Coupling Relationship between Ground Collapse Fracture and Water-Conducting Fracture Zone Development

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Abstract. The coupled development of ground collapse fissures and water-conducting fracture zones is the common hazard in mining areas, causing serious threats to mine water control and ecological safety. This study reviews the research progress on collapse fissures and water-conducting fracture zones in domestic and abroad systematically, summarizing their formation mechanisms, distribution characteristics, hazard impacts, monitoring and prevention techniques. Highlighting the development patterns and the two different geological conditions (shallow-buried thick coal seams, karst areas, loess regions), and analyzes the coupling mechanisms of ground collapse fissures and water-conducting fractures in spatiotemporal evolution and hazard triggering. Aiming at limitation of current predictive models and monitoring methods, some new research directions are proposed, including constructing multi-parameter coupling prediction models, integrating satellite-air-ground monitoring, strengthening the studies on lithology-engineering response mechanisms, and coordinating ecological restoration with engineering measures, in order to provide scientific guidance about the mine water hazard prevention and environmental protection under complex geological conditions.

Keywords: ground collapse fracture; water-conducting fracture zone; ground settlement; subsidence-fracture coupling mechanism; multiparameter prediction.

1. Introduction

During the coal resource extraction, the coupling development of ground collapse fractures and water-conducting fracture zones as the challenging issue in mining engineering and hydrogeology. Due to the unclear overburden-hydrology coupling mechanism, prediction models for the height of the water-conducting fracture zone under complex geological conditions (multi-seam mining, deep inclined coal seams) could exhibit errors range from 15 % to 20 %, directly threatening the safety of water resources in mining areas [1-3]. Ground surface fractures cause surface subsidence, building damage, and farmland yield reduction, and through synergistic interaction with water-conducting fracture zones, they exacerbate soil moisture loss and vegetation degradation, leading to severe ecological and economic losses [4-5]. Existing research lacks the unified understanding of the full-chain coupling mechanism of ***overburden failure-fracture propagation-hydraulic conduction***. Regional empirical models are often inapplicable, and prediction deviations are significant; hindering the formation of a unified multi-factor coupling prediction model. Therefore, it is necessary to further investigate from the multidisciplinary perspective to improve the universality and accuracy of model predictions. This research systematically reviews domestic and abroad studies on ground collapse fractures and water-conducting fracture zones, summarizing formation mechanisms, disaster impacts, and monitoring and prevention, compares the development differences under various geological conditions, analyzes the coupling evolution mechanism, and proposes strategies such as constructing multi-parameter coupling prediction models, integrating satellite-air-ground monitoring, implementing coordinated prevention and control with ecological restoration, providing reference for mine water hazard prevention and ecological environment protection.

2. Research Status and Deficiencies

2.1 Domestic

2.1.1 Ground Collapse Fracture

China coal resources are widely distributed, and large-scale mining leads to frequent occurrences of ground collapse fractures [3, 6]. Fractures have two types: collapse-type and tensile-type. Collapse-type fractures are mostly located above the goaf, with large scale and long duration, under severe cases develop into sinkholes, tensile fractures often strip-shaped, aligned with the direction of working face advancement, and serve as important channels for precipitation infiltration and percolation of surface water [7]. Research methods include geological research, borehole sampling, remote sensing monitoring, and three-dimensional geological modeling [8], obtaining the location, scale, and development status of fractures, providing fundamental data for disaster assessment and mitigation.

2.1.2 Water-Conducting Fracture Zone Development

Research focus on the height prediction, development patterns, and prevention techniques of the water-conducting fracture zone [2, 16]. The height is controlled by factors such as the mining height-to-thickness ratio, burial depth, roof lithology, overburden structure, and mining methods [9, 10]. Common in-situ measurement methods include borehole television, drill cuttings analysis, and upward borehole water injection, which directly determining the height of the fracture zone [19, 21]. Physical similarity simulation and numerical simulation (FLAC3D, UDEC) reflect the evolution process [11]. Some studies integrate geophysical prospecting methods (microseismic monitoring and transient electromagnetic surveys) to achieve dynamic monitoring [11]. Recently, the trend shifted from single-technology approaches to comprehensive integration, combining empirical formulas, simulations, geological measurements, and dynamic monitoring [5].

