V. Civil, Hydraulic, and Architectural Engineering

1 Engineering research fronts

1.1 Trends in Top 10 engineering research fronts

The Top 10 engineering research fronts in the field of civil, hydraulic, and architectural engineering are summarized in Table 1.1.1. These fronts cover a variety of disciplines, including structural engineering, architectural design and theory, geological engineering, transportation engineering, municipal engineering, hydraulic engineering, urban planning and landscaping, and surveying and mapping engineering. The experts nominated three of these fronts: "performance perception assessment and rehabilitation of in-service road, rail, and airport infrastructure", "multi-scale spatial optimization of high-density urban built environment guided by safety and resilience", and "risk identification and control of pathogenic microorganisms in urban water system". The other seven were identified using the co-citation clustering method applied to the top 10% of highly cited papers, and they were agreed, in expert panel meetings, to be worthy of places in the Top 10. Table 1.1.2 presents annual statistics on the core papers published between 2017 and 2022 that are relevant to these Top 10 research fronts.

(1) AI-based structural damage identification and performance prediction

AI-based structural damage identification and performance prediction is a technology that aims to build intelligent models by integrating cutting-edge information technologies, methods and equipment, such as the Internet of Things, big data, machine learning, etc., for the accurate identification of structural damage and the prediction of performance under different loadings and environmental conditions. It is also possible for the model to conduct self-learning and reinforcement based on fusion of real-time

Table 1.1.1 Top 10 engineering research fronts in civil, hydraulic, and architectural engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	AI-based structural damage identification and performance prediction	54	3 616	66.96	2020.6
2	Methods and technologies for carbon-emission reduction in urban regeneration	45	2 229	49.53	2020.0
3	Spatio-temporal distribution and intelligent evaluation of giant geological disaster chains	109	6 081	55.79	2019.6
4	Performance perception assessment and rehabilitation of in-service road, rail, and airport infrastructure	25	852	34.08	2019.9
5	Life-cycle disaster resilience of structural and engineering systems	37	1 456	39.35	2020.8
6	Co-fermentation of municipal sludge and refuse for efficient resource utilization	73	3 012	41.26	2020.0
7	Coordinated evolution of groundwater quantity, quality and environmental impact and groundwater sustainable utilization	72	5 307	73.71	2020.1
8	Multi-scale spatial optimization of high-density urban built environment guided by safety and resilience	16	681	42.56	2020.3
9	Risk identification and control of pathogenic microorganisms in urban water systems	17	816	48.00	2019.4
10	Intelligent object detection in high-resolution remote sensing images	151	14 846	98.32	2020.2

Table 1.1.2 Annual number of core papers published for the Top 10 engineering research fronts in civil, hydraulic, and architectural engineering

No.	Engineering research front	2017	2018	2019	2020	2021	2022
1	AI-based structural damage identification and performance prediction	1	3	8	9	19	14
2	Methods and technologies for carbon-emission reduction in urban regeneration	5	5	8	6	11	10
3	Spatio-temporal distribution and intelligent evaluation of giant geological disaster chains	17	18	14	21	22	17
4	Performance perception assessment and rehabilitation of in-service road, rail, and airport infrastructure	3	3	6	2	4	7
5	Life-cycle disaster resilience of structural and engineering systems	1	2	5	6	4	19
6	Co-fermentation of municipal sludge and refuse for efficient resource utilization	1	1	2	1	6	2
7	Coordinated evolution of groundwater quantity, quality and environmental impact and groundwater sustainable utilization	11	5	9	10	14	23
8	Multi-scale spatial optimization of high-density urban built environment guided by safety and resilience	1	0	3	4	5	3
9	Risk identification and control of pathogenic microorganisms in urban water systems	5	4	6	5	1	4
10	Intelligent object detection in high-resolution remote sensing images	11	15	18	38	29	40

data from structural responses and from radar/vision/sound sensors. The research on AI-based structural damage identification and performance prediction is of great significance, as it can improve the functionality, economy, reliability and safety of structures during their life cycles. The major topics covered by this research front include: ① new sensing equipment for structural damage detection and monitoring; ② standardization and fusion of structural health monitoring data; ③ structural damage detection and localization based on machine learning algorithms; ④ data-driven structural performance prediction methods; and ⑤ physics-informed intelligent models for structural performance prediction. The main development trend is to build a system for the holographic perception of structural status and providing intelligent diagnosis, and to improve ability in structural damage identification and performance prediction models in terms of interpretability, generalization, accuracy, etc. With the integration of physical information and prior knowledge, models can be evolved and widely applied in engineering projects in complex scenarios. Between 2017 and 2022, 54 core papers relevant to this research front were published. These papers received 3 616 citations, with an average of 66.96 citations per paper.

(2) Methods and technologies for carbon-emission reduction in urban regeneration

The methods and techniques for carbon-emission reduction in urban regeneration primarily refer to the integration of strategies to reduce carbon emissions relating to urban renewal design. These methods and techniques introduce carbon-emission reduction approaches and technologies into the process of updating various urban elements, thereby significantly promoting low-carbon development and sustainability in cities. The primary technological directions encompass: ① simulation of energy consumption and microclimate environments in existing urban areas; ② optimization of urban regeneration design schemes and decision-making tools that are subject to carbon reduction goals; ③ integration of carbon-emission reduction technologies with building materials and innovative construction techniques in urban regeneration; and ④ integrated design of carbon-emission reduction technologies for diverse types and scales of urban regeneration elements. The development trend in the field involves integrating interdisciplinary knowledge such as building energy-saving technologies, renewable energy technologies, geographic information science, computer science, and artificial intelligence. This integration facilitates the blending of urban regeneration elements with carbon-emission reduction technologies. Furthermore, the development of digital platforms allows for multi-scenario simulations, application, and monitoring feedback, effectively supporting sustainable and organic urban regeneration. Between 2017 and 2022, 45 core papers relevant to this research front were published. These papers received 2 229 citations, with an average of 49.53 citations per paper.

