster science, safety engineering, and system science while considering the mine lifeline system as the main line. Based on the analysis methods for fault type, effect analysis, and multi-index synthesis, a comprehensive evaluation method for the impact of earthquake-induced secondary disasters in coal mines was proposed. The method involves the following steps. First, according to the historical information on regional earthquake disasters, the situation of mine earthquake disaster fortification, and the risk of earthquake disasters, the possibility of earthquake-induced secondary disasters in coal mines is evaluated according to the complexity of mine occurrence conditions. Second, the severity of the consequences of secondary disasters induced by an earthquake is evaluated in terms of three aspects: casualties, economic losses, and disaster prevention and mitigation ability. Finally, the risk grade of the secondary disasters induced by the earthquake is determined by constructing a risk grade matrix of a mine disaster bearing body. The evaluation method covers numerous factors, including the current situation in terms of pre-disaster preparedness, the level of the earthquake disaster, and the ability of the post-disaster management to offer emergency disaster reduction and relief, thus achieving full coverage of all the key influencing factors before, during, and after the disaster. Using the proposed evaluation method, the quantitative expression of the impact assessment of earthquake-induced secondary
disasters in coal mines was realized, which provides a reference for the quantitative assessment of the impact of earthquake disasters on the coal mining industry.

**Keywords:** Earthquake; coal mine; secondary disaster; hidden danger investigation; evaluation method.

1. **Introduction**

With China’s social development entering a new era, the demand for safety levels associated with a better life has led to more stringent safety requirements [1]. On October 10, 2018, General Secretary Xi personally deployed nine key projects of natural disaster prevention and capacity improvement at the third meeting of the Central Financial and Economic Affairs Commission. Among them, the first project involves natural disaster risk investigation and key hidden danger investigation, and addresses the basic number of hidden dangers associated with natural disaster risk [2]. Notably, earthquakes are regarded as being the foremost natural disaster due to their sudden and huge destructive power, the disastrous consequences, and the long-term impact [3,4]. China is also one of the countries suffering from the most serious earthquake disasters in the world.

Coal mining is one of the production industries that has been seriously affected by earthquake disasters. In 1976, the Tangshan earthquake, which measured 7.28 on the Richter scale, caused varying degrees of damage to the underground engineering of the Kailuan coal mine, with the mine water inflow increasing significantly [5,6]. Meanwhile, the 5.12-magnitude Wenchuan earthquake that occurred in 2008 caused a sharp increase in the mine water inflow of the Sichuan coal group [7]. After more than eight earthquakes, including the Izu Islands earthquake of 1903, the Nevada earthquake of 1932, and the Southern California earthquake of 1952, the mines in the epicentral region of strong earthquakes and those in the cross-cutting earthquake action zones suffered serious damage [8] including support damage, roof collapse, shaft wall collapse, and mine flooding. In terms of the theoretical research on earthquake-induced secondary disasters in coal mines, Chen and Zheng [9,10] studied the temporal and spatial distribution characteristics of coal mine disasters and seismicity in China, and revealed that the cluster occurrence of coal mine disasters and seismicity are the basic characteristics of the attendant temporal and spatial distribution. Elsewhere, Xie Xiaojian [11] studied the relationship between seismicity and coal mine disasters and accidents and concluded that the seismicity can control these events to a certain extent, and that the influence range of the seismicity on coal mine accidents is more than that pertaining to ground losses. Meanwhile, Cai et al. [12] proposed the nucleation mechanism of coal mine gas disasters induced by earthquakes and deemed that the earthquake energy has the possibility of causing the nucleation of coal mine gas disasters, while an active structure, such as a channel of energy transfer, is required between the earthquake epicenter and the gas mine. The code for the seismic design of buildings (GB 50011-2010) [13] regulates the seismic design requirements of sites, industrial plants, houses, etc., while the specific code for the seismic design of coal mines (GB 51185-2016) [14] specifies the seismic design requirements for mines and coal preparation plants.

Hidden danger investigation and the related treatment present one of the most important means to improving the basic security level [15,16]. On April 1, 2020, the work safety committee of the State Council called for the modernization of the coal mine safety governance system and governance capacity, implementing and enhancing the responsibility and management system with a focus on the “fundamental elimination of potential accidents.” Elsewhere, Professor Li Shuang of the China University of mining and technology [17] proposed promoting the construction of a dual prevention mechanism based on the viewpoints of various government supervision departments, coal mine leaders, mechanism construction personnel, and coal mine practitioners, with the aim of achieving the goal of “preventing risks, eliminating hidden dangers, and containing accidents.” Meanwhile, Wang [18] proposed a dual prevention mechanism covering the investigation and treatment of hidden dangers.
according to the production characteristics of coal mines, and proposed specific countermeasures for the investigation and treatment of hidden dangers.

An objective risk assessment of an earthquake disaster is the starting point of the prevention and control of any secondary disasters induced by the earthquake. In the 1990s, the Federal Emergency Office and the National Institute of Building Sciences in the U.S. jointly developed the Hazus system for earthquake disaster losses.[10] Meanwhile, in Japan, the administrative agencies of the central government have the responsibility of assessing the earthquake disaster losses, including in terms of rivers, roads, forestry and fishery facilities, educational facilities, health and welfare facilities, and other public facilities.[20] In Australia, a disaster assessment tool has been devised to assess the direct and indirect economic losses,[21] while in Italy, a three-stage evaluation has been implemented, which includes earthquake simulation and emergency evaluation achieved within a few minutes after the earthquake hits and a dynamic evaluation achieved within 10 min to 2 h. Moreover, the investigation and evaluation of any personnel arriving at the earthquake site is carried out.[22]

Clearly then, both domestic and foreign experts and scholars have devoted extensive research efforts to studying earthquake disaster assessments. However, the majority of the secondary disasters induced by the earthquake remain at the level of phenomenon statistics, while the hidden danger investigation and hazard assessment of earthquake-induced secondary disasters in coal mines have not been systematically explored, a lack that must be addressed. Therefore, in this study, a hidden danger investigation system of earthquake-induced secondary disasters in coal mines was proposed and constructed based on the theories of earthquake disaster science, safety engineering, and system science while considering the mine lifeline system as the main line. Furthermore, a comprehensive method for the evaluation of the impact of earthquake-induced secondary disasters in coal mines was proposed based on fault-type analysis, effect analysis, and comprehensive multi-index analysis.

2. Investigation contents and index system of hidden danger of secondary disasters induced by earthquakes

2.1. Investigation contents

After the occurrence of an earthquake disaster, the earthquake action causes changes in the stress environment and the natural environment in the area where the coal mine is located. This results in the structural damage or destruction of the disaster bearing body of the coal mine, thus inducing various types of secondary disasters. Here the more serious secondary disasters include earthquake-induced secondary mine water disasters, earthquake-induced secondary gas disasters, earthquake-induced secondary rock burst disasters, earthquake-induced secondary electrical accidents, and earthquake-induced secondary hoist and transportation accidents, all of which can result in casualties and equipment damage.

The investigation into the hidden danger of secondary disasters induced by earthquakes in coal mines is mainly aimed at the disaster bearing body, the ground engineering, the shaft engineering, the hoisting system, the ventilation system, the water supply and drainage system, the power supply and distribution system, the communication system, and the rescue and fire-fighting facilities. Meanwhile, various auxiliary facilities (e.g., the compressed-air station used for the emergency rescue system) constitute important lifeline projects in coal mines [23], and are also the main disaster bearing bodies for the resistance to earthquake forces. Whether or not potential safety hazards occur in the secondary disaster bearing body of the coal mine determines the anti-seismic capacity of the mine. If there is no hidden danger in the disaster bearing body of the mine, the possibility of secondary disasters will be low following an earthquake, and even if a secondary disaster does occur, the degree of impact is expected to be small. However, if there are many hidden dangers associated with earthquake-induced secondary disasters and the disaster bearing bodies do not meet the seismic requirements, the possibility of secondary disasters will be high following an earthquake, and the impact is expected to be greater, which is not conducive to the development of post-disaster emergency rescue work and the
recovery of the production work \[24\]. The main disaster bearing bodies of secondary disasters induced by earthquakes are shown in Figure 1.