2.2 International

2.2.1 Ground Collapse Fracture

Internationally, research on mining-induced ground surface fractures began earlier, particularly in coal mining areas of Europe, North America, and Australia, where mature monitoring and prevention systems established. Emphasizing placed on high-precision monitoring and dynamic assessment, often integrating unmanned aerial vehicle photogrammetry, InSAR, and LiDAR [12]. Numerical simulations (3DEC, FLAC3D) are combined with geological monitoring to analyze overburden movement patterns and the mechanisms of fracture formation [1].

2.2.2 Water-Conducting Fracture Zone Development

Research on water-conducting fracture zones is integrated with hydrogeological conditions, focusing on relationships between fracture zones, aquifers, faults, and water inrush incidents [13, 14]. International studies adopt multi-source information fusion, combining drilling, geophysical surveys, numerical simulations, and hydrochemical analysis to improve prediction accuracy and applicability [1]. Studies have developed empirical models based on geological measurements, enabling rapid estimation of fracture zone height according to mining height, burial depth, and roof lithology [15].

2.3 Research Limitations

Existing research still shows deficiencies in regional applicability, dynamic monitoring, multi-factor coupling, ecological and environmental effects, and prevention technologies. Prediction models rely on data from specific mining areas, making difficult to generalize [2, 16], monitoring technologies remain limited in timeliness and spatial coverage [11, 31], many studies focus on single factor and lack exploration of multi-factor coupling effects [5, 17], gantitative assessments of the long-term ecological and environmental impacts of fracture zones are scarce [4, 18], And the prevention and control measures are still dominated by single-technology approaches, lacking an integrated management system [8].

3. Methods and Theories

3.1 Research Methods

Methods for ground collapse fractures and water-conducting fracture zones including the geological research and borehole measurement, physical similarity simulation, numerical simulation, geophysical exploration, and multi-source technology integration. Geological research and borehole measurement acquire information on the location-width-depth-extension direction of fractures through survey line layout, profile mapping, and core sampling [8]. Techniques such as borehole television, drill cuttings analysis, and upward borehole water injection directly reveal the height and connectivity of the fracture zone [19]. Numerical simulation, based on software such as FLAC3D and UDEC used to build models with different geological and mining parameters to predict the overburden stress field, displacement field, and fracture evolution patterns [2]. The results depend on model parameters and validated with geological measurements. In geophysical exploration, microseismic monitoring capture energy-release events induced by mining in real time, enabling inference of the dynamic evolution of fractures [11].

3.2 Ground Collapse Fracture

3.2.1 Definition, Morphology, and Distribution Characteristics

Ground collapse fractures refer to geological condition in mining-induced disturbances cause instability in surface rock-soil structure, resulting in tensile cracking or collapse [6]. Based on morphological features, classified into collapse-type and tensile-type fractures. Collapse-type fractures are distributed above the goaf, accompanied by large-scale subsidence and even the formation of sinkholes, with considerable width and depth, and exhibit persistence and destructiveness [7]. Tensile fractures generally banded or strip-shaped, parallel to the direction of working face advancement, and act as an important channel for surface water infiltration and precipitation percolation [17]. The distribution characteristics of fractures are influenced by the combination of factors such as mining depth, mining height-to-thickness ratio, roof lithology, overburden structure, and geological structure [5].

3.2.2 Prevention and Monitoring Methods

For the prevention and control of ground collapse fractures, the comprehensive approach combining engineering measures, mining optimization, and ecological restoration adopted. Under the engineering measures, mining optimization involves reasonably controlling the mining height, advancement rate, and working face layout to reduce the magnitude of overburden movement and thereby lower the likelihood of fracture formation at the source [2]. Ecological restoration measures, such as soil covering, reclamation and vegetation restoration, which stabilize surface structures and improve the ecological environment [9]. In terms of monitoring, primary methods include fixed-point field observation, aerial survey and remote sensing, and InSAR deformation analysis [5, 12].