(3) Spatio-temporal distribution and intelligent evaluation of giant geological disaster chains

The giant geological disaster chain refers to a series of geological disaster events, which include one or more secondary disasters induced by an initial event, directly or indirectly. Compared to a single geological disaster, a giant geological disaster chain shows significant uncertainty. It features a complex formation mechanism with multiple disasters affecting each other and a disaster-enlarging effect caused by the chain-like cumulative amplification process. In recent years, the engineering constructions in high-altitude and cold regions in China, represented by the Sichuan-Tibet Railway, have been facing the threat of giant geological disaster chains. The disaster scale has reached hundreds of millions cubic meters and serious casualties and economic losses have resulted. Accurately predicting the spatio-temporal distribution of such chains and intelligently assessing their ongoing disaster risks is crucial for ensuring the safety, economy, and sustainability of engineering constructions. The current research focuses on: ① spatio-temporal distribution characteristics and intelligent identification of geological disaster chains in complex disaster prone environments; ② formation and evolution mechanism of geological disaster chains and establishment of dynamic models; ③ resilience and risk assessment and optimization methods for preventive structures of geological disaster chains; and ④ real time monitoring and warning, intelligent evaluation and response to preventive decisions for large-scale giant geological disaster chains. The development trend involves distinguishing the spatio-temporal distribution pattern of giant geological disaster chains and clarifying the catastrophe mechanism. On this basis, multi-source data and intelligent algorithms can be integrated to predict the development trend of geological disaster chains and to assess potential risks and impacts. Meanwhile, a real-time monitoring and early warning system needs to be developed based on intelligent technology. At last, an intelligent risk assessment, prevention, control and decision-making system should be built for large-scale and giant geological disaster chains. Between 2017 and 2022, 109 core papers relevant to this research front were published. These papers received 6 081 citations, with an average of 55.79 citations per paper.

(4) Performance perception assessment and rehabilitation of in-service road, rail, and airport infrastructure

The assessment and rehabilitation of in-service road, rail, and airport infrastructure involve the utilization of intelligent perception technologies and comprehensive evaluation methodologies for real-time monitoring, assessment, and prediction of the performance status of existing transportation infrastructure such as roads, railway tracks, and airport facilities. This is essential for accommodating the growing demand for passenger and freight transportation by facilitating necessary improvements and expansions to enhance safety, reliability, and sustainability of transportation infrastructure and adapt to the continually evolving environment and user needs. Compared to new infrastructure development, repair and expansion of in-service road, rail, and airport projects are confronted with more intricate temporal, spatial, and ecological constraints. Research directions within this field encompass the following: ① structural health monitoring and assessment, i.e., utilizing sensor technologies, non-destructive testing methods, and other tools to perform real-time monitoring and comprehensive assessment in order to detect potential structural issues, prevent accidents with efficient and precise assessment, and enhance structural and functional durability; ② traffic load perception and optimization, i.e., leveraging intelligent transportation systems, with big data analytics, and related methodologies to real-time perceived traffic flows for accurate traffic management and scheduling; ③ environmental assessment and enhancement, i.e., monitoring and analyzing factors such as climate and geology to study the impact of traffic loads and environmental changes on structures for optimizing the design and maintenance strategies of transportation infrastructure and ultimately enhancing durability and adaptability; and ④ rehabilitation and expansion planning and design, i.e., integrating analysis of structural in-service state evolution patterns and performance perception assessment to formulate rational plans for facility rehabilitation and expansion, aligning with future transportation development demands. Future developments in this field are anticipated to concentrate on the following areas: high-precision intelligent perception and assessment; sustainability and environmentally friendly low-carbon design; comprehensive performance optimization algorithms and decision models; digital construction and engineering management. Between 2017 and 2022, 25 core papers relevant to this research front were published.

These papers received 852 citations, with an average of 34.08 citations per paper.

(5) Life-cycle disaster resilience of structural and engineering systems

The life-cycle disaster resilience of structural and engineering systems refers to the evaluation and improvement of their resilience to natural and man-made disasters throughout their entire life cycle, including design, construction, maintenance, and demolition. Traditional research on disaster resilience of structural and engineering systems is mainly focused on design and construction stages, with less attention paid to maintenance and demolition stages. As a great number of structural and engineering systems accumulate in various countries around the world, research on disaster resilience of existing structural and engineering systems has significant social significance and strategic value for the construction of resilient cities. Its main research directions include: ① assessment of life-cycle disaster resistance and resilience improvement of a single structure; ② assessment and improvement of disaster resilience of building systems throughout their entire lifespan; ③ assessment and improvement of disaster resilience of lifeline systems such as water, electricity, gas and communication networks; and ④ construction of resilient cities with multiple systems for considering disaster resilience throughout infrastructure lifespan. The main development trend for future research relates to the life-cycle damage mechanism, resilience assessment and resilience improvement for complex and giant systems. Based on this, combined with health monitoring, big data and artificial intelligence, accurate assessment and significant improvement of the life-cycle disaster resilience of urban engineering systems can be achieved. At the same time, the development of intelligence of urban engineering system resilience and disaster prevention can be accelerated, and the disaster resistance safety of urban engineering systems can be improved. This will also lead to establishment of a resilient disaster prevention and control system for the entire lifespan of urban engineering systems. Between 2017 and 2022, 37 core papers relevant to this research front were published. These papers received 1 456 citations, with an average of 39.35 citations per paper.

(6) Co-fermentation of municipal sludge and refuse for efficient resource utilization

Municipal sludge is the inevitable product of municipal sewage treatment, with the dual attributes of "pollution" and "resource". Harmless treatment and resource utilization of sludge are the key measures for promotion of the synergy between pollution control and carbon-emission reduction in the field of water pollution prevention and control. The collaborative anaerobic fermentation treatment of municipal sludge and organic wastes such as refuse can produce significant economic and environmental benefits, which is conducive to improving the degradation efficiency of organic matter and the stability of fermentation systems, and significantly increasing the output of high-value products. Thus, the co-fermentation of municipal sludge and refuse is an effective way to realize the harmless treatment and resource utilization of municipal sludge. The current research focuses on: ① the co-fermentation mechanism and resource efficiency of municipal sludge and refuse under different conditions; ② optimization and control technology of municipal sludge and refuse co-fermentation; ③ the high-value directional transformation mechanism of municipal sludge and refuse co-fermentation; and ④ research and development of municipal sludge and waste co-fermentation equipment. The main development trend in the future is gradual clarification of the influencing factors regarding urban sludge and waste co-fermentation efficiency and energy consumption. On this basis, attention is placed on optimization of the resource path of the municipal sludge and refuse co-fermentation process, strengthening the production of new clean biofuels in the co-fermentation process, further reducing the cost of co-fermentation, and building an efficient resource technology and equipment system of municipal sludge and refuse co-fermentation. Between 2017 and 2022, 73 core papers relevant to this research front were published. These papers received 3 012 citations, with an average of 41.26 citations per paper.