![Diagram showing coal mine areas and facilities](image)

1. Coal mine surface engineering facilities, 2. mine rescue and fire-fighting facilities, 3. coal mine power supply system, 4. coal mine hoisting system, 5. shaft support, 6. main drainage system 7. personnel instructions, 8. communication system, 9 fan station

Figure 1. Distribution diagram of main disaster bearing bodies of coal mine secondary disasters induced by earthquakes

The hidden dangers related to the main disaster bearing bodies in coal mines are as follows:

1. **Hidden danger of earthquake resistance in surface engineering of coal mine construction.** Coal mine construction is mostly carried out in mountainous areas or areas adjacent to goaf collapse areas. Collapsed mines and waste piles, landslide areas, debris flow, and further collapse of the goaf collapse areas can easily occur under the action of earthquake force, which will seriously affect the safety of the engineering facilities in the coal mine construction site. Therefore, if the surface engineering is close to a poor geological body, this presents a hidden danger.

2. **The hidden danger of underground engineering earthquake resistance.** Shaft damage and abnormal water inflow occur more commonly following earthquakes. Notably, an enhancement of the structural strength of the shallow shaft wall and the anti-disaster drainage capacity of the main drainage of the mine are crucial to reducing the damage caused by an earthquake disaster, providing valuable time for personnel evacuation and disaster resistance following the earthquake and creating the conditions for rapid production recovery. Therefore, an insufficient mine shaft support strength and an insufficient main drainage capacity pertain to the area of underground engineering seismic risk.

3. **Seismic hazard of mine hoisting and ventilation system.** Ensuring the normal operation of the disaster bearing body of the hoisting and ventilation system following an earthquake is a crucial condition for guaranteeing the safety of the coal miners. During an earthquake, the lifting machine room, the ventilation machine room, and the various cranes are prone to damage, and this presents the hidden danger of equipment damage and casualties. Here, the mine hoisting ventilation system cannot operate normally following the earthquake, and the cranes are not equipped with fall-prevention facilities, all potential seismic hazards of the disaster bearing body.

4. **Hidden danger of mine water supply and drainage system and their resistance to earthquakes.** The water supply and drainage system can provide services for disaster reduction and post-earthquake relief. Surface subsidence is easily caused by coal mining operations, and the subsidence will become serious when encountering the impact of an earthquake, which will lead to an increase in the damage to the water supply and drainage pipelines. It is thus crucial to maintain two or more water supply lines and to guarantee the provision of drinking water for the recovery following an earthquake-induced coal mine disaster.

5. **Seismic hidden danger of important power facilities.** The power facilities are the lifeline of a mine. The seismic measures should be strengthened during the structural construction and the
installation of the power supply and distribution system to create good conditions for post-disaster recovery. Following an earthquake, an abnormal increase in gas and coal dust in the mine is highly likely. However, the use of explosion-proof (or intrinsically safe) electrical equipment can reduce the possibility of secondary disasters, such as gas and coal dust explosions.

(6) **Seismic hazard of the communication system.** The communication system includes the communication center and the dispatch and monitoring center. Mine information is one of the necessary conditions for high-yield and efficient modern mine construction. The communication system is conducive to the implementation of post-earthquake rescue operations. The dispatch and monitoring center is the core brain of the mine information system, which is set independently to facilitate earthquake fortification and post-earthquake recovery. In the case of the paralysis of the main means of communication following an earthquake, communicating with the periphery via alternative means is crucial to understanding the disaster situation, shortening the rescue time, and reducing the number of losses.

(7) **Hidden danger associated with mine rescue and fire-fighting facilities and their resistance to earthquakes.** The mine rescue and fire-fighting facilities include the rescue team, the rescue garage, various complex buildings, and the auxiliary fire-fighting facilities (e.g., the compressed-air station used for the emergency rescue system), which play an important role in the process of post-earthquake disaster relief and are of great significance to the organization and implementation of post-disaster emergency rescue and production recovery operations.

### 2.2. The Index system

The investigation of the hidden dangers of secondary disasters induced by earthquakes provides the basis for improving the seismic fortification capacity of coal mines, providing guidance for accurately improving the seismic level of the mines. Therefore, in this study, an investigation system for earthquake-induced secondary disasters in coal mines was constructed. The construction of the investigation system was based on the following principles: (1) focusing on the mine lifeline system, which is conducive to rapid rescue and recovery operations following an earthquake; (2) preventing the occurrence of serious secondary earthquake disasters such as inundation, fire, and explosions during an earthquake; and (3) ensuring the safety of the mine escape passage and the attendant water, electricity, and ventilation facilities. The hidden danger investigation system of coal mine secondary disasters induced by earthquakes incorporates two main facets: basic information on coal mine earthquake disaster prevention and the control and main disaster bearing body of the mine lifeline. Here, the basic information covers five aspects: spatial location, mine economic information, personnel information, disaster prevention and mitigation capacity, and historical disaster information, while the main disaster bearing bodies of the mine lifeline include the industrial site, the coal preparation plant, the water supply system, the power supply and distribution system, the shaft support, the mine safety exits, the ventilation system, the gas storage system, the hoisting system, the main drainage system, and a further 10 aspects. The main investigation key indicators related to the above-stated contents are listed in Table 1.

Table 1. Basic information on earthquake disaster and key indicators of hidden dangers in the mine lifeline disaster bearing body

| Serial number | First level indicators | Secondary indicators                        | Third level indicators                                                                 |
|---------------|------------------------|---------------------------------------------|----------------------------------------------------------------------------------------|
| 1             | Basic information      | Spatial location                            | Coal mine location, coal mine main shaft coordinates, coal mine area, etc.             |
| 2             |                        | Mine economic information                   | Net value of fixed assets, annual output, etc.                                        |
| 3             |                        | Personnel information                       | The number of mine personnel, single shift staff, safety management personnel, etc.    |
| 4             |                        | The ability of fortification and disaster    | Mine rescue team category, number of mine rescue team personnel, etc.                  |
|               |                        | reduction                                   |                                                                                         |
3. Evaluation method for earthquake-induced secondary disasters in coal mines

According to the objective development process of disasters, the impact assessment methods of earthquake-induced secondary disasters in coal mines can be divided into the following three types: pre-disaster assessment, disaster period tracking or monitoring assessment, and post-disaster actual measurement assessment. Here, the pre-disaster assessment is the key to improving the prevention and control of earthquake-induced secondary disasters in coal mines [25], and three key factors must be included in this assessment. The first relates to the possible intensity and frequency of future disasters, the second relates to the determination of the disaster degree and disaster rate in the history of the region, and the third relates to the investigation of the population density and the disaster prevention and mitigation capacity. Based on the vulnerability assessment of the disaster bearing body, this study integrates specific key indicators, including the possibility level of earthquake occurrence, the population in the affected area after the disaster, the possible economic loss, and the disaster resistance and reduction capacity, further extending the risk assessment of earthquake-induced secondary disasters in coal mines through a possibility assessment and a consequence severity assessment.

3.1. Possibility assessment

Based on the theories of earthquake disaster science, safety engineering, and system science [26, 27], the possibility assessment index system of coal mine disasters induced by earthquakes was constructed. Here, the main factors include the historical information on earthquake disasters in coal mines \(L_1\), the standard situation of earthquake disaster bearing bodies \(L_2\), the possible occurrence level of earthquake disasters \(L_3\), and the complexity of coal mine occurrence conditions \(L_0\). Each factor can be divided into the following four levels: almost impossible, less likely, more likely, and most likely.
with values of 1, 2, 3, and 4, respectively. Therefore, the calculation formula for the possibility level value is as follows:

\[ L = \sum (k_i \cdot L_i) \quad (i = 1, 2, 3, 4) \quad (1) \]

where \( L \) is the occurrence possibility level value (the higher the value, the greater the possibility) and \( k_i \) is the weight value of each factor. Here, the weight value of the historical information on earthquake disasters is \( k_1 \), the weight value of the standard situation of earthquake disaster bearing bodies is \( k_2 \), the weight value of the possible occurrence level of earthquake disasters is \( k_3 \), and the weight value of the complexity of coal mine occurrence conditions is \( k_4 \):

\[ k_1 + k_2 + k_3 + k_4 = 1 \quad (2) \]

Finally, \( L_i \) is the value assigned to each factor considered in the possibility assessment.

The historical information on coal mine earthquake disasters (\( L_1 \)) mainly includes the disaster degree and disaster rate in the area where the coal mine is located. Specifically, this includes the frequency of earthquake disaster activity and the number of disaster activities within a specific unit of time, mainly reflecting the activity degree of certain sudden disasters. In general, if the frequency of disasters is historically high, the possibility of further disasters will also be high. Based on the statistics of the frequency of secondary disasters in coal mines affected by earthquake disasters, the grade judgment standard for assessing the possibility of occurrence based on the occurrence times of historical disasters in coal mines was determined, as presented in Table 2.

Meanwhile, \( L_2 \) relates to the vulnerability assessment of the lifeline systems, which include the industrial site, the coal preparation plant, the water supply system, the power supply and distribution system, the shaft support, the safety exits, the ventilation system, the gas storage system, the hoisting system, and the main drainage system. In general, if there are fewer substandard items, the possibility of secondary disasters will be lower. Based on the statistics of the frequency of secondary disasters in coal mines affected by earthquake disasters, the judgment standard of the occurrence possibility level was determined herein according to the standard situation of the earthquake disaster bearing body, as presented in detail in Table 2.

The possible occurrence level of earthquake disasters (\( L_3 \)) was largely evaluated according to the regional seismic fortification intensity in the area where the coal mine is located. If the fortification intensity is high, the possibility of the earthquake occurrence level will be higher. Through the statistical division of the national seismic fortification intensity, the judgment standard for determining the earthquake occurrence possibility level based on the seismic fortification intensity was determined herein, as presented in detail in Table 2.

The complexity of coal seam occurrence conditions (\( L_4 \)) mainly includes the following four factors: hydrogeological type, coal mine gas grade, coal mine impact risk grade, and coal seam spontaneous combustion grade. Here, the more complex the occurrence conditions of the coal seam, the greater the risk of secondary disasters, and the higher the possibility of occurrence. Based on the statistical division of coal seam occurrence conditions, the judgment standard of earthquake occurrence possibility grade value based on coal seam occurrence conditions was determined, as summarized in Table 2.

| Index | Weight value | Interpretation | Classification | Possibility | Assignment |
|-------|--------------|----------------|----------------|-------------|------------|
| Historical Information of Coal Mine Earthquake Disaster (\( L_1 \)) | \( k_1 \) | The grade value is obtained from the historical occurrence times of coal mine earthquake disaster. | Three times or more since the construction of mine | Probably | 4 |
| | | | It happened twice since the construction of mine | More likely | 3 |
It happened once since the construction of mine  Less likely  2
Never happened since the construction of mine  Almost impossible  1

| Standard Situation of Natural Disaster Fortification ($L_2$) | $k_2$ | The grade value is obtained from the standard situation of earthquake disaster prevention in coal mine. |
| --- | --- | --- |
| Eight or more non-standard items | Probably | 4 |
| 4–7 substandard items | More likely | 3 |
| 1–3 substandard items | Less likely | 2 |
| All fortifications are up to standard | Almost impossible | 1 |

| Earthquake Disaster Risk ($L_3$) | $k_3$ | From the seismic intensity of the area where the coal mine is located, the seismic hazard grade value of the coal mine is obtained. |
| --- | --- | --- |
| Nine degrees and above | Probably | 4 |
| Eight degrees | More likely | 3 |
| Seven degrees | Less likely | 2 |
| 6 degrees | Almost impossible | 1 |

| Complexity of Coal Mine Occurrence Conditions ($L_4$) | $k_4$ | The grade value is obtained from the complexity of coal mine occurrence conditions. |
| --- | --- | --- |
| The hydrogeological type is very complex coal mine or rock burst coal mine or coal and gas outburst coal mine; | Probably | 4 |
| The hydrogeological type is complex coal mine or coal mine with mining depth more than 800 m or high, gas coal mine or coal mine with serious spontaneous combustion (class I) | More likely | 3 |
| The hydrogeological type is medium coal mine or coal mine with mining depth of 400–800 m or spontaneous combustion medium (class II) coal mine; | Less likely | 2 |
| The hydrogeological type is simple coal mine or coal mine with mining depth less than 400 m or low gas coal mine or coal mine not easy to undergo spontaneous combustion (Class III); | Almost impossible | 1 |

3.2. Consequence severity assessment

The consequence severity index ($S$) of coal mine secondary disasters induced by earthquakes was constructed as an index to evaluate the severity of the consequences of the disaster. The consequence severity index is calculated and generated according to the number of casualties ($S_1$), the economic losses ($S_2$), and the disaster prevention and mitigation capacity ($S_3$). Each factor can be divided into four grades from low to high: small, commonly, large, and great.[28,29] The calculation formula for the consequence severity level value is as follows:

$$S = \sum (k_i \cdot S_i) \ (i = 1, 2, 3) \ (3)$$
where $S$ is the consequence severity grade value and $k_i$ is the weight value of each factor. Here, the weight value of casualties is $k_1$, the weight value of possible economic losses is $k_2$, and the weight value of the disaster prevention and reduction capacity is $k_3$.

$$k_1 + k_2 + k_3 = 1. \ (4)$$

Finally, $S_i$ is the value assigned to each factor considered in consequence severity assessment.

The number of casualties ($S_1$) that may be caused by secondary disasters specifically refers to the number of potential casualties due to the impact of earthquake disasters in coal mines. The higher the number of potential casualties, the greater the severity of the consequences. Referring to the classification standard of production safety accidents and fully considering the influence of the regional concentration of coal mine operators, the judgment standard of the secondary disaster consequence severity based on the number of possible casualties was determined, as presented in detail in Table 3.

The possible economic loss ($S_2$) specifically refers to the cost of the post-treatment operations and the costs related to the damaged property due to the earthquake disaster. The higher the possible economic losses, the greater the severity of the consequences, i.e., the higher the severity level of the consequences. Referring to the classification standard of production safety accidents and fully considering the general status of the fixed assets in the coal mines, the grade judgment standard for assessing the severity of secondary disaster consequences based on possible economic losses was determined, as presented in detail in Table 3.

The disaster prevention and reduction capacity ($S_3$) is specifically related to the emergency response capacity and the emergency rehabilitation capacity. The higher the ratio of healthcare and rescue workers to the total workforce, the stronger the emergency response and aftermath capacity, and the lower the severity level. The specific judgment criteria are summarized in Table 3.

### Table 3. Evaluation table of consequence severity level

| Index                                      | Weight value | Interpretation                                                                 | Classification       | Seriousness | Assignment |
|--------------------------------------------|--------------|--------------------------------------------------------------------------------|----------------------|-------------|------------|
| Casualties ($S_1$)                         | $k_1$        | The number of casualties that may be caused by natural disasters.              | [100, $\infty$)     | great       | 4          |
|                                            |              |                                                                                | [50, 99]             | large       | 3          |
|                                            |              |                                                                                | [10, 49]             | commonly    | 2          |
|                                            |              |                                                                                | [0, 10]              | Small       | 1          |
| Economic Loss ($S_2$)/million              | $k_2$        | Personal injury and death caused by natural disaster, the cost of aftercare and the value of damaged property. | [100, $\infty$)     | great       | 4          |
|                                            |              |                                                                                | [50, 100]            | large       | 3          |
|                                            |              |                                                                                | [10, 50]             | commonly    | 2          |
|                                            |              |                                                                                | [0, 10]              | Small       | 1          |
| Disaster Prevention and Mitigation Capacity ($S_3$) | $k_3$     | The ratio of health care and rescue workers to the total workforce             | [0, 0.5%)           | great       | 4          |
|                                            |              |                                                                                | [0.5%, 5%)           | large       | 3          |
|                                            |              |                                                                                | [5%, 10%)            | commonly    | 2          |
|                                            |              |                                                                                | [10%, 1)             | Small       | 1          |

### 3.3. Hazard level
According to the assessment results, the hazards can be divided into the following four levels: general (Level IV), large (Level III), major (Level II), and particularly significant (Level I), as presented in Table 4.

| Hazard level | Occurrence Possibility Level Value |
|--------------|------------------------------------|
| [1, 1.5]     | [1.5, 2.5]                        |
| [2.5, 3.5]   | [3.5, 4]                           |

Table 4. Hazard level matrix

| Hazard level | Consequence Severity Level Value |
|--------------|----------------------------------|
| [1, 1.5]     | [1.5, 2.5] [2.5, 3.5] [3.5, 4]   |
| General (IV) | General (IV) Large (III) Large (III) |
| [1.5, 2.5]   | [2.5, 3.5] [3.5, 4]               |
| General (IV) | Large (III) Large (III) Major (II) |
| [2.5, 3.5]   | [3.5, 4]                           |
| Large (III)  | Large (III) Major (II) Particularly significant (I) |
| [3.5, 4]     | [3.5, 4]                           |
| Large (III)  | Major (II) Particularly significant (I) Particularly significant (I) |

4. Application and Verification

4.1. Seismic geological environment
Based on the method of investigation and impact assessment of earthquake-induced secondary disasters in coal mines, all the coal mines in a city of Guizhou Province were systematically investigated and evaluated. The investigation of the geological structure of the city indicated that the geological structure of the city is complex, while it lies adjacent to the east side of the south end of the North–South seismic belt, and is located in the east Sichuan fault block uplift area and the north central Guizhou to east Chongqing medium strong uplift area. Since 2010, there have been two major earthquakes in the city area, with an earthquake with a magnitude of 3.1 and a focal depth of 7 km occurring on June 26, 2015, and an earthquake with a magnitude of 2.8 and a focal depth of 7 km occurring on February 17, 2014. The magnitude of the two earthquakes was small, the impact on the coal mine was small, and no secondary disasters occurred. The geological environment in this area is fragile, and the geological disasters tend to be hidden, sudden, and damaging. There are 1,425 potential geological disaster spots, which are wide and prone to occur, and the prevention task is heavy. When extreme natural disasters and climatic conditions such as earthquakes and short-term heavy rainfall are encountered, geological disasters are easily induced, which can cause massive and sudden landslides, collapses, ground collapses, and debris flow. Among them, landslides account for a large proportion of the secondary disasters.

4.2. Investigation results
Through the investigation of 29 normal production coal mines in this area, a total of 69 hidden dangers were identified. These hidden dangers were mainly distributed in the power supply and distribution system, the water supply system, the shaft support, the mines’ main drainage system, and the coal preparation plant. The distribution proportion of hidden dangers in each system is shown in Figure 2, while the proportion of coal mines with hidden dangers in the system is shown in Figure 3.
The data presented in Figure 2 indicated that among the 69 hidden dangers identified, the number of hidden dangers in the power supply and distribution system accounted for 38.46%, while those in the water supply system accounted for 32.69%, a total of 71.15%. Meanwhile, the number of hidden dangers in the industrial sites, coal preparation plants, mine safety exits, mine ventilation systems, mine gas storage systems, and mine hoisting systems was small. However, the coal mine power supply line (cable) path of the power supply and distribution system and substations of 35 kV and above do not avoid the geological impact. The water supply system is mainly drinking water, with the water source a single source, and the surface water pipeline path is within the mining ground subsidence area.

The data presented in Figure 3 indicated that among the 29 coal mines involved in the survey, 15 had hidden dangers in the power supply and distribution system, accounting for more than half of the total (51.72%). Meanwhile, eight coal mines had a single source of drinking water, while the path of the surface water pipeline is within the mining subsidence area, with the overall number of coal mines here accounting for 27.59%. Thus, the power supply and distribution system and the water supply system present the weak link of seismic fortification in this area, which is closely related to the geological environment.

4.3. Assessment results of hazard level

Using the secondary disaster assessment method of earthquake-induced coal mine disasters proposed in this paper, the seismic disaster risk level was assessed using 29 normal production coal mines in the region. Here, the seismic disaster risk level of 28 coal mines was found to be large (Level III), while that of one was deemed to be major (Level II).

The evaluation method can fully cover the main seismic disaster bearing bodies of coal mines, while the evaluation results were largely consistent with the actual seismic disaster risk in the region,
which is of great significance for accurately investigating the hidden dangers of coal mine seismic disasters and improving the seismic fortification level and seismic capacity of coal mines.

5. Conclusions

In view of the lack of investigation and impact assessment methods pertaining to earthquake-induced secondary disasters in coal mines, an appropriate investigation system was devised based on the theories of earthquake disaster science, safety engineering, and system science while considering the mine lifeline system as the main line. Based on the fault type, effect, and comprehensive multi-index analytical methods, a comprehensive evaluation method for the impact of earthquake-induced secondary disasters in coal mines was proposed and verified. Based on the investigation, the following conclusions can be drawn:

(1) The investigation system includes the following three types of evaluation: basic information on coal mine earthquake disaster prevention and control, ground engineering investigation, and mine engineering investigation. Here, the basic information on coal mine earthquake disaster prevention includes six categories and 32 basic information items, while the ground engineering aspect includes four categories and 12 investigation indexes, and the mine engineering aspect includes six categories and 12 investigation indexes.

(2) The possibility of earthquake-induced secondary disasters in coal mines was evaluated in terms of the following four aspects: the historical information on regional earthquake disasters, the standard situation of mine earthquake disaster prevention, the risk of earthquake disasters, and the complexity of mine occurrence conditions. Following this, the severity of the consequences of secondary disasters induced by earthquakes was evaluated in terms of the following three aspects: casualties, economic losses, and disaster prevention and mitigation capacity. Finally, the risk grade of secondary disasters induced by earthquakes was determined by constructing a risk grade matrix of the mine disaster bearing body.

(3) The evaluation method covers numerous factors, including the current situation regarding pre-disaster preparedness, the level of the earthquake disaster at the time of occurrence, and the post-disaster emergency disaster reduction and relief capacity, thus achieving full coverage of all the key influencing factors before, during, and after the disaster. By employing the evaluation method presented in this study, the quantitative expression of the impact assessment of earthquake-induced secondary disasters in coal mines was realized, providing a reference for the quantitative assessment of the impact of earthquake disasters in coal mines.

(4) The investigation and evaluation cases indicated that the investigation and evaluation of the hidden dangers of earthquake-induced secondary disasters in coal mines are highly pertinent and involve high operability. Moreover, the evaluation results were largely consistent with the actual disaster risk level in the region, fully covering the main earthquake disaster bearing bodies in coal mines, which is of great significance to the investigation of the hidden dangers of secondary disasters in this industry and has the potential for accurately improving the seismic fortification level and seismic capacity of coal mines.

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