3.3 Water-Conducting Fracture Zone Development

3.3.1 Definition, Morphology, and Distribution Characteristics

The water-conducting fracture zone refers to the fracture-developed area formed between the caving zone and the bending subsidence zone after overburden failure induced by coal mining, possessing a certain capacity for water conduction [2]. The fractures in this area as the combination of tensile and shear types, with high connectivity, enabling the establishment of hydraulic connections between the overlying aquifer and the goaf [17]. The fracture density in the water-conducting fracture zone decreases from bottom to top its width and height are controlled by mining depth, mining height, roof lithology, and overburden structure [20]. Under shallow-buried thick coal seam mining conditions, the fracture zone extends upward to the aquifer floor and connects with surface fractures. In deep mining, the fracture zone height is smaller and the closure rate is faster [16].

3.3.2 Influencing Factors of Development

The height and development conditions of the water-conducting fracture zone result from the combined influence of multiple factors. Mining height is the direct controlling factor, and increasing mining height increases the height of the fracture zone [11]; mining depth has restrictive effect, and the fracture zone is lower in deep mining [2]. Hard roof strata break with wide fractures and slow closure, while weak strata develop fractures that close easily under compression [8]. The thickness of strata, lithologic assemblage, and degree of joint development in the overburden determine the continuity of fracture development [19]. Structural factors such as faults and folds guide the extension direction of fractures and form concentrated water-conducting zones [22]. Mining methods (longwall caving, backfilling), advance rate, and the intensity of ground pressure manifestation influence the morphology of the fracture zone [17].

3.3.3 Prevention and Monitoring Methods

The key to preventing and controlling water hazards in the water-conducting fracture zone is to reduce fracture development, block water-conducting channels, and monitor fracture evolution dynamically. Engineering measures include backfilling mining, sectional mining, leaving water-resistant coal pillars, and grouting reinforcement, which reduce the height of the fracture zone and decrease the risk of penetration [8, 23]. In shallow-buried thick coal seam areas, pre-splitting blasting or staged mining controls roof movement and reduces the formation of large-scale fractures [2]. In monitoring, borehole television, acoustic logging, and transient electromagnetic methods directly or indirectly detect fracture distribution; microseismic monitoring obtains spatial and temporal information of fracture development in real time [11]. Recently, the combined application of InSAR, seismic CT, and measured borehole data has improved the accuracy and coverage of dynamic fracture zone monitoring [5].

4. Typical Regional Geological Backgrounds

4.1 Domestic

4.1.1 Eastern Region

The eastern region includes the North China Plain, the East China bedrock undulation zone, and parts of the Southwest karst area. In North China (Hebeiprovince), the Quaternary loose deposits are thick, and the combined effects of groundwater over-extraction and coal mining lead to ground fissures and subsidence, with fissures mostly distributed along faults in strip or network patterns [5]. In Eastern China bedrock undulation zone (Suzhou-Wuxi-Changzhou, Changzhou Henglin), the roof lithology of shallow to medium-depth coal seams varies, and local faults occur. Mining activities result in stepped subsidence zones and tensile fissures [3, 24]. In the Southwest karst landfrom (Laibin in Guangxi, Shanjiaoshu in Guizhou, and Dayanglin in Zhenjiang, Jiangsu), karst development combined with mining activities and groundwater level changes leads to sinkholes and fracture groups [6, 22, 25]. These regions have dense populations, with fractures and subsidence exert impacts on urban construction and the ecological environment.

4.1.2 Western Region

The western region includes the Loess Plateau in northwest China, the multi-seam mining area at the junction of Shanxi, Shaanxi, and Inner Mongolia, and the deep mining area in Shaanxi and Inner Mongolia. In shallow and thick coal seam areas, the overburden consists of thick loess or weathered sandstone with low roof strength, where mining activities lead to penetrating fractures and large-scale surface subsidence [17, 26]. In the multi-seam mining area at the junction of Shanxi, Shaanxi, and Inner Mongolia, repeated mining of multiple seams causes repeated damage to the overburden structure. The height of the water-conducting fracture zone increases and connectivity strengthens, in some areas connects with surface fractures, which increases the risk of water hazards [2, 19]. In the deep mining area of Shaanxi and Inner Mongolia, thick coal seams and deep mining dominate. The overburden shows large-scale damage, fractures close slowly, faults and structural planes strongly control fracture development. Some fracture zones maintain long-term water-conducting capacity [27]. Under arid and semi-arid climatic conditions, fracture development accelerates surface water infiltration and soil moisture loss, leading vegetation degradation and land desertification [4].

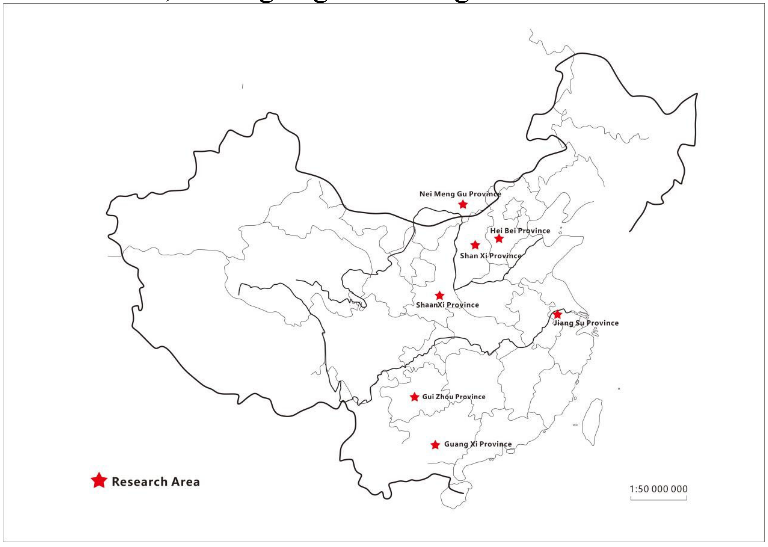

Fig. 1 Distribution of Domestic Research Areas

4.2 International

4.2.1 Europe

In the Ligurian Alps of northern Italy, complex structures and dense faults allow mining-induced disturbances to activate existing structural fractures, causing surface deformation and sliding [28]. In coalfields of northern Germany, the Quaternary loose layer is thick and the connection between groundwater and the goaf fracture zone causes water inrush and surface subsidence [12]. Coalfields in the United Kingdom lie in ancient belts, where coal seams occur at variable depths. Mining-induced fractures extend along ancient structural zones and connect with goaf water, forming compound hazards [18].

4.2.2 Circum-Pacific Region

The Pacific region include coalfields in North America, Southeast Asia, and parts of Russia. In Pennsylvania, coal seams occur at great depth with hard roofs; mining-induced fractures show bending and subsidence, tensile fracture height remains low, and long-term stability remains poor [29]. In coalfields of Alberta, thick rock overlies the coal seams, and mining-induced fractures concentrate in roof fracture zones [30]. In shallow coal seams of Southeast Asia (Jharkhand in India, South Sumatra in Indonesia), loose strata and abundant groundwater cause the water-conducting fracture zone to extend upward to aquifers after mining, increasing the risk of water inrush [31]. Some coalfields in Siberia lie in permafrost areas, where mining-induced fractures lead to ground thawing and trigger surface subsidence [14].

4.2.3 Africa and Oceania

In African coal mining areas (South Africa), open-pit and shallow underground mining dominate, overburden damage covers a wide range, and mining-induced fractures connect with natural weathering fractures, intensifying surface water loss and soil erosion [18]. In the coalfields of New South Wales, Australia, stratigraphic structure shows stability differences. Hard roof areas develop fractures with greater height and slow closure, while soft roof areas develop fractures that close under compression and retain permeability for a long period [13]. Prevention and control combine backfill mining and surface subsidence monitoring, supplemented by dynamic evaluation of hydrogeological conditions.

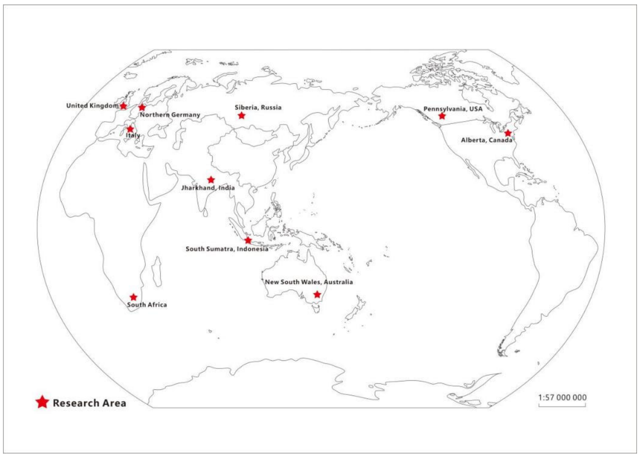

Fig. 2 Distribution of International Research Areas

4.3 Summary

From the geological conditions and coal mining practices in typical regions at domestic and abroad, the development of ground collapse fracture and water-conducting fracture zones controlled by lithology, coal seam depth, structural conditions, and hydrogeological environment. In eastern mining areas, which located in densely populated and economically developed regions, the thickness of overburden, fault structures, and groundwater over-extraction influence fracture patterns, which threaten infrastructure [5, 24]. In western mining areas, coal seam occurrence conditions are complex. In shallow-buried thick coal seam areas, fractures penetrate to the surface. In deep multi-seam mining areas, the water-conducting fracture zone reaches high levels and shows low closure rate. In environmentally fragile areas, fracture development causes ecological degradation [2, 26]. Internationally, fractures in European mining areas relate to tectonic activity and ancient geological structures [28]. Mining conditions in the Pacific show variation. In North America and Russia, mining occurs in deep or permafrost areas, and fracture stability depends on hydrogeological conditions [14, 29], Shallow coal seams in Southeast Asia contain abundant groundwater, and the risk of water inrush is high [31]. Mining areas in Africa and Australia are influenced by climate, lithology, and hydrogeological conditions, and fracture development shows clear regional differences [13, 18].

5. Discussion

5.1 Spatial Distribution

Ground collapse fractures and water-conducting fracture zones show clear differences in spatial distribution, while under certain conditions they remain interconnected. Ground collapse fractures occur above goafs and along their boundaries, forming strip-like, arc-shaped, or network patterns, with orientations consistent with the direction of face advance, major structural lines, and principal stress [5, 7]. The spatial distribution of water-conducting fracture zones depends on mining depth, coal seam dip angle, roof lithology, and multiple-seam mining. Their height and extent extend upward into the aquiclude of certain thickness, with shapes funnel-like, arch-like, and segmented [2, 32].

Table 1 Comparative Analysis of Differences and Correlation Characteristics between Ground Collapse Fracture and Water-Conducting Fracture Zone

Characteristic Category	Ground Collapse Fracture	Water-Conducting Fracture Zone
Spatial Location	Above goaf and boundaries; may extend to low-lying areas outside goaf	In overburden above goaf, extends upward from immediate roof into the aquiclude

Formation Time Characteristics	Lag after mining; hours–days (shallow), months (deep)	Forms with mining; rises with face advance; height increases when key strata break
Morphological Structure	Tensile, shear, step-shaped; width mm–cm; length tens of meters	Funnel, arch, segmented zone. narrower middle, wider top/bottom, gaps with debris
Controlling Factors	Overburden thickness, material, surface load, rainfall, slope	Overburden structure, roof mechanics, mining height ratio, repeated mining, key strata position
Hydrological Effect	Infiltration pathways, groundwater decline, soil desiccation	Determines aquiclude capacity and water-hazard risk, forms inrush pathways once connected
Disaster Type	Farmland degradation; building/road damage, surface water change, ecological degradation	Mine water inrush, gas leakage; aquiclude instability, stress-induced secondary hazards
Correlation Manifestation	In shallow thin aquiclude, connects with fracture zone to form surface-to-deep pathway	Acts as extension of surface fractures, hydraulic connection strengthens to form a mining-induced fracture system

5.2 Formation Mechanisms

Ground collapse fractures and water-conducting fracture zones share commonalities and differences in formation mechanisms. The former caused by mining-induced instability of the overburden structure and surface deformation, involving mining-induced stress disturbance, overburden fracture propagation, and surface response [7]. The latter originates from the bending, tensile, and shear failure of strata under mining influence, with fracture height and connectivity determined by the lithological properties and structural composition [2, 32]. Hard roofs form high fracture zones, weak rock strata produce high-density and low-height fractures [16]. Repeated mining of multiple seams promotes the upward extension and expansion of the fracture zone [26]. Ground fractures reflect the transfer of mining-induced energy to the surface, the water-conducting fracture zone reflects the overall mechanical failure of the overburden. Under shallow burial conditions, show closed connection; the correlation weakens with rock thickness and aquicludes in deep condition [6, 22].

5.3 Physical Properties

Ground collapse fractures and water-conducting fracture zones show differences in width, depth, extension, and permeability. Ground fractures have a width of several millimeters to several tens of centimeters and a depth of several meters to more than 10 m; in shallow burial areas, extend to the upper limit of the fracture zone [7]. The fracture zone high fracture density and strong permeability; its height and extent depend on overburden properties and mining method. Hard roof develops large-spaced throughgoing fractures, weak strata form dense and intersecting micro-fractures [2, 32].

5.4 Hazards and Prevention Measures

Ground collapse fractures threaten surface structures, transportation, and farmland ecology, leading to foundation subsidence, road fracture, and farmland water loss [5, 24]. Water-conducting fracture zones alter hydrogeological conditions, form hydraulic pathways, and trigger water inrushes that endanger underground safety [2, 32]. The remediation of surface fractures involves backfilling and compaction, vegetation restoration, and drainage improvement [4, 33]; the prevention and control of water-conducting fracture zones rely on leaving waterproof coal pillars, grouting reinforcement, and backfill mining [8, 23].

5.5 Spatiotemporal Relationship

Ground collapse fractures and water-conducting fracture zones show coupling in spatiotemporal evolution, the patterns vary with mining conditions and geological settings. Ground fractures appear after mining disturbance, forming within days to weeks in shallow seams and within months in deep seams, and their development influenced by rainfall and freeze-thaw cycles [17, 33]. Ground fractures follow the direction of working face advance and the boundaries of the goaf. The development of water-conducting fracture zones occurs with mining, height and extent changing with the advance, and further rising and expanding during repeated multi-seam mining [2, 26]. In shallow buried thick coal seam and karst areas, the ground collapse fractures and water-conducting fracture zones connect in short time to form hydraulic pathways; in deep areas with thick aquicludes, this connection is weakened and the timing and extent of surface fracture appearance are constrained by surface conditions [6, 22].

5.6 Coupling Analysis

Ground collapse fractures and water-conducting fracture zones show correlation in formation mechanism and spatial distribution, evident in shallow seams or areas with thin aquicludes. In mining areas with thick aquicludes, the fracture zone reaches considerable height, not extending to the surface, and the distribution of surface fractures is controlled by shallow soil properties, topography, and rainfall conditions [7, 33]. In such cases, the direct hydraulic connection weakens, and their hydrogeological correlation remains low. Structural conditions exert a controlling influence. Faults and joints act as transmission channels, leading to water inrush or surface subsidence in areas with thick aquicludes [6, 22].

Table 2 Main Controlling Factors Affecting the Coupling Degree between Ground Collapse Fracture and Water-Conducting Fracture Zone

factor	High Coupling Scenario	Low Coupling Scenario
burial aquiclude	Shallow-buried thick seams, thin, fractured aquiclude, disturbance reaches surface	Deep seams, thick, intact aquiclude; fractures hard to reach surface
lithological	Hard brittle roof, well-developed joints, weak key strata	Plastic soft rock/clay-rich; good closure, low permeability
mining method	High mining height, full extraction, repeated multi-seam/advance mining, multiple roof breaks	Local mining, waterproof pillars/backfill, reduced overburden breakage
hydrogeological	High water table; karst or water-rich Quaternary, fractures connect to hydraulic pathways	Low water table, well-sealed aquifer, poor infiltration
structural	Active faults/fracture belts linking surface to deep, high-permeability channels	Stable structure, few or sealing faults, poorly developed fractures
external environment	Heavy rainfall or frequent freeze–thaw, promotes expansion/connection	Arid or weak seasonality, scarce rain, weak infiltration
human activities	Large-scale surface works with mining, intensify opening/subsidence	Low development; minimal additional load, weaker coupling

6. Conclusion and Foresight

6.1 Conclusions

This research systematically summarizes the research conditions of ground collapse fractures and water-conducting fracture zones in domestic and abroad, reviewing major advances in formation mechanisms, hazard impacts, and monitoring and prevention technologies. Comparative analysis indicates that domestic research provided depth insights into development patterns, establishing empirical formulas and models. The advancement of monitoring techniques provided tools for fracture-fracture zone coupling research, together with theoretical models, form the theoretical foundation and methodological framework of this study.

(2) Analyzing the geological characteristics of typical regions, revealing the regional differences in fracture and fracture zone development, emphasizing the importance of site-specific approaches. It is necessary to formulate tailored monitoring, early-warning, and prevention strategies based on the collapsibility of loess, the high-permeability structures of karst, and the superimposed effects of shallow-buried multi-seam mining.

(3) Ground collapse fractures and water-conducting fracture zones differ in causes, physical properties, and hazard modes; surface fractures influenced by shallow soil and climatic conditions, exhibiting large apertures; water-conducting fracture zones controlled by deep rock and mining activities, characterized by dense fractures with deep extension. The two interact through vertical penetration and hydraulic processes, forming the positive feedback loop of overburden failure and surface subsidence. Prevention and control aim to cut off connection channels spatially, implement proactive measures in timely manner, and integrate monitoring, modeling, and engineering methods into a comprehensive strategy.

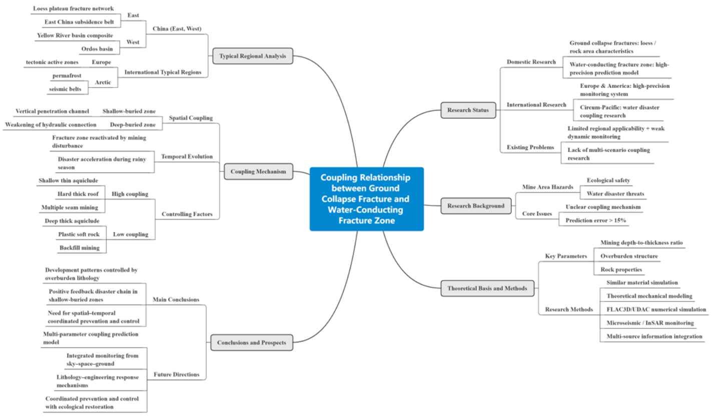

Fig. 3 Research Flowchart

6.2 Limitations and Foresight

Existing prediction and risk assessment models are dependent on specific geological conditions and lack the universality of multi-factor coupling; it is necessary to integrate parameters such as lithology, structural features, and mining activities, and combining them with machine learning to improve prediction accuracy. Monitoring technologies integrate InSAR, microseismic, and borehole methods to achieve real-time correlated observations. The mechanisms of interaction between lithological differences and mining activities are still not well understood, requiring multi-field coupling experiments and targeted engineering measures. Meanwhile, ecological-engineering synergy should strengthened by establishing long-term monitoring systems and promoting the simultaneous implementation of disaster prevention and ecological restoration.

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