(7) Coordinated evolution of groundwater quantity, quality and environmental impact and groundwater sustainable utilization

Groundwater plays a critical role in the urban and rural water supply, economic and social development, and ecological and environmental maintenance in China. The coordinated progress relating to groundwater quantity, quality and environmental impact concerns the interactions and change in groundwater resources, involving water quality and ecological and geological environmental effects. The sustainable utilization of groundwater is aimed at ensuring that groundwater resources can meet the long-term stable development of human society and the whole environmental system, and can avoid ecological and geological problems and disasters caused by over-exploitation. China's groundwater resources are under great threat due to increased human activity and climate change. The current research focuses on: ① theoretical research of groundwater circulation and distribution, and pollutant migration and transformation; ② development of methodology of groundwater monitoring-simulation-evaluation; ③ technological investigation of groundwater over-exploitation prevention and groundwater remediation; and ④ management of sustainable utilization of groundwater. Future development trends include the following: ① addressing the challenging theoretical task of groundwater circulation as well as the migration and transformation of material and energy in a changing environment; ② developing new methods for air-space-ground integrated groundwater monitoring and interpretation; ③ establishing multi-scale multi-process technical systems for groundwater simulation and prediction and groundwater quantity-quality-environmental impact evaluation; ④ to exploring key technologies for warning, control and prevention of groundwater over-exploitation and its secondary disasters; ⑤ completing key technical challenges on contamination source identification and ecological restoration; ⑥ creating multi-source groundwater storage and sustainable utilization technologies in the continent and ocean; and ⑦ proposing multi-objective optimization management system for different scenarios and groundwater resource regulation measurements and strategies. Between 2017 and 2022, 72 core papers relevant to this research front were published. These papers received 5 307 citations, with an average of 73.71 citations per paper.

(8) Multi-scale spatial optimization of high-density urban built environment guided by safety and resilience

The high-density urban built environment, guided by requirements for safety and resilience, concerns urban planning and design that prioritizes the creation of a living environment that is both secure, disaster-resistant, and sustainable under conditions of high population density. Unlike conventional cities, high-density cities face distinct challenges such as heightened safety risks associated with high-risk buildings, suboptimal performance of disaster-resistant building, low standards of evacuation of buildings, and inadequate building maintenance systems. In recent years, China’s increased frequency of extreme weather and climate events, has subjected the country’s high-density urban disaster prevention systems to rigorous testing. Consequently, the safety and resilience of high-density urban development have formed the basis of a critical research trend. It is of great importance to explore typical disaster scenarios related to high-risk, disaster-resistant, and disaster-avoidance buildings and bolstering urban resilience to effectively manage the profound impacts of climate change. The current research focuses on: ① reevaluation and reformulation of building codes tailored to high-density cities; ② ongoing dynamic monitoring and assessment of buildings within high-density urban areas; ③ enhancement of the resilience and sustainability of buildings in high-density environments; ④ the renewal and renovation of high-density urban building stocks; and ⑤ optimizing disaster resilience in high-density urban and rural built environments within land-sea integrated regions. The development trend of research is to identify vulnerabilities and to gauge the quality of the built environment in high-density cities. On this basis, a combination of research into safety hazards and resilience, coupled with multi-scale analysis and predictive assessment of the myriad risks inherent in mega-city environments, will drive the optimization of high-density urban settings from the perspective of sustainable development. Advanced methodologies like deep learning, data mining, and digital twin technology will be harnessed for this purpose. Between 2017 and 2022, 16 core papers relevant to this research front were published. These papers received 681 citations, with an average of 42.56 citations per paper.

(9) Risk identification and control of pathogenic microorganisms in urban water systems

Urban water environment is closely related to natural circulation and human production activities. There are risks of outbreak and spread of pathogenic microorganisms such as pathogens and viruses in urban water system, mainly from human and animal feces, garbage, domestic sewage and hospital sewage. The migration and spread of pathogenic microorganisms in urban water systems can lead to outbreak of epidemic diseases, posing a serious threat to environmental safety and public health. Effective identification, control, and deep reduction of pathogenic microorganisms in urban water systems, as well as ensuring water safety, are urgent issues that need to be addressed. The main technical directions include: ① building a basic database of the specific types, distribution, transmission patterns, and removal pathways of pathogenic microorganisms in urban rivers/lakes; ② rapid identification, characterization, and risk assessment of pathogenic microorganisms in the water quality monitoring and evaluation system; ③ the inactivation of pathogenic microorganisms by conventional disinfection techniques (chlorine based disinfectants, ozone, UV, etc.) and combined disinfectants; ④ development of novel membrane separation technologies and adsorbents based on the principles of physical separation and adsorption; ⑤ microbial metabolism technologies such as activated sludge process, membrane bio-reactor (MBR) process, etc.; and ⑥ progress towards a comprehensive risk management and control technology system for pathogenic microorganisms, including water source control, water plant removal, and pipeline network protection. Facing the ecological security of urban water systems, future research focuses and challenges mainly include building a database of resistance groups/pathogens/pathogenic viruses in typical water systems, developing a list of water borne pathogenic microorganisms for priority control in river basins, establishing indicative pathogenic microorganisms for health risk assessment, developing high-throughput detection methods with supporting equipment, and establishing a comprehensive control technology system. Between 2017 and 2022, 17 core papers relevant to this research front were published. These papers received 816 citations, with an average of 48.00 citations per paper.

(10) Intelligent object detection in high-resolution remote sensing images

Intelligent object detection methods in high-resolution remote sensing images utilize knowledge engineering, deep learning, logical reasoning, swarm intelligence, and other new artificial intelligence technologies and means, to obtain category and location information from high-resolution remote sensing images. Such technologies are widely used in military and civilian fields such as reconnaissance, surveillance, early warning, and search and rescue. Development trends in this research front include: ① general intelligent target detection methods, which aim to address the challenges faced in remote sensing image target detection, such as class imbalance, high background complexity, multi-scale changes in targets, special imaging perspectives, and small/micro object detection; and ② development of specialized object intelligent detection methods in remote sensing images for significant targets such as airports, buildings, aircraft, ships, vehicles, clouds, and sea ice. The main development trend in the future will be a focus on the challenges of small object detection and multimodal object detection, continuously optimizing the intelligent object detection model, constructing an intelligent high-resolution remote sensing object detection method system guided by knowledge and based on algorithms, thereby promoting intelligent understanding of remote sensing scenes and providing support for the construction of remote sensing image intelligent interpretation systems. Between 2017 and 2022, 151 core papers relevant to this research front were published. These papers received 14 846 citations, with an average of 98.32 citations per paper.

1.2 Interpretations for three key engineering research fronts

1.2.1 AI-based structural damage identification and performance prediction

The damage of civil engineering structures is related to their health status, and directly affects their safety and serviceability. Traditional methods of structural damage identification and performance prediction usually rely on physical sensors and mechanical models, while using AI methods can extract complex damage feature patterns from large amounts of multi-source multi-modal data, and analyze the key parameters that characterize structural performances. Additionally, the model can perform self-learning and reinforcement based on real-time data, to improve the accuracy and robustness of the results in damage identification and performance prediction. The research on AI-based structural damage identification and performance prediction can provide a scientific basis for structural health monitoring, maintenance reinforcement and performance enhancement. This is of great significance in reducing infrastructure operation and maintenance costs, improving management and maintenance strategies, and optimizing the life-cycle design of structures. The major topics in this research field include:

1) New sensing equipment for structural damage detection and monitoring. Efforts are devoted to: ① achieving qualitative perception and quantitative determination of structural damage in different scenarios and scales using various sensing technologies, such as visual and acoustic sensors, microwave radar, distributed Fiber Bragg Grating, nanomaterial sensors, etc.; ② developing new integrated equipment and the corresponding distributed intelligence technology for structural damage detection and monitoring; and ③ establishing intelligent structural damage detection and monitoring systems that are capable of serving in an

autonomous, comprehensive, and efficient way.

2) Standardization and fusion of structural health monitoring data. For the development of AI algorithms and model optimization, studies are carried out to establish the standard for the acquisition, transmission, storage, and usage of structural monitoring data. Technologies such as knowledge graphs, Bayesian networks, probabilistic graphical models, etc., are applied for the aggregation of multi-source and multi-scale data, providing high-availability data for structural damage identification and performance prediction.

3) Structural damage detection and localization based on machine learning algorithms. Based on machine learning models such as deep learning, support vector machine, clustering algorithm, etc., the damage mechanism is studied and surrogate models are built for structural damage detection and localization. Meanwhile, the models are iterated autonomously for self-learning and reinforcement using real-time data for environmental and structural concerns, thereby improving the accuracy and reliability of damage identification.

4) Data-driven prediction methods of structural performance. Considering the complex influencing factors of performances and the scarce data feature of engineering structures, data processing methods are proposed for feature extraction and feature analysis, and the data dimension is reduced effectively and efficiently. By combining active learning, reinforcement learning, and transfer learning, data-driven models relating to key characteristic parameters are established to predict various aspects of structural performances, including the mechanical performance, disaster prevention and mitigation resilience, and life cycle performance.

5) Physics-informed intelligent models for structural performance prediction. By the development of data, knowledge, models, and intelligent algorithms, mechanical theories and experts' priori knowledge can be introduced to propose a hybrid paradigm of physics-informed intelligent modeling for structural performance prediction. It is important for AI models to break through the bottleneck of the data dependency of model training and the deficiency in interpretability and generalization ability due to the "black box". Such a breakthrough can drastically improve the accuracy and practicability of the data-driven model for performance prediction on engineering structures.

As shown in Table 1.1.1, 54 core papers concerning "AI-based structural damage identification and performance prediction" were published between 2017 and 2022, with each paper being cited 66.96 times on average. The top five countries in terms of output of core papers on this topic are Vietnam, Belgium, China, Republic of Korea, and the USA (Table 1.2.1). China is one of the most active countries, having published 25.93% of the core papers. The five countries with the highest average citations were the USA, Algeria, Belgium, Vietnam, and Japan. The papers published by Chinese authors were cited 66.36 times on average, which is slightly below the overall average. As illustrated by the international collaborative network depicted in Figure 1.2.1, close cooperation was observed among the ten most productive countries.

The five institutions that published the most core papers were Ghent University, Ton Duc Thang University, Ho Chi Minh City Open University, Southeast University, and University of Transport & Communications (Table 1.2.2). In terms of number of publications, the top three institutions collaborated frequently, focusing on AI models for structural damage identification. They proposed various algorithms to solve the inverse problems in structural health monitoring, i.e. identifying structural damage based on responses such as structural stiffness, frequencies, and strain energy, etc. Their research primarily applies to laminated composite structures, and is also applicable in actual bridges. As illustrated in Figure 1.2.2, the ten most productive institutions have conducted collaborative studies in this regard.

As shown in Table 1.2.3, the five most active countries in terms of paper citing were China, the USA, Vietnam, Republic of Korea, and Iran. The top five institutions in terms of citing core papers were Tongji University, Southeast University, Ghent University, Ho Chi Minh City Open University, and Harbin Institute of Technology (Table 1.2.4). According to the citations of core papers, there were differences between the top five countries in terms of output of core papers and the five most active countries in terms of paper citations, which indicates that this front has received attention from scholars from different countries.

Based on the above statistics, the proportion of paper citations in China is far higher than the proportion of core papers from China, indicating that Chinese researchers pay close attention to this front.

In the next ten years, the key development direction in this research front is to build a holographic perception system for structure status, to establish a structure intelligent diagnosis system driven by multi-modal large models and to enhance model performance for structural damage identification and performance prediction. On one hand, these developments rely on highly-integrated intelligent perception technology, combined with multi-source multi-modal data fusion modeling, which significantly improves the capacity and quality of available data. On the other hand, the damage mechanism and performance evolution process of structures under multi-factor multi-objective conditions can be taken into account for the exploration of the new paradigm that combines knowledge-driven learning models and physics information. Hence, it can achieve the improvement of structural damage identification and performance prediction in terms of interpretability, generalization, accuracy, etc. Relevant research studies can be applied to the operation and maintenance of existing structures, as well as to the design and construction of new structures, thus there is a great potential of development and a wide range of practical scenarios (Figure 1.2.3).

Table 1.2.1 Countries with the greatest output of core papers on "AI-based structural damage identification and performance prediction"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Vietnam	22	40.74	1 607	73.05	2020.2
2	Belgium	20	37.04	1 585	79.25	2020.0
3	China	14	25.93	929	66.36	2020.9
4	Republic of Korea	14	25.93	913	65.21	2020.9
5	USA	10	18.52	1 041	104.10	2020.2
6	Algeria	10	18.52	900	90.00	2020.2
7	Japan	6	11.11	430	71.67	2020.0
8	Italy	6	11.11	266	44.33	2020.2
9	Canada	5	9.26	289	57.80	2021.2
10	India	4	7.41	279	69.75	2021.2

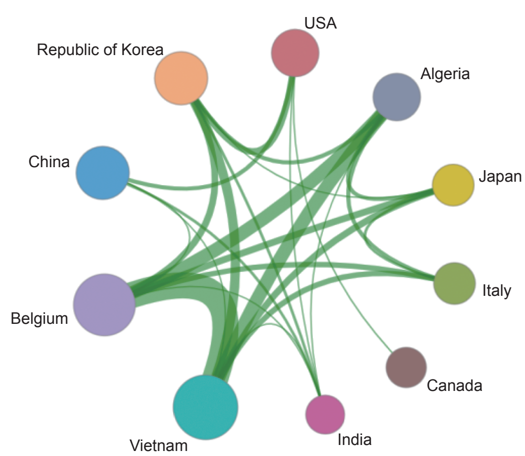

Figure 1.2.1 Collaboration network among major countries in the engineering research front of "AI-based structural damage identification and performance prediction"

Table 1.2.2 Institutions with the greatest output of core papers on “AI-based structural damage identification and performance prediction”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Ghent University	20	37.04	1 585	79.25	2020.0
2	Ton Duc Thang University	13	24.07	1 192	91.69	2019.5
3	Ho Chi Minh City Open University	8	14.81	500	62.50	2021.2
4	Southeast University	8	14.81	380	47.50	2021.2
5	University of Transport & Communications	7	12.96	499	71.29	2020.0
6	Chang’an University	6	11.11	256	42.67	2021.3
7	University of California, Los Angeles	4	7.41	393	98.25	2019.8
8	Hanyang University	4	7.41	351	87.75	2020.2
9	Mouloud Mammeri University of Tizi-Ouzou	4	7.41	319	79.75	2020.5
10	Tongji University	4	7.41	315	78.75	2020.5

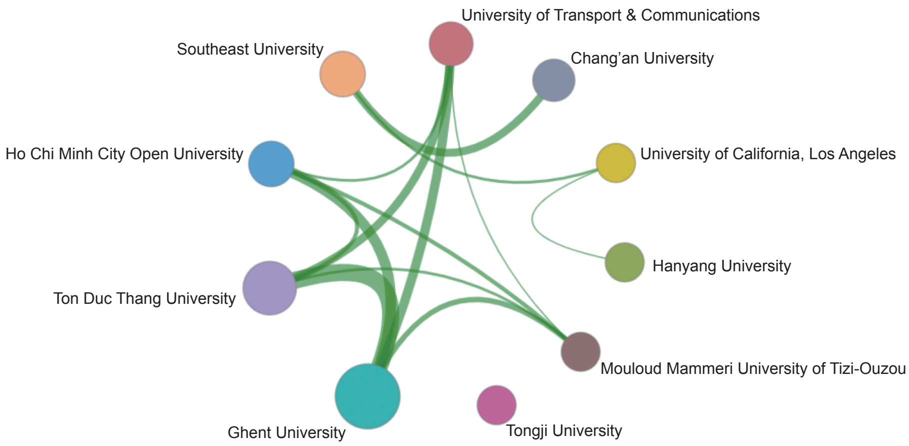

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “AI-based structural damage identification and performance prediction”

Table 1.2.3 Countries with the greatest output of citing papers on “AI-based structural damage identification and performance prediction”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	868	40.07	2021.7
2	USA	235	10.85	2021.5
3	Vietnam	169	7.80	2021.4
4	Republic of Korea	144	6.65	2021.6
5	Iran	142	6.56	2021.6
6	India	138	6.37	2021.7
7	Italy	105	4.85	2021.7
8	Australia	102	4.71	2021.7
9	Canada	99	4.57	2021.7
10	Saudi Arabia	87	4.02	2021.6

Table 1.2.4 Institutions with the greatest output of citing papers on “AI-based structural damage identification and performance prediction”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Tongji University	95	17.66	2021.7
2	Southeast University	87	16.17	2021.7
3	Ghent University	74	13.75	2021.0
4	Ho Chi Minh City Open University	43	7.99	2021.7
5	Harbin Institute of Technology	41	7.62	2021.8
6	The Hong Kong Polytechnic University	40	7.43	2021.9
7	Ton Duc Thang University	36	6.69	2020.5
8	Dalian University of Technology	33	6.13	2021.7
9	Yonsei University	31	5.76	2021.7
10	University of Transport & Communications	30	5.58	2020.8

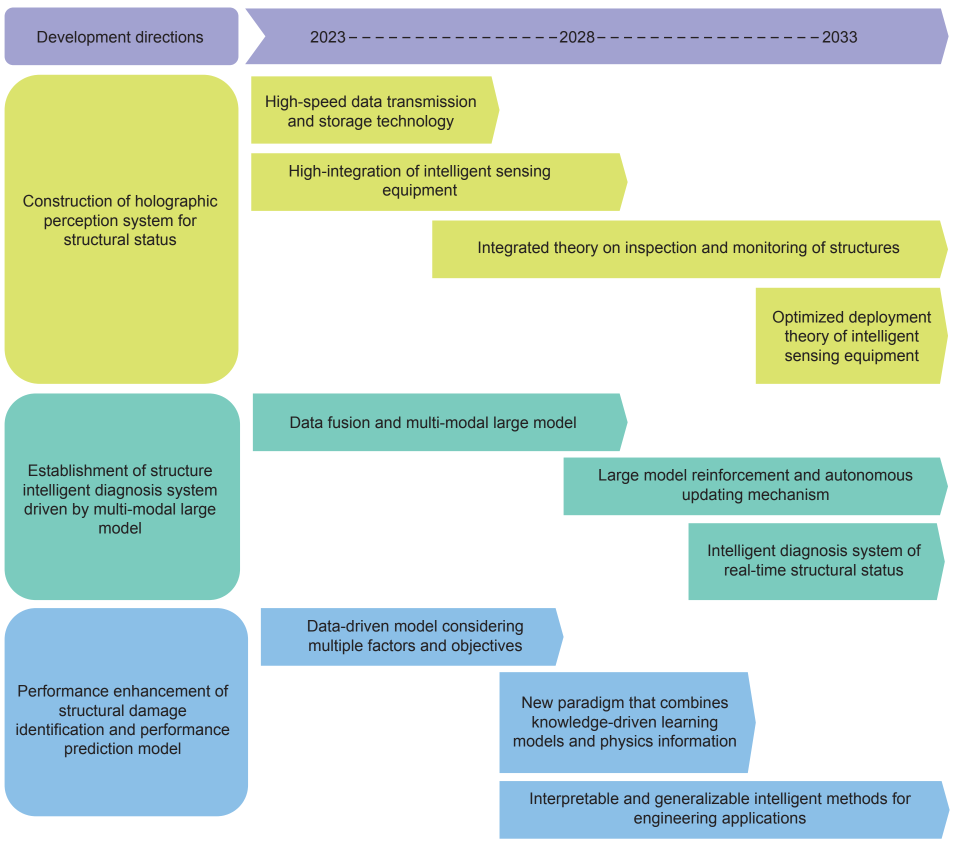

Figure 1.2.3 Roadmap of the engineering research front of “AI-based structural damage identification and performance prediction”

1.2.2 Methods and technologies for carbon-emission reduction in urban regeneration

Urban regeneration, optimizing the physical conditions, spatial forms, and functions of the entire urban system, plays a crucial role in improving the currently high-energy consumption and high-carbon-emitting components of cities. It offers pivotal intervention for reducing urban carbon dioxide emissions. However, the current approach to urban regeneration primarily relies on traditional models, which face challenges such as difficulty in integrating urban regeneration targets with carbon-emission reduction technologies, limited perspectives on integration, low digital precision, and a lack of practical applications.

Therefore, the forefront and focus of research and development in urban regeneration methods and technologies lie in establishing systematic integration and collaborative mechanisms for applying various carbon-emission reduction technologies in urban regeneration. This involves exploring methods utilizing machine learning, genetic algorithms, and other techniques to optimize design and decision-making processes, as well as innovation of the integration of high-performance building materials with carbon-emission reduction technologies. The primary technological directions encompass:

1) Simulation of energy consumption and microclimate environment in existing urban areas. This involves leveraging extracted building big data information and relevant standard specifications, combined with GIS and building energy simulation tools, to automatically generate regional models of building energy consumption and carbon emissions. These models enable rapid modeling at the regional scale and can be automatically calibrated based on real-world data.

2) Optimization of urban regeneration design schemes and decision-making tools under carbon reduction goals. This involves utilizing advanced technologies and methods such as machine learning, big data analytics, and genetic algorithms to develop systems and platforms for scenario simulation and low-carbon assessment. These systems and platforms identify the current carbon dioxide emissions status and reduction potential of different urban regeneration measures, and generate the most suitable urban regeneration schemes through multi-objective optimization.

3) Integration of carbon-emission reduction technologies with building materials and innovative construction techniques in urban regeneration. The construction industry is considered a major consumer of raw materials and energy. In the maintenance and renovation of existing buildings and infrastructure, the application of high-performance building materials and innovative construction techniques integrated with carbon-emission reduction technologies can prove advantageous in addressing the challenges of low energy efficiency and high carbon emissions faced by the construction industry.

4) Integrated design of carbon reduction technologies for diverse types and scales of urban regeneration elements. Urban regeneration involves comprehensive and complex system engineering projects. In addition to in-depth research on the application of carbon-emission reduction technologies to individual urban regeneration elements, it is essential to establish the coupling of emission reduction technologies to utilization by various urban elements. This includes areas such as energy, buildings, transportation, waste management, and carbon sequestration techniques.

As shown in Table 1.1.1, 45 core papers concerning "methods and technologies for carbon-emission reduction in urban regeneration" were published between 2017 and 2022, with each paper being cited 49.53 times on average. The top five countries in terms of output of core papers on this topic are China, the USA, the UK, Italy, and Australia (Table 1.2.5). China is the most active country, having published 55.56% of the core papers. The five countries with the highest citations per paper were China, Australia, the USA, Singapore, and Israel. The papers published by Chinese authors were cited 62.40 times on average, which is above the overall average. As illustrated by the international collaborative network depicted in Figure 1.2.4, close cooperation was observed among the ten most productive countries.

The five institutions that published the most core papers were China University of Mining & Technology, East China Normal University, Wuhan University, Shanghai Jiao Tong University, and University of Shanghai for Science and Technology (Table 1.2.6). The forefront directions at China University of Mining and Technology primarily include research on the development of renewable energy, smart city policies, and industrial integration to enhance energy efficiency, reduce carbon emissions, and mitigation of the impact of air pollution. This research aims to provide empirical evidence and policy insights. At East China Normal University, the forefront directions mainly involve studying the spatio-temporal variations of CO_2 from a multi-scale perspective and examining the impact of government policies on ecological efficiency. This research aims to provide scientific foundations for feasible CO_2 emission reduction policies. At Wuhan University, the forefront directions focus on studying the distribution characteristics and deployment potential of different renewable energy sources, as well as the influencing mechanisms on their power generation efficiency. Additionally, attention is given to the spatio-temporal distribution patterns of PM2.5, CO_2, and their influencing factors. As illustrated in Figure 1.2.5, the ten most productive institutions have conducted collaborative studies in this regard.

As shown in Table 1.2.7, the five most active countries in terms of citations were China, the USA, the UK, Australia, and Italy. The top five institutions in terms of citations were Chinese Academy of Sciences, China University of Mining & Technology, Chongqing University, Wuhan University, and Tsinghua University (Table 1.2.8). China ranked first in the quantity of core papers produced and the number of citations of core papers, indicating that Chinese researchers pay close attention to this front.

Summarizing the above statistics, Chinese scholars have performed well and become leaders in the research of “methods and technologies for carbon-emission reduction in urban regeneration”.

The key development directions for the forefront of “Methods and technologies for carbon-emission reduction in urban regeneration” in the next 5–10 years will be as follows: the development and application of carbon reduction materials in urban regeneration; integration of new energy and building technologies; optimization of low-carbon design in urban regeneration; integration of carbon-emission reduction technologies; application of digital technologies and verification of carbon-emission reduction effectiveness.

Specifically, in the construction and computation of energy consumption and carbon emissions simulations, efforts will be made to improve the accuracy of precise accounting and dynamic prediction of carbon emissions from urban-scale building clusters, catering to different scales of urban regeneration design.

In terms of technology integration and application, there will be a focus on promoting iterative updates of individual carbon-emission reduction engineering technologies in urban and neighborhood renewal projects, while establishing integrated carbon-emission reduction technologies for multi-system coupling in urban regeneration projects.

Regarding the development of decision support tools for low-carbon urban regeneration, the emphasis will be on establishing comprehensive platforms for optimizing solutions with various emission reduction technologies, and clarifying the “low-carbon” goals, indicators, and technological pathways for different regions and stages of urban development (Figure 1.2.6).

Table 1.2.5 Countries with the greatest output of core papers on “methods and technologies for carbon-emission reduction in urban regeneration”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	25	55.56	1 560	62.40	2020.3
2	USA	5	11.11	258	51.60	2021.2
3	UK	4	8.89	157	39.25	2021.0
4	Italy	4	8.89	65	16.25	2019.2
5	Australia	3	6.67	171	57.00	2018.0
6	Singapore	3	6.67	130	43.33	2017.7
7	Germany	3	6.67	122	40.67	2019.3
8	Bangladesh	3	6.67	98	32.67	2022.0
9	Malaysia	3	6.67	98	32.67	2022.0
10	Israel	2	4.44	84	42.00	2019.0

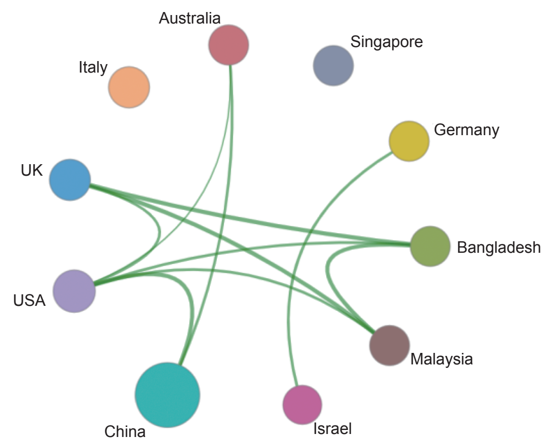

Figure 1.2.4 Collaboration network among major countries in the engineering research front of "methods and technologies for carbon-emission reduction in urban regeneration"

Table 1.2.6 Institutions with the greatest output of core papers on "methods and technologies for carbon-emission reduction in urban regeneration"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China University of Mining & Technology	6	13.33	327	54.50	2021.7
2	East China Normal University	4	8.89	311	77.75	2018.2
3	Wuhan University	4	8.89	244	61.00	2019.5
4	Shanghai Jiao Tong University	4	8.89	212	53.00	2020.0
5	University of Shanghai for Science and Technology	4	8.89	212	53.00	2020.0
6	Chongqing University	3	6.67	202	67.33	2021.3
7	Hebei University of Technology	3	6.67	202	67.33	2021.3
8	Technical University of Munich	3	6.67	122	40.67	2019.3
9	Khulna University of Engineering and Technology	3	6.67	98	32.67	2022.0
10	Rajshahi University of Engineering and Technology	3	6.67	98	32.67	2022.0

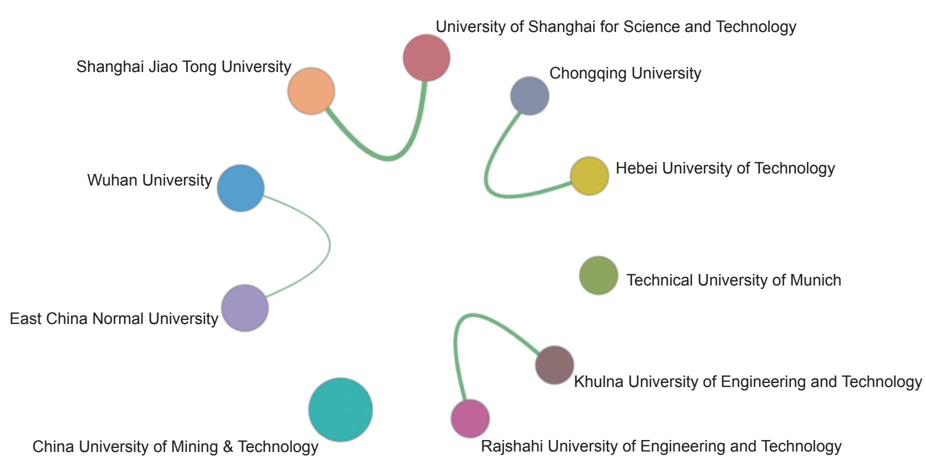

Figure 1.2.5 Collaboration network among major institutions in the engineering research front of "methods and technologies for carbon-emission reduction in urban regeneration"

Table 1.2.7 Countries with the greatest output of citing papers on "methods and technologies for carbon-emission reduction in urban regeneration"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	1 194	66.70	2021.5
2	USA	149	8.32	2021.3
3	UK	100	5.59	2021.5
4	Australia	75	4.19	2021.3
5	Italy	59	3.30	2021.1
6	Spain	43	2.40	2021.3
7	Singapore	37	2.07	2021.2
8	Germany	36	2.01	2021.2
9	Japan	33	1.84	2021.3
10	Malaysia	32	1.79	2021.6

Table 1.2.8 Institutions with the greatest output of citing papers on "methods and technologies for carbon-emission reduction in urban regeneration"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	126	23.25	2021.0
2	China University of Mining & Technology	62	11.44	2021.8
3	Chongqing University	60	11.07	2021.5
4	Wuhan University	54	9.96	2021.1
5	Tsinghua University	41	7.56	2021.2
6	China University of Geosciences	37	6.83	2021.2
7	Tianjin University	35	6.46	2021.5
8	Beijing Normal University	33	6.09	2020.8
9	Shandong University	33	6.09	2021.2
10	Shanghai Jiao Tong University	32	5.90	2020.9

1.2.3 Spatio-temporal distribution and intelligent evaluation of giant geological disaster chains

Giant geological disaster chains often occur in high-altitude frigid mountainous areas worldwide. With the increase of construction scale, major engineering constructions around the world gradually expand to those regions with harsh geological conditions. However, complex terrain and geomorphic conditions, dense regional fault zones, and frequent strong earthquake activities pose significant disaster risks to engineering construction and safe operation. In addition, as "amplifiers" of global warming, high-altitude frigid mountainous areas have been affected by frequent extreme climate events worldwide in recent years, accelerating the occurrence of giant geological disaster chains, posing huge challenges to major engineering construction, operation, and management. Studying the spatio-temporal distribution and intelligent evaluation of giant geological disaster chains is of great significance for ensuring safe production and accelerating infrastructure construction.

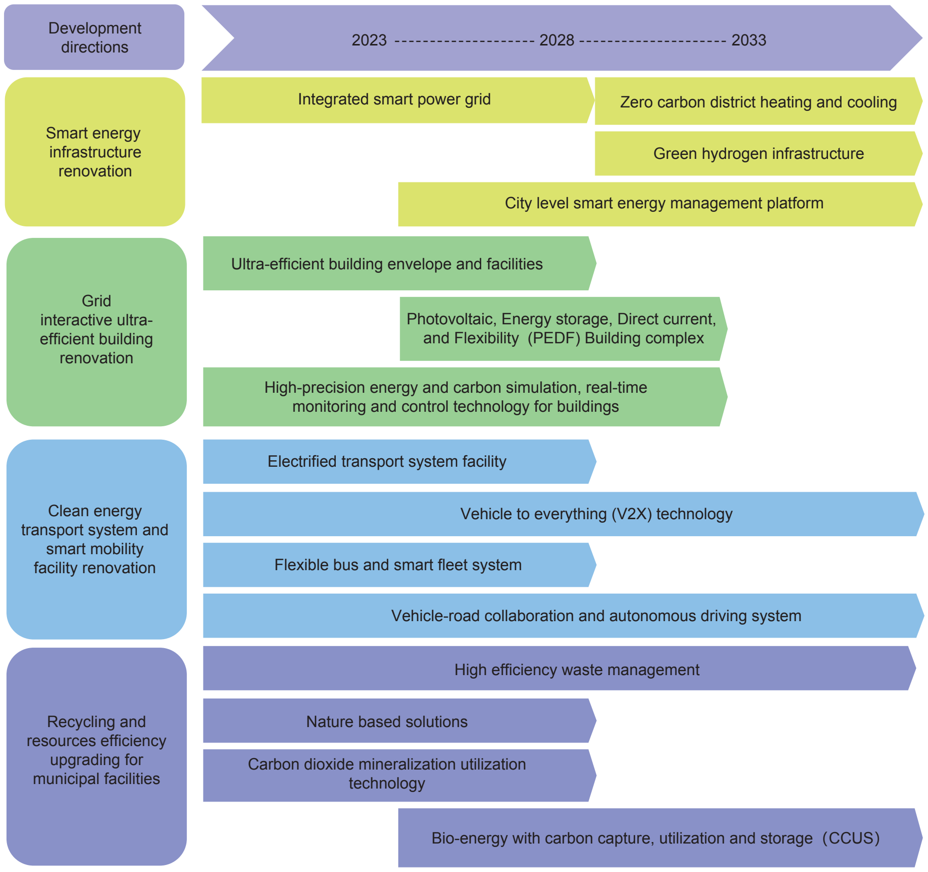

Figure 1.2.6 Roadmap of the engineering research front of "methods and technologies for carbon-emission reduction in urban regeneration"

Currently, the major topics of this research front include:

1) The spatio-temporal distribution characteristics and intelligent identification of geological disaster chains in complex disaster-prone environments. The geological disaster chain often occurs in high-altitude remote mountainous areas. The following issues are of interest: ① combining multi-source heterogeneous data interpretation algorithms based on the comprehensive remote sensing technology of multiple sources such as satellite, aerial, ground, and underground; ② establishing a database of geological disaster chains in mountainous areas to reveal the relationship between the formation of geological disasters and complex disaster gestation factors; ③ identifying the main disaster causing factors and summarizing the spatio-temporal development and distribution patterns of geological disaster chains; ④ establishing early identification markers for different types of geological disaster chains by machine learning image recognition technology; and ⑤ realizing intelligent identification of key sections of potential mutual transformation in the geological disaster chain.

2) The construction of a dynamic model for the genetic and chain evolution mechanism of geological disasters. Efforts are devoted to: ① the effects of complex disaster gestation conditions such as seismic motion, rainfall, and temperature on the mechanical properties of disaster bodies such as pore water pressure, stress, and strength; ② coupled studies from the perspectives of macroscopic geological dynamic processes and microscopic particle mechanical characteristics to reveal the critical mechanical conditions for the transformation of multiphase (solid-liquid) and multistage (flow-blockage-collapse) disasters; and ③ establishing a multi-scale coupled dynamic model that considers the macro and micro interconnected effects.

3) Establishment of resilience and risk assessment and preventive structure optimization methods for geological disaster chains. The aims are to: ① construct a random evaluation method for the disaster range to address the suddenness, uncertainty, and

complex attributes of the giant geological disaster chain; ② conduct large-scale spatio-temporal risk prediction and risk zoning evaluation combined with artificial intelligence algorithms; ③ use a Pareto optimality method to achieve local optimization and adjustment of high-risk section lines; ④ evaluate the impact resistance performance of different types of protective structures with stochastic dynamic equations and obtain the stochastic dynamic response laws of engineering structural performance indicators; and ⑤ characterize the failure probability and vulnerability of engineering structures from the probability density function level and carry out structural design based on the concept of recoverability.

4) Real time monitoring and warning, intelligent evaluation, and response to preventive decisions for large-scale giant geological disaster chains. The aftermath of geological disaster chains often involves large-scale hazards across administrative regions (national boundaries, provincial boundaries, county boundaries), resulting in delay in disaster assessment and difficulty in intelligent coordination of risk management. The requirement, therefore, is to: ① upgrade the risk assessment parameters of intelligent algorithms based on multi-source monitoring data and dynamic numerical simulation results; ② build an intelligent dynamic evaluation system and a standardized early warning system for the entire processes of geological disaster chains, including early identification, investigation and evaluation, monitoring and warning, and risk zoning; and ③ make different resilient risk prevention and control measures for different warning levels.

As shown in Table 1.1.1, 109 core papers concerning “spatio-temporal distribution and intelligent evaluation of giant geological disaster chains” were published between 2017 and 2022, with each paper being cited 55.79 times on average. The top five countries in terms of output of core papers on this topic are China, Australia, the USA, Italy, and the UK (Table 1.2.9). China is one of the most active countries, having published 77.06% of the core papers. The five countries with the highest citations per paper were Norway, India, Vietnam, Iran, and Australia. The papers published by Chinese authors were cited 56.32 times on average, which is above the overall average. As illustrated by the international collaborative network depicted in Figure 1.2.7, close cooperation was observed among the ten most productive countries.

The five institutions that published the most core papers were China University of Geosciences, Chengdu University of Technology, Nanchang University, Chinese Academy of Sciences, and Newcastle University (Table 1.2.10). China University of Geosciences has focused on landslide displacement prediction based on multi-source data fusion and artificial intelligence algorithms, Chengdu University of Technology and Nanchang University have focused on the landslide susceptibility prediction based on machine learning algorithms. As illustrated in Figure 1.2.8, the ten most productive institutions have conducted collaborative studies in this regard.

As shown in Table 1.2.11, the five most active countries in terms of paper citations were China, the USA, Italy, Iran, and India. The top five institutions in terms of citations of core papers were China University of Geosciences, Chinese Academy of Sciences, Chengdu University of Technology, Chang’an University, and Duy Tan University (Table 1.2.12). China ranked first in the quantity of core papers produced and the number of citations of core papers, indicating that Chinese researchers pay close attention to this front.

Based on the statistical data above, research on “spatio-temporal distribution and intelligent evaluation of giant geological disaster chains” is still in its infancy. