



Review

Damage and control of mining surface deformation: Research status, hot spots and trends

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ABSTRACT

In order to master the research status, hotspots and trends of mining surface deformation (MSD) in metal mines, exploring the green and sustainable development path of mines, 2241 articles in the Web of Science database in recent 30 years were visually analyzed with "metal mine" and "surface deformation" as search keywords. Draw the knowledge map of authors and hot keywords, and discuss the research progress and prospect of MSD based on the environmental impact. The results show that MSD research has experienced three stages: slow start, steady development and rapid development. MSD research involves the whole life cycle of mine mining damage source control, process monitoring and later restoration. MSD research keywords can be divided into five main clusters, among which subsidence prediction, backfilling mining, fracture failure, Geo-mechanical modeling and backfill materials are representative research hotspots. With the progress of the times, MSD research presents the evolution characteristics of iterative replacement, from shallow to deep, and subject integration. Furthermore, it puts forward three frontier research directions for the future: MSD intelligent early warning, mine intelligent backfilling-mining integration, mine ecological restoration and environmental governance throughout the whole life cycle.

1. Introduction

As a basic energy source in China, metal mineral resources have always been in the core position in social and economic development. In the last 30 years, with the rapid development of industry, the demand for metal mineral resources has been increasing, and open-pit mines have been converted to underground mining [1]. The proportion of underground mining is increasing year by year, which brings a series of eco-environmental problems (environmental pollution, surface deformation and surface subsidence), safety problems and rock mechanics problems [2–4]. Large-scale overburden movement and surface deformation, destruction and subsidence induced by underground mining seriously threaten the ecological environment, such as water resources, land, soil and vegetation in mining areas [5–7]. It also restricts the development of agriculture, transportation, construction and other industries, and has a bad influence on the sustainable development of society, the economy and the environment [8–12].

Since the mid-to-late 1960s, the research on mining surface

deformation (MSD) in metal mines has been representative, such as Goodman's research on surface subsidiarity and tip-slip in deep mining, and three methods of planting reclamation and ecological restoration have been put forward [13]. Klukanová et al. studied the environmental pollution caused by metal mine drainage and the influence of underground mining on slope slip and landslide, and put forward a monitoring system for the environmental impact of mining activities [14]. In the early stage, there was insufficient knowledge about MSD, and there were few related studies. On the one hand, scholars study surface deformation based on specific geological conditions [15–17]. On the other hand, they focus on the study of ecological environment deterioration caused by mining in metal mines, such as the study of the influence of mine waste and mine drainage on vegetation growth and organisms [18]. Since 2000, MSD and ecological environment deterioration in mining areas have gradually attracted attention from all walks of life. Nichol studied the surface movement caused by silver-lead-zinc mining in North Wales, and effectively predicted and controlled the surface collapse [19]. Lamb used satellite radar interferometry to investigate the problems of mine

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drainage and surface subsidence, which can effectively obtain the surface morphological changes in mining areas [20]. Li et al. established a prediction model of rock mass deformation and displacement by using fuzzy measure theory, which effectively predicted the deformation and safety assessment of mining surface buildings [21]. Ryu et al. put forward a simple and effective risk assessment method of surface subsidence due to mining based on Difficulty Equality, and applied it to the abandoned gold mines and coal mines [22]. The above research is the basic embryonic form of surface deformation research in metal mines at present, which mainly involves mine drainage, ecological environment, mining area reclamation, monitoring, prediction and control of surface deformation and failure. The early research on this topic is few and single, and each research direction is relatively independent, which can clearly sort out its development vein.

In recent decades, with the complexity of mining conditions, ore body occurrence and stress environment, environmental problems such as surface deformation and destruction induced by mining have become more obvious [23,24]. At the same time, scholars have made more in-depth research on MSD in metal mines, and their research directions, research methods and research contents have been continuously expanded, which has gradually formed a comprehensive research theme of interdisciplinary integration. Therefore, it is necessary to summarize and evaluate the research progress of MSD in recent decades. On the one hand, it is helpful to speed up the construction of green mines, on the other hand, it also points out a new development direction for this research topic.

Looking at the existing literature, there is still a lack of overall summary and systematic comment on the research progress of MSD in metal mines, and it is difficult to grasp the research hotspots and development trends of this topic. In recent years, the related research methods of scientific bibliometrics have developed rapidly [25–29], among which VOSviewer is a relatively mature visual bibliometrics tool. It provides a reliable way for literature induction, summary and analysis of research results, and has the advantages of strong visibility, wide analysis angle and reliable data results [30–32]. In this paper, the bibliometrics method is used to visually analyze the related literature in the database of Science Network (WOS), so as to grasp the research status and development trend of MSD in metal mines. First of all, the development history of MSD research is divided, and the core research direction and policy support in each development stage are analyzed. Secondly, summarize and analyze the academic ideas and directions of the main scholars of MSD research. Then, the keywords of literature research related to MSD are summarized and classified, and the evolution process of research hotspots in different development stages is analyzed. Further put forward the frontier research direction of helping mine ecological environment management, which provides reference for accelerating the construction of green mines.

2. Data sources and analysis methods

2.1. Data sources

Based on the Web of Science (WOS) database, the research samples were collected, and the related literature on MSD in metal mines was statistically analyzed. In order to avoid missing or irrelevant retrieval, this paper takes "Metal mine" and "Surface deformation" as the key words and adopts the relationship of "AND". The publication year of literature was set from 1994 to 2023, with a total period of 30 years. The retrieval date was December 31st, 2023, and a total of 5390 articles were retrieved. The research areas are further defined as "engineering", "mining mineral processing", "mechanics", "environmental sciences ecology", "geochemistry geophysics", "geology" and "science technology other topics". The literature types are limited to journal articles. After excluding patents, review articles, meetings and other irrelevant documents, a total of 2241 literature samples that meeting the analysis requirements are obtained.

2.2. Analysis methods

In WOS, the publication years, authors, title, citation times and other information of 2241 documents were derived, and summarized and counted. According to VOSviewer software, the knowledge map of the basic information of each document is obtained. On this basis, the literature is summarized, and the main research contents and keywords of surface deformation in metal mines are clustered and analyzed, so as to obtain the evolution and development trend of research hotspots under this theme. Labels (circles) with different colors in the knowledge map represent different categories or groups of elements, their sizes represent the number of corresponding elements, and the network lines between labels represent the close relationship between elements.

3. The relationship between annual publication and policy

According to the publication time and annual distribution of 2241 literature samples (Fig. 1), it can be known that the related literature on the study of MSD in metal mines is increasing year by year. The research process can be divided into three stages: slow start-up stage (1994–2010), steady development stage (2011–2017) and rapid development stage (2018–2023). There are 295, 677 and 1269 published literature in the three stages, accounting for 13.2%, 30.2% and 56.6% of the total literature, respectively. The development of MSD research in different periods is closely related to the implementation of relevant policies. These policies guide the development of MSD research [33–40].

- (1) Slow start-up stage (1994–2010): the average number of papers published in this stage is less than 20, and scholars have insufficient understanding and investment in the related research on MSD. Although the concept of sustainable development was first put forward in 1987, it was in the stage of full social and economic development, and all industries had a great demand for mineral resources [33,34]. In the process of development, they blindly pursued the maximization of economic benefits, and did not pay attention to mining damage and ecological environment protection [14]. After 2000, with the continuous deepening and implementation of the concept of sustainable development, scholars further explored the study of surface deformation and ecological environment damage caused by mining [19–22], and the number of papers increased slowly year by year.
- (2) Steady development stage (2011–2017): In this stage, the average number of papers published reached 97, and scholars paid attention to mining damage and ecological environment damage. This is due to the continuous revision and improvement of the concept of sustainable development. Taking China as an example, the 2012 People's Republic of China (PRC) National Report on Sustainable Development pointed out that efforts should be made to build a resource-saving and environment-friendly society, establish an ecological compensation mechanism, and strengthen energy conservation and emission reduction [35,36]. In this case, scholars have invested a lot in the study of MSD and ecological environment destruction, and achieved fruitful results [32]. In addition, Canada, Australia, Romania and other countries have also formulated many policies and regulations to promote the sustainable development of mining, and formed an evaluation framework for the systematic sustainable development of the mining industry [37–39]. However, due to the constraints of mining geological conditions, key technologies and equipment, they can only maintain steady development.
- (3) Rapid development stage (2018–2023): the average number of published documents in this stage has increased sharply to 211, and scholars have invested heavily in the study of mining damage and ecological environment damage, and they have been deepening. Taking China as an example, in 2018, the Ministry of Natural Resources issued the Code for the Construction of Green

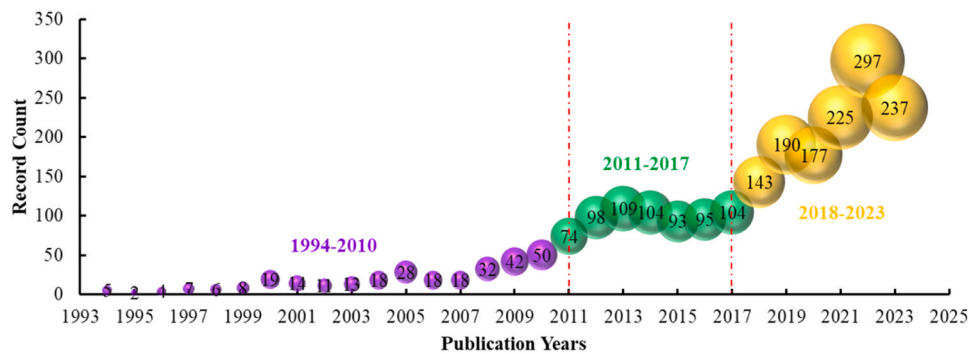


Fig. 1. Annual evolution trend of the number of papers published.

Mines in Nonferrous Metals Industry, which clearly defined green mines, and in 2019, 953 national green mining enterprises were selected. Driven by the national and industrial level, the concept and technical framework of green mine construction are gradually maturing, with the deepening of related research, the continuous improvement of theory and the rapid development of technological innovation [40]. At the same time, relevant policies such as Paris Agreement and UNFCC [41] signed by countries at this stage to realize the United Nations Decade of Ecological Restoration (2021–2030) have also accelerated the development of this field.

4. Analysis of representative authors and citations

Due to the huge number of all authors in 2241 literature samples, this paper mainly analyzes the influential authors and their research teams. Firstly, the literature samples are sorted according to the total citation times of a single article from high to low, and then the first author and the corresponding co-author of each document are counted in detail (counting the first author). Finally, the co-authors are divided into the same group to form a research team.

As shown in Fig. 2, according to the number of published papers and the cooperative relationship among authors, the research team represented by Guo Guangli, Zhang Jixiong, Wu Aixiang, Li Liang, Liu Lin, Wong MH and Chen Shaojie has been formed. The close cooperation between the members of their respective teams has a great influence on

the development and progress of MSD research. At the same time, the authors who have published more than 20 articles under this research theme are Guo Guangli (38 articles), Zhang Jixiong (34 articles), Li Huaizhan (25 articles) and Li Meng (21 articles), all of whom come from the first two large research teams. Among them, the team of Guo Guangli is mainly engaged in strip mining, solid filling mining to control surface subsidence and mining surface subsidence prediction research. Through numerical simulation, similar simulation, SAR monitoring, theoretical analysis and other means, the main achievements include the prediction method of surface dynamic subsidence based on parameter sensitivity [42], the prediction model of surface dynamic subsidence of solid filling mining [43,44], and the prediction method of the influence of abandoned goaf on the surface subsidence of adjacent working faces [45]. Zhang Jixiong’s team is mainly engaged in the research on controlling surface subsidence by filling mining and the research and development of related filling materials. Using coal gangue, fly ash and construction waste as recycled aggregate to fill goaf can effectively control surface subsidence and realize the coordinated development of mineral resources exploitation and the environment [46,47]. For filling materials, a hybrid artificial intelligence model is proposed to predict the compaction characteristics of gangue filling materials [48], and its compression deformation behavior and filling performance are verified by related mechanical tests [49]. The team of Wu Aixiang is mainly engaged in mine filling mining and research on filling body characteristics. By filling the goaf with solid waste paste, the surface subsidence is controlled and the effective treatment of solid waste or tailings is

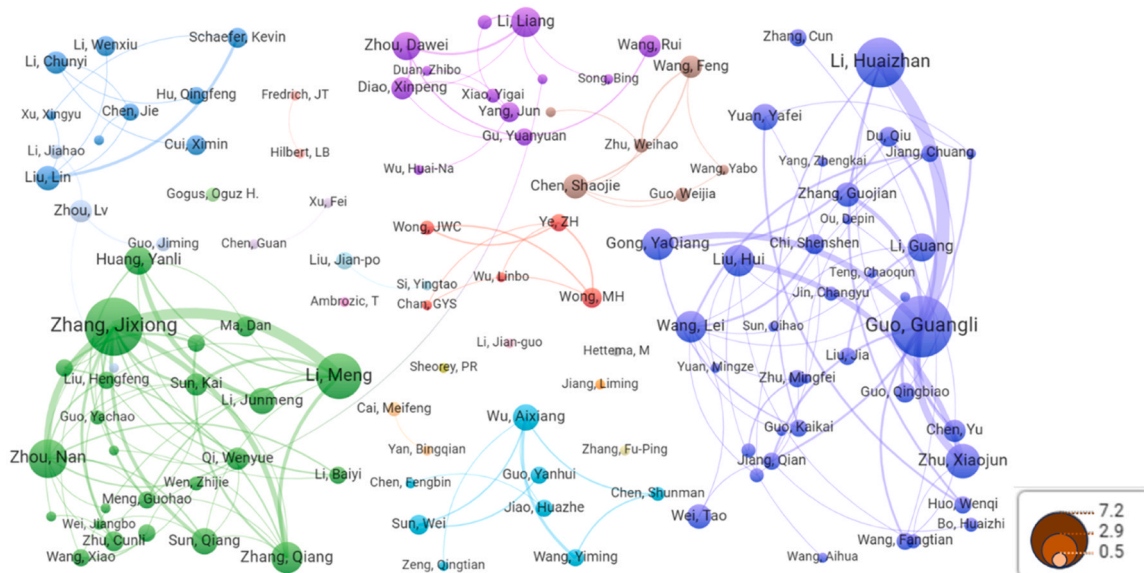


Fig. 2. The number of articles by the main authors and their cooperative relationship.

realized [50]. As a filling body, its strength and mechanical properties are very important. Therefore, the microstructure, cracks and defect characteristics of the filling body are obtained through uniaxial mechanical experiments, mathematical prediction models and CT scanning, so as to determine the optimal filling material [51,52]. Many research achievements of the above scholars and teams mainly involve the control of surface subsidence by filling mining and the research and development of filling materials. This research direction has played a good role in promoting the progress and development of green mining in mines, and realized the integrated treatment of surface subsidence and solid waste during mining.

As shown in Fig. 3, there are 12 authors with the maximum citation of more than 100 times in a single article, such as Wong MH (cited 866 times), Ma Dan (cited 174 times), Liu Lin (cited 166 times), Sheorey PR (cited 164 times), etc. Among them, Liu Lin and Zhang Jixiong not only published a large number of articles, but also were cited many times. Their influence on the study of MSD is obvious. However, scholars such as Wong MH, Ma Dan, Sheorey PR, Wu Huaina, Sun Wei, Jiang Liming, Chen Shaojie, Ambrozic T, etc., although the number of published articles is slightly less, their single articles are cited many times and increase year by year, which has great influence. Its academic achievements were published from 2000 to 2019, and its research directions mainly include mine ecological restoration [53], surface subsidence control by filling mining [54–56] and monitoring and prediction of surface subsidence in mining [57–63]. It involves the whole life cycle of mining damage source control, damage process monitoring and damage repair, and plays an important leading role in MSD research. Since the publication of the above-mentioned literature, the annual citations have steadily increased, as shown in Fig. 4. After 2022, although the citation amount of some literature showed a downward trend, the annual citation heat was still high, which accelerated the development of this theme and promoted the pace of green mine construction.

It should also be emphasized that some internationally renowned scholars such as Guo Wenbing, Peng Syd S., Luo Yi, etc. and their teams have made great contributions to the surface subsidence and control during mining. Guo and his team have been engaged in research on green mining, mining damage and protection for a long time, and the research results focus on the law of strata movement and surface deformation and form a systematic goaf filling and overlying strata separation grouting technology to reduce subsidence [64–67]. Peng

et al. has made outstanding achievements in the fields of mining strata control and surface subsidence. He emphasized the important position of strata control in the field of mining engineering, covering overburden failure and surface subsidence, and introduced various methods of research on mining surface control [68,69]. Its research results have laid a theoretical foundation in this field and promoted the development of mining damage and strata control. Luo is an internationally recognized authority in the field of mining surface subsidence prediction, and the developed surface subsidence prediction software is widely used in the USA with its comprehensive functions and reliable accuracy [70–74]. Its research results have great influence on the industry, and also laid a solid foundation for intelligent early warning of mine disasters and construction of smart mines.

The research of the above-mentioned famous scholars covers the whole chain from theoretical exploration, technological innovation to engineering application. It not only promotes the progress of mining engineering, but also provides an important guarantee for mine safety, green mining and ecological environment protection. Its achievements enjoy a high reputation and influence in academia and industry at home and abroad.

5. Research keywords clustering and hotspots evolution analysis

5.1. Keywords cluster analysis

Summarize the keywords of the literature cited more than 10 times in the literature sample, and the keywords "Metal Mine" and "Surface Deformation" will not be counted, and then carry out synonymous integration to obtain 429 main research keywords, as shown in Fig. 5. These keywords are an important part of MSD research, and they are closely related. Judging from the number and frequency of published relevant documents, this kind of keywords is also a hot research direction of MSD theme. All keywords can be further classified into five main clusters: Environmental Sciences Ecology (cluster I), Mining Engineering (cluster II), Rock Mechanics (cluster III), Engineering Geology (cluster IV) and Science Technology Other Topics (cluster V).

5.1.1. Cluster I: Environmental Sciences Ecology

There are 77 keywords in the cluster I, among which the main

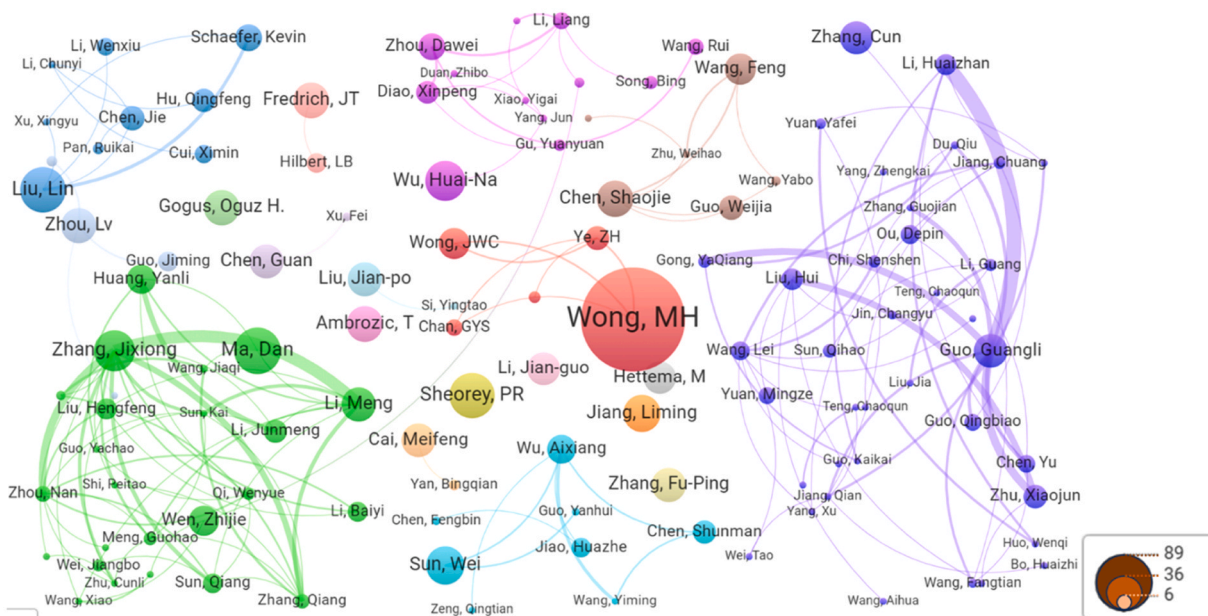


Fig. 3. Network knowledge map of maximum citation times in a single article.

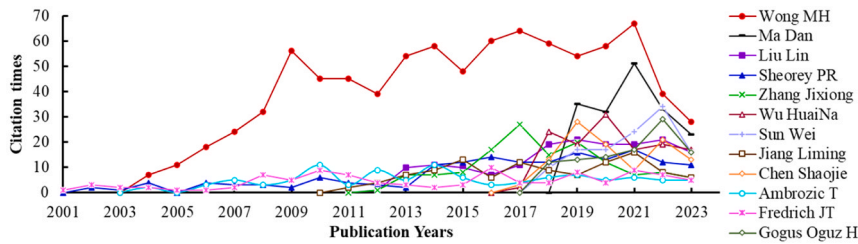


Fig. 4. Annual citation times of main literatures.

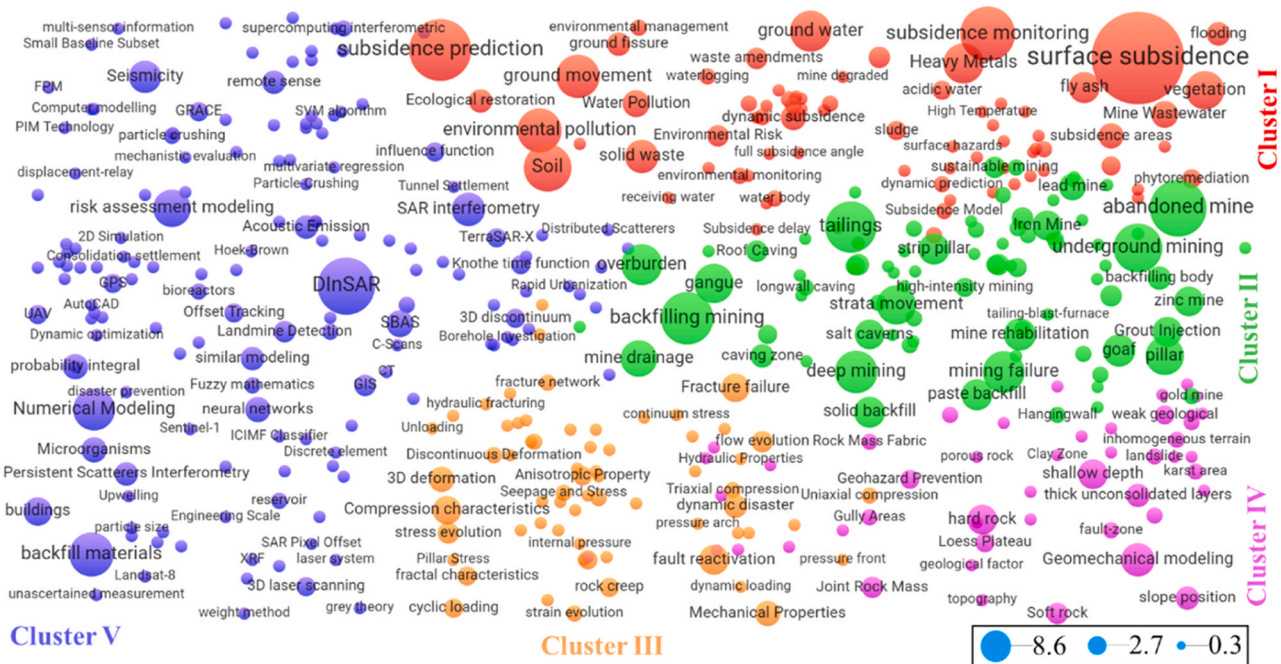


Fig. 5. Keywords clustering knowledge map.

research keywords include surface subsidence, subsidence prediction, subsidence monitoring, soil, environmental pollution, ground movement, ground water, etc. The keywords in this cluster are mainly related to research fields of surface damage and ecological environment damage caused by mining. It covers a series of environmental and ecological problems in mining areas, such as the mechanism of surface subsidence, monitoring and prediction of surface subsidence, destruction of soil and

water resources, ecological environment pollution, vegetation destruction, heavy metal pollution, waste stacking and so on.

The mechanism of surface subsidence in the process of mining shows that caving mining, in particular, will induce serious surface fissures, movement and subsidence [3]. The typical surface damage is shown in Fig. 6. By monitoring the surface fissures and the displacement of the footwall, Villegas made it clear that the response of the footwall to



Fig. 6. Common surface damage caused by mining.

mining is similar to that of the rock slope, and the horizontal strain of the outermost ground fissure is the factor that may induce the surface damage [75]. Woo can effectively analyze the relationship between caving depth and subsidence area through field database and numerical simulation, and the surface deformation caused by caving is discontinuous and asymmetric [76]. It is very important to monitor and predict the surface subsidence from the source. InSAR technology, remote sensing technology, SBAS technology and GPS technology are widely used to monitor the surface subsidence and deformation in mining, and good results have been achieved [77,78]. Based on the on-site monitoring data, the surface subsidence prediction model and multi-parameter modified prediction model can be modified by time function model and probability integral method, and better surface subsidence prediction accuracy can be obtained [79]. In the process of surface damage, surface and underground water, vegetation and soil will be destroyed. At the same time, heavy metals, solid and liquid wastes caused by mining will pose a great threat to the ecological environment of the mining area [80,81]. Among them, cadmium (Cd) pollution is the most important challenge for the treatment of soil and water environments in China. In the central, southern and southwestern parts of China, the Cd content is relatively high. Compared with other metal mines, Pb-Zn and W mining areas have more Cd accumulation and serious pollution risks [82]. Therefore, it will be particularly important for ecological restoration and management of mining areas, in which vegetation succession under human intervention is an effective way [83, 84].

5.1.2. Cluster II: Mining Engineering

There are 87 keywords in cluster II, among which the main research keywords include abandoned mine, backfilling mining, tailings, deep mining, mining failure, overburden, gangue, strata movement and so on. This cluster mainly focuses on the research fields of mining, covering the utilization of abandoned mine, backfilling mining, tailings treatment, overburden migration and other related research contents. Goaf filling plays an important role in controlling overburden movement and surface subsidence, as shown in Fig. 7.

However, traditional filling mining is a complex and expensive mining technology, and it may not achieve the expected effect of surface deformation control [85]. With the integration of interdisciplinary, advanced experimental methods and techniques, the filling mining technology in metal mines has developed rapidly, forming many new theories and methods. Among them, mine filling technology can be divided according to filling position, filling quantity, filling materials, filling power and filling performance, as shown in Fig. 8a. Through numerical simulation and on-site monitoring, the vertical crater backfill method can effectively control surface subsidence and building deformation for iron ore with complex conditions [86]. Similar to mining under farmland, Sijiyang Iron Mine adopts sublevel filling mining method to control stope stability and reduce surface subsidence on the premise of ensuring the self-stability of filling body [87]. Common metal mine filling technologies include tailings filling, low-cost cemented filling, high-concentration cemented filling and paste filling, as shown in Fig. 8b. Since 2000, the latter two filling technologies have dominated

metal mine filling [88]. A lead-zinc mine in Inner Mongolia is filled with cement and tailings in proportion, which can not only effectively control surface subsidence and grassland destruction, but also properly solve the environmental problems caused by tailings stacking [89]. In order to further realize the comprehensive treatment of solid waste and subsidence area, solid waste is prepared into paste for filling, and the filling scheme of "horizontal partition and vertical stratification" is formulated [55]. Although paste filling is an effective waste and surface subsidence management technology, it can be used to fill underground cavities or surface subsidence pits, but its economic cost and even the loss of cement and other materials can not be ignored in the filling process [90].

5.1.3. Cluster III: Rock Mechanics

The cluster III summed up 64 keywords. The main research keywords include fault reactivation, fracture failure, compression characteristics, mechanical properties, 3D deformation, dynamic disaster and so on. This cluster mainly focuses on the research of mine rock mass (rock) mechanics. It covers the law of fault activation, the fracture mechanism of rock mass, rockburst dynamic disasters and other related research contents.

After ore mining, the surrounding rock, overlying strata and surface stress environment (stress magnitude and stress direction) will change [91,92], and overburden migration and surface subsidence will be intensified under the disturbance of mining stress [93,94]. Especially in special structural zones with faults, mining disturbance will induce fault activation, leading to large-scale caving of rock mass (Fig. 9) and large-scale overburden movement, which will lead to surface subsidence [95]. At the same time, the development of cracks and fracture failure in surrounding rock and overburden under the influence of mining is also a prerequisite for inducing ground cracks and even surface subsidence [96,97]. Combining finite element with discrete element, the discontinuity and stability of the footwall are studied through fracture network, and three stages of footwall rock settlement, gradual and stability during mining are obtained [98].

In addition, for backfill mining, the strength, compression, mechanics and deformation characteristics of the filling body are also the focus of attention of scholars. The ratio of filling waste to cement directly determines its mechanical properties, fracture characteristics and microstructure [51]. When cemented coal gangue is used as filling material, fly ash and coal gangue are commonly used as filling materials, but corn stalk fly ash with equal weight shows better mechanical properties when replacing fly ash [99].

Under certain conditions, such as deep mining, the above-mentioned series of mechanical problems of rock mass (rock) will become more complicated. The integrity and stability of surrounding rock are worse, and the ground pressure is severe, and roof caving, slab off and support failure often occur, as shown in Fig. 10. In the high-stress environment, in addition to solving the problems of overburden migration and surface deformation, it will also face dynamic disasters such as rockburst [100]. When a large number of surrounding rock explosions occur in a mine to form a mine earthquake, it will seriously threaten safety production and surface stability [101]. Rock mechanics, as a theoretical basis, is in the core position in the research of surface deformation and control in metal

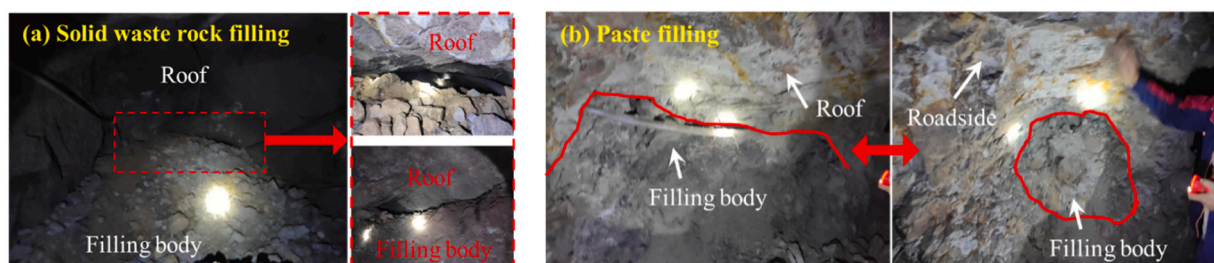
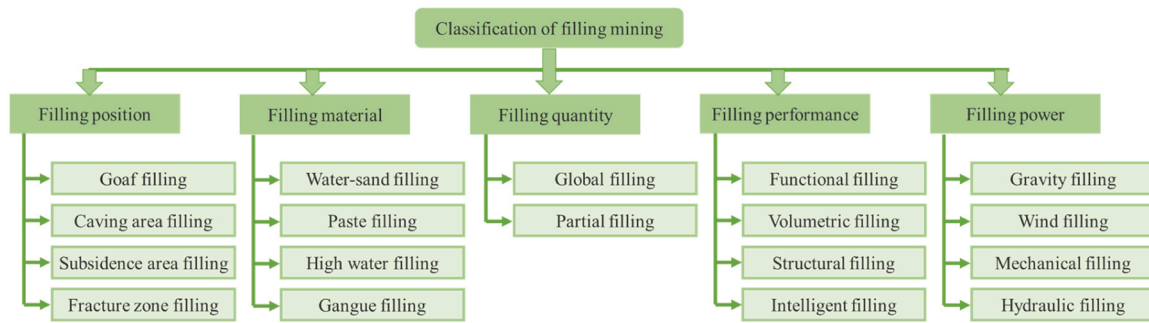
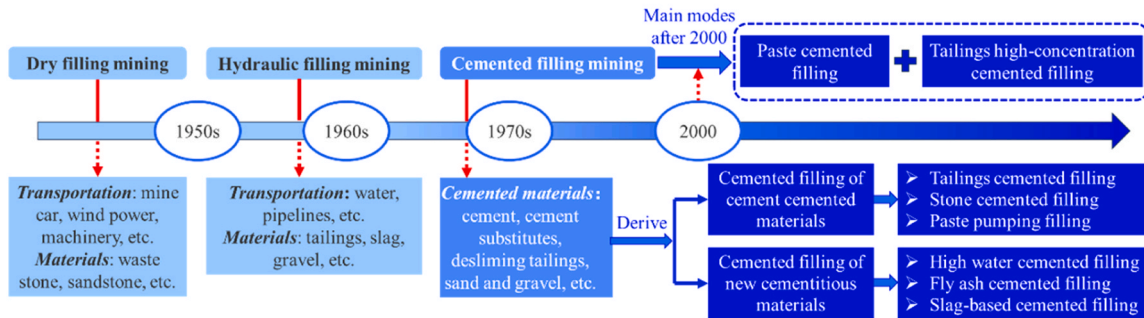


Fig. 7. Real effect of goaf filling.



(a) Classification of filling technology



(b) Development history of backfill mining

Fig. 8. Classification and development course of mine filling technology.



Fig. 9. Rock mass fracture and caving in fault zone.

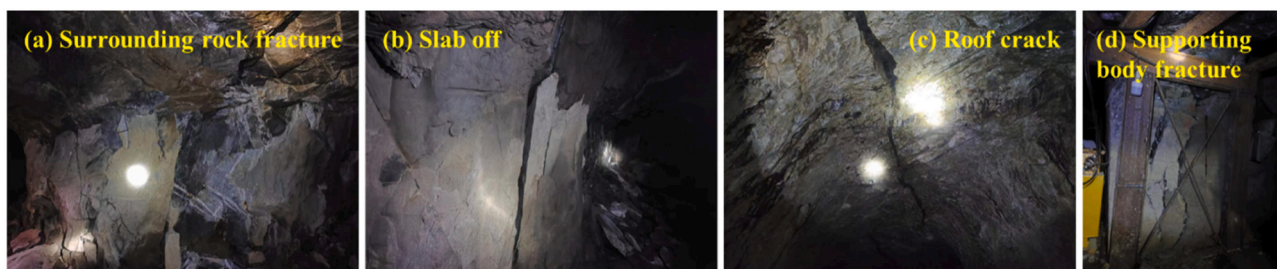


Fig. 10. Fracture and instability of surrounding rock and supporting body.

mines mining.

5.1.4. Cluster IV: Engineering Geology

There are 48 keywords in cluster IV, among which the main research keywords include geo-mechanical modeling, hard rock, shallow depth,

loess plateau, geo-hazard prevention, weak geology and so on. This cluster mainly focuses on mine geology, covering geomechanics, ore body occurrence conditions, mining geological disasters and other related research topics.

As a prerequisite for mining, the ore body occurrence environment

directly affects the MSD, as shown in Fig. 11. There are many related studies, including specific occurrence conditions and geological conditions, such as the buried depth of ore bodies [102,103], thickness of ore bodies, number of ore bodies, steep ore bodies [104,105], slope surfaces [106,107] and loess plateau. Under different geological conditions, the degree of MSD varies. For steeply inclined ore bodies, there are two subsidence centers on the surface, and the subsidence of the upper wall is much larger than that of the lower wall, and with the increase of mining depth, the subsidence center shifts to the upper wall [104]. For mining slope-shaped surface damage, landslides mostly occur in open-pit mine slopes, and their damage is mainly controlled by slope geological discontinuity [106]. At the same time, under the coupling effect of mining and rainfall, the dynamic seepage law of slope is also of great engineering significance to its stability [107].

The ore bodies are located in different geo-mechanical environments under the above different geological conditions, and will show different geological disasters after mining. Accurately mastering the mine geo-mechanical environment is the basis of evaluating mining dynamic disasters and rock mass deformation [108], and it is also the premise of evaluating the effect of waste filling goaf [109], so as to effectively control surface disasters. Of course, scholars also pay special attention to the study of prediction and control of mining geological disasters. Among them, the Internet of Things technology has a good application in the prediction and early warning of common mine geological disasters such as surface subsidence, landslides and ground fissures, and it is also an important means to prevent mining geological disasters in the future [110].

5.1.5. Cluster V: Science Technology Other Topics

There are 153 keywords in cluster V, among which the main research keywords include DInSAR, backfill materials, numerical modeling, risk assessment modeling, SAR interferometry, SBAS, neural networks, microorganisms, etc. The keywords in this cluster are mainly the research methods of MSD and other related science and technology, which are complementary to the research topics and disciplines in the first four clusters. This complementarity not only expands the breadth and depth of research on surface deformation caused by mining in metal mines, but also promotes collaborative innovation in mining engineering, geological engineering, surveying and mapping science, environmental science and computer technology.

The research methods of MSD and backfill mining mainly covered by this cluster include numerical simulation, physical simulation, field test, indoor mechanical test (CT scanning, acoustic emission, etc.) [102,108]. Monitoring technologies of MSD include DInSAR, SAR interferometry, SBAS, remote sensing, UAV, GPS, detection radar, Internet of Things, etc. [77,78,110]. Evaluation and prediction methods of MSD include risk assessment, neural network, fuzzy mathematics, probability integral, intelligent model, multivariate regression, convolution model, grey theory, cloud model and genetic algorithm [61,79,111]. The calculation methods of MSD include Knothe time function, influence function, SVM

algorithm, least square method, Bayesian discriminant, membership function, LSTM algorithm and so on [58,78]. At the same time, the cluster also involves the research and development of filling materials (solid materials, paste materials, high-water materials, ultra-high-water materials, etc.) in the control of surface deformation and subsidence [49, 112].

The above research methods and technologies on MSD not only rely on traditional methods such as surface observation stations, geotechnical tests and numerical simulation, but also integrate cutting-edge technologies such as InSAR remote sensing monitoring, big data analysis and artificial intelligence prediction, which significantly improve the accuracy and efficiency of research results. In recent years, with the continuous development of high-precision monitoring technology, intelligent prediction models and green mining concepts, the research methods and technologies of surface deformation in metal mines have gradually matured, which provides a solid scientific support for mine safety, prevention and control of geological disasters and sustainable development of mining areas.

5.2. Research hotspots evolution analysis

Based on keyword cluster analysis, this paper further summarizes the relevant hotspots in different research stages of MSD (Fig. 12) and analyzes its evolution characteristics.

In the slow start-up stage (1994–2010), the related research on the cluster I and the cluster II was the main focus. The research hot keywords include abandoned mine, surface subsidence, tailings, environmental polarization and Heavy Metals. During this period, under the great demand for mineral resources, mining was the main direction, such as abandoned mines, tailings, mine drainage and so on. With scholars' attention to mining damage and ecological environment protection, research in this field has also been well developed in the later period, including mining surface subsidence, heavy metal environmental pollution, surface subsidence prediction, mining vegetation soil destruction and other research contents. However, the research methods of mine geology, mine rock mass (rock) mechanics, mining surface deformation and control are relatively weak. This stage lasts the longest, but the development of various disciplines and research fields is relatively slow and in the starting state.

In the steady development stage (2011–2017), the related research of cluster I, cluster II and cluster V has been accelerated, and other clusters have followed up steadily. The research hotspots include surface subsidence, subsidence prediction, backfilling mining, DInSAR, abandoned mine, tailings, numerical modeling and so on. During this period, under the guidance of a series of policies such as sustainable development, scholars have invested more in the research of surface deformation and ecological environment damage caused by mining, such as surface subsidence, subsidence prediction, subsidence monitoring and soil damage caused by mining. At the same time, in addition to the continuous research on abandoned mines, tailings, overlying strata and

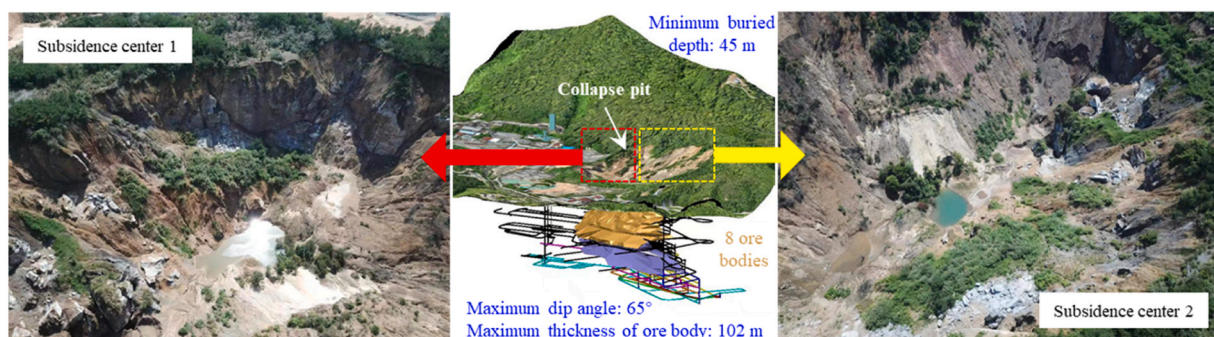
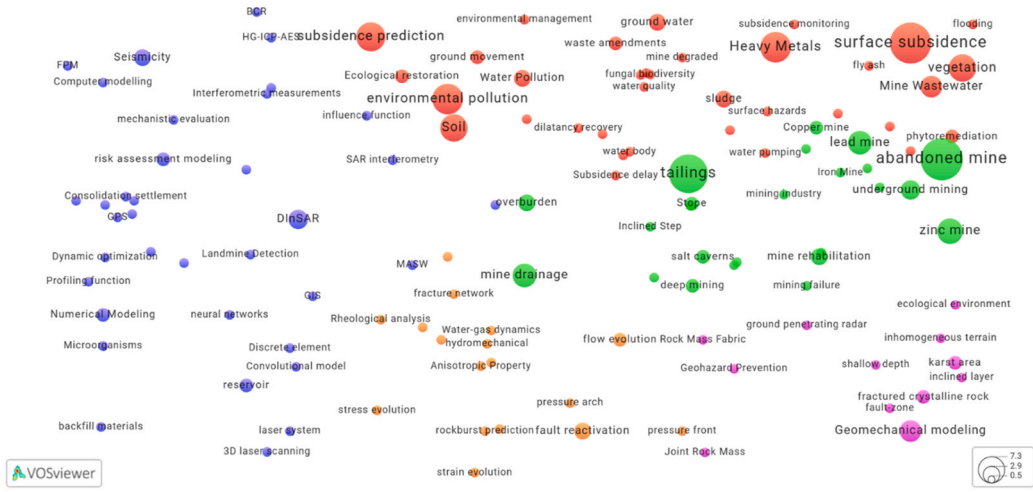
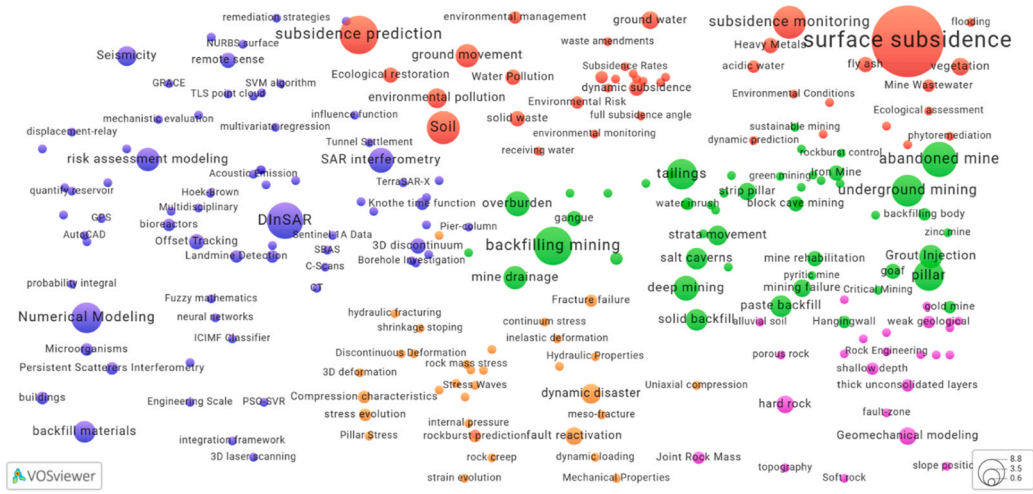


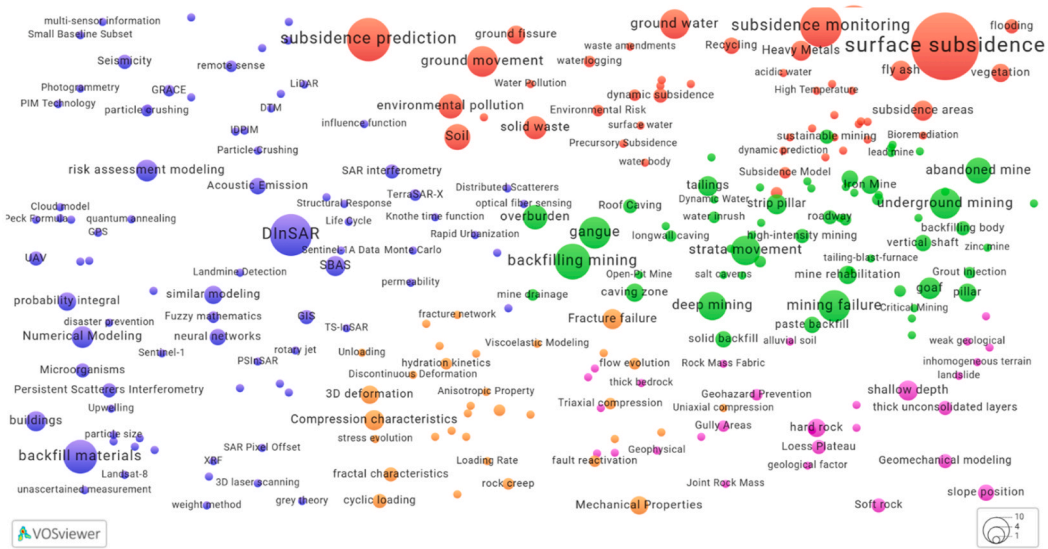
Fig. 11. Surface subsidence under complex occurrence of ore body.



(a) Slow start-up stage (1994-2010)



(b) Steady development stage (2011-2017)



(c) Rapid development stage (2018-2023)

Fig. 12. Knowledge map of keywords stage evolution.

strata movement, scholars have also made unprecedented progress in the research on paste filling, solid filling and grouting filling related to filling mining. During this period, scholars also accelerated the development of MSD research methods and other related science and technology. It mainly includes research methods such as numerical simulation, monitoring technologies such as DInSAR and SAR interferometry, evaluation and prediction methods such as risk assessment, and research and development of filling materials corresponding to filling mining. The development of mine geology and mine rock mass (rock) mechanics is also steadily followed by other fields, and its main research hotspots are hard rock, geomechanics, mining fault activation, dynamic disasters and so on.

In the rapid development stage (2018–2023), the related research of cluster I, cluster II and cluster V continued to develop rapidly, and other clusters followed suit. The research hotspots include surface subsidence, subsidence prediction, subsidence monitoring, DInSAR, backfilling mining, backfill materials, gangue, mining failure, ground movement, strata movement, ground water, deep mining and abandoned mine. During this period, under the background of green mine construction, coupled with the promotion of sustainable development, double carbon policy and industry norms, scholars have invested heavily in the study of surface deformation and ecological environment damage caused by mining. Mining-induced subsidence prediction, subsidence monitoring and soil destruction are still hot research contents, and they are developing continuously and rapidly. In the field of mining, in addition to the continuous research on abandoned mines, underground mining, overlying strata and strata movement, scholars have also made rapid progress in the research on filling mining, gangue filling, deep mining and mining damage. Among the research methods of MSD and other related science and technology, the research and development of DInSAR monitoring technology and filling materials have developed rapidly. The development of mine geology and mine rock mass (rock) mechanics also keeps pace with other fields.

With the progress of the times, the relevant academic ideas and research hotspots of MSD are constantly born, replaced and improved, and the research direction is from shallow to deep, which has obvious cross-integration characteristics. According to the trend of published articles in Fig. 1, the progress of MSD research from slow start-up stage to steady development stage is mainly reflected in the guidance of policies and the breakthrough of academic ideas. Thereby promoting the development of basic technology and technology. However, restricted by the complex geological conditions of the mine, the rock mechanics of the basic mine and key technologies, the overall development is relatively stable. The breakthrough from steady development stage to rapid development stage is mainly reflected in the innovative development and breakthrough of key technologies. At the same time, with the promotion of a series of policies and the improvement of academic concepts, the overall development speed has been accelerated.

6. Research prospect of MSD frontiers

According to the evolution characteristics of research hotspots under the theme of MSD from 1994 to 2023, combined with the research hotspots in the rapid development stage (2018–2023), the past and present research deficiencies are criticized, and the future frontier research direction is put forward, with a view to accelerating the construction of green mines.

6.1. Intelligent early warning platform for MSD

The most direct manifestations of surface damage caused by mining are surface deformation and subsidence, and effective monitoring is the premise of building an early warning platform and implementing damage control [61,70,71,74,79]. The surface deformation and subsidence caused by mining is a process from slow gradual change to sudden change. The traditional monitoring technology of surface deformation is

not only costly and complicated to operate, but also has certain errors. The characteristics of MSD are different because of the influence of many factors such as ore body occurrence conditions, geological conditions and mining methods. MSD has the characteristics of wide range and non-uniformity, so it is difficult to meet the requirements of dynamic monitoring and prediction of complex surface deformation and settlement with a single monitoring technology or a prediction model under specific conditions [113,114].

With the accelerated application of new generation information technologies such as artificial intelligence, big data, cloud computing, etc., the intelligent early warning platform for surface deformation caused by mining in mines (Fig. 13) will be one of the important trends for green mines to develop to a higher stage in the future [115]. The intelligent early warning platform should be designed with data layer, analysis layer and application layer [116]. It aims to solve the problems of complex monitoring data sources, difficult information transmission, low early warning ability and efficiency of traditional technology, and completely realize "unmanned", "intelligent" and "automation" in all aspects of data collection, analysis and application. First of all, the data layer of the intelligent early warning platform for MSD should have the characteristics of huge basic data, multi-source, multi-angle, omni-directional and full-time domain, including not only 2D data obtained by traditional monitoring technologies (DInSAR, SAR, UAV, radar, etc.) [77,78,110], but also 3D spatial data obtained by numerical simulation and geological model, which together constitute the basic database. Secondly, the analysis layer of the intelligent early warning platform for MSD plays the role of connecting the data layer and the application layer, aiming at processing the input information by means of classification, mining, management and transmission. Then, the application layer of the intelligent early warning platform for MSD aims to further spread the analyzed data as early warning information through mining technology, and its key technologies are the development of decision-making application programs and the integration of data-driven systems and multi-information. On the one hand, the construction of the intelligent early warning platform is to make up for the shortcomings of traditional monitoring technology and prediction models and reduce the safety risks in mining areas [116]. On the other hand, it provides precursor warning information for surface deformation control during mining, grasps the best control state and reduces the environmental risk in the mining area.

6.2. Mine intelligent backfilling-mining integration technology

Backfilling mining has obvious advantages in solving the problems of surface subsidence, soil erosion and mine waste pollution in mining areas. At the same time, this technology can effectively improve the recovery rate and maintain the safety of the stope. After nearly 30 years of development, it has become an irreplaceable part of green mining [66, 67]. However, the traditional mine filling mining technology has the advantages of economical filling, high management cost and high consumption of filling materials. Especially in recent years, deep mining is facing challenges such as high stress, high ground temperature and high osmotic pressure, and the above-mentioned series of problems are more obvious. In the process of filling with high efficiency, high quality and low cost, we should also give consideration to high efficiency and low loss mining in mines [90].

With the accelerated application of new generation information technologies such as artificial intelligence, Internet of Things and 5G [48,110], the integrated technology of mine intelligent backfilling-mining (Fig. 14) will be one of the important trends for the development of intelligent mines to a higher stage in the future [117–120]. For the mining link, it is necessary to promote the construction of intelligent mining equipment, digitalization of the mining environment, remote control of the production process, informationization of production management and networking of information transmission, and fully realize safe, economical, environment-friendly

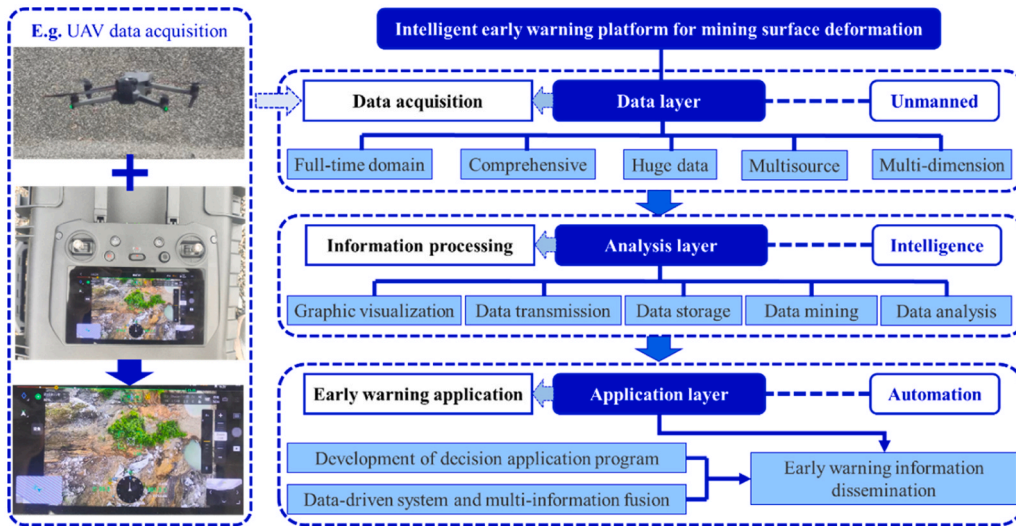


Fig. 13. Construction of MSD intelligent early warning platform.

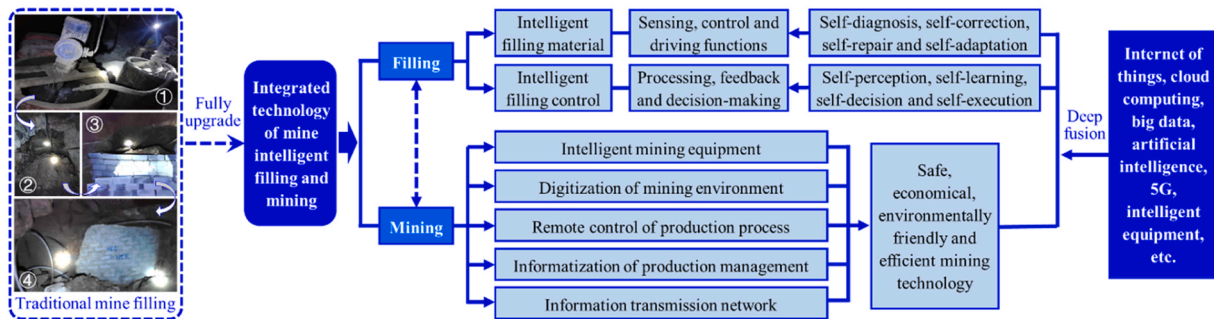


Fig. 14. Integrated technology of mine intelligent backfilling-mining.

and efficient mining technology [117,118]. For the filling link, the key to realizing intelligent filling is the intelligence of filling material and filling control. Among them, the intelligent filling material integrates the functions of sensing, control and driving, and can realize the intelligent functions of "healthy" self-diagnosis, deviation self-correction, damage self-repair and environmental adaptation of the filling material system structure [119,120]. Thereby improving the overall performance of the filling body. Intelligent filling control is a control mode with intelligent information processing, intelligent information feedback and intelligent control decision. This control makes the filling system, such as mixing and pipeline transportation, have the basic abilities of self-perception, self-learning, self-decision and self-execution. However, in the process of filling mining in mines, "mining" and "filling" are inseparable. It is necessary to deeply integrate modern mine filling and mining with Internet of Things, cloud computing, big data, artificial intelligence, 5 G and intelligent equipment to form an intelligent integrated technology.

6.3. The concept of ecological restoration and environmental management in the whole life cycle

A series of geological disasters, environmental pollution and resource destruction in the process of mining seriously deviate from the concept and goal of green mine construction. Surface subsidence, ground fissures, underground and surface water damage, soil damage and vegetation damage induced by underground mining, slope instability, landslide and debris flow induced by open-pit mining, and waste water, waste gas, waste residue and other wastes discharged by mines. They have seriously damaged the mine ecological environment. In the

face of severe ecological environment problems in mines, restoration and treatment are inevitable for a long time to come. Although some achievements have been made in mine restoration and management at this stage, it still faces great challenges. Especially in special mining areas (arid areas and alpine areas), the high cost of restoration, harsh climatic conditions, irregular terrain, shortage of water resources and serious soil erosion on the surface are all factors that lead to the failure of ecological restoration in mining areas. Meanwhile, mining is a long-term and dynamic process. The surface deformation and ecological damage caused by mining also have obvious temporal and spatial evolution characteristics, and it is difficult for a certain stage or local restoration and treatment to play a role in the whole life cycle of mines production [121,122]. This is also the main reason for the failure of ecological restoration and environmental management.

Mine ecological restoration and environmental management must run through its whole life cycle (Fig. 15). Incorporate existing ecological restoration and environmental treatment technologies (physical methods, chemical methods, phytoremediation, microbial remediation, new material remediation, etc.) into the whole cycle of mine construction period, mine production period and mine abandonment period. At the same time, source loss is also the key to the success of mine ecological restoration and environmental management. For example, in the process of mining, the surface subsidence can be controlled by filling or grouting the goaf, and the water resources and the destruction of soil and vegetation can be protected [32].

In addition, the transformation of abandoned mines and the development of new energy bases in the post-mining era are the continuation of the mine life cycle [8,123-127]. When the mine is in the late mining stage or abandoned state, the green transformation of the mine is very

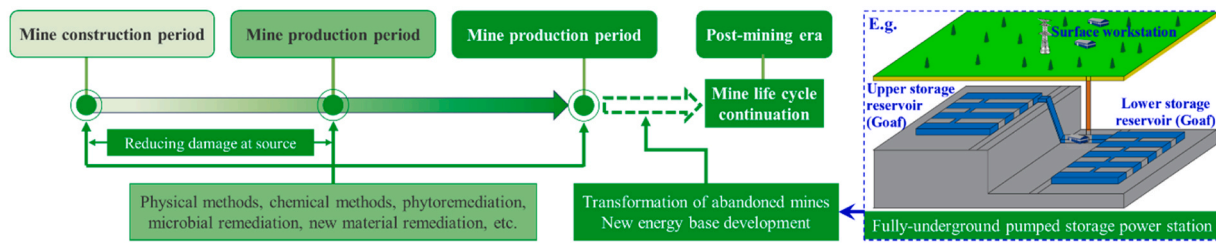


Fig. 15. Concept of mine ecological restoration and environmental management in the whole life cycle.

important. Based on the huge underground space resources after mining, we should rationally develop and utilize them, such as the development and utilization of pumped storage power stations with ground subsidence pits or different sublevel goaf as upper and lower reservoirs, the reconstruction of ecological parks and artificial lakes with ground subsidence pits, the reconstruction of underground laboratories, underground hospitals and underground shelters with mine goaf, etc.

It is worth mentioning that the reconstruction of pumped storage power stations by using abandoned mines is a great pioneering work in the post-mining era [127-129]. Taking this as an example, an effective path to extend the life cycle of mines can be explored. Underground mining will inevitably leave a lot of idle space, such as goaf, roadway and chamber. However, abandoned and closed mines have caused a lot of waste of groundwater and space resources, which will run counter to the concept of green mine construction. Therefore, in view of the underground metal mines that are close to closure or resource transformation, it is urgent to combine their spatial resource distribution with local energy demand for rational development. The construction of mine pumped storage system aims at utilizing underground space resources such as goaf and roadway (Fig. 15). By regulating intermittent renewable energy (wind energy, solar energy, etc.) to generate electricity, the functions of peak regulation, frequency modulation, phase modulation and emergency standby are realized, and the stability of power supply is guaranteed [126,129].

With regard to the construction of pumped storage power stations in abandoned mines, some related projects abroad are already in the planning stage. In 2012, Gridflex Energy plans to build a storage reservoir in a limestone mine in Kentucky [130]. In 2014, New Summit Hydro applied for and planned to build a storage power station with a total reserve of 1.5 GW in limestone of Norton Ohio [130]. In addition, Australia, Spain and South Africa have successively carried out the design and research of pumped storage power stations in coal mines and metal mines [124,131,132]. At present, research on the construction of pumped storage power stations by using abandoned mines in China is in its infancy. Representative projects such as Luanping Pumped Storage Power Station in Hebei Province, the upper reservoir is arranged at the top of the mountain, and the lower reservoir adopts iron ore pits [126].

The underground goaf space of metal mine has the characteristics of high sealing degree, stable environment, high rock strength, potential difference and good engineering foundation. In the process of rebuilding energy storage reservoirs and power stations, the investment in basic projects is reduced and the construction period is shortened, and its application advantages are remarkable. At the same time, the reconstruction of pumped storage power stations by using abandoned mines is also a concrete embodiment of the continuation of the mine life cycle, which will produce great social value and economic benefits.

7. Conclusions

In this paper, using bibliometrics method, with "Metal mine" and "Surface deformation" as search keywords, the related literature in the WOS database in the past 30 years is visually analyzed, and the research status, research hotspots and development trend of MSD are grasped as a whole. The main conclusions are as follows.

- (1) The research on MSD in metal mines has experienced three stages: slow start-up stage (1994–2010), steady development stage (2011–2017) and rapid development stage (2018–2023). Especially in the stage of rapid development, the number of published documents, research direction and research hotspots are increasing rapidly. Judging from the highest cited distribution of research results, MSD research involves the whole life cycle of controlling the source of mining damage, monitoring the damage process and repairing the damage later.
- (2) Through keyword cluster analysis, five main clusters are divided. In the past 30 years, surface subsidence, subsidence prediction, abandoned mine, backfilling mining, fault reactivation, fracture failure, geo-mechanics modeling, hard rock, DInSAR and backfill materials are representative research hotspots of each cluster. They are closely related to each other and have strong interdisciplinary properties.
- (3) With the progress of the times, the academic concepts and research hotspots related to MSD are constantly born, replaced and improved, and the research direction is from shallow to deep, and cross-integration. In the future, the intelligent early warning of MSD, the integration of intelligent backfilling-mining and the ecological restoration and environmental management of mines in the whole life cycle will be the three frontier research directions under this theme.

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CRediT authorship contribution statement

Yu Xiong: Writing – original draft, Software, Writing – review & editing, Visualization. **Dezhong Kong:** Project administration, Funding acquisition, Conceptualization, Writing – review & editing, Methodology, Data curation. **Gaofeng Song:** Writing – review & editing, Funding acquisition, Conceptualization, Methodology, Formal analysis. **Jinzhong Li:** Validation, Visualization, Software. **Zehong Qin:** Visualization, Formal analysis, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets generated during and analyzed during the current study are available from the corresponding author on reasonable request.

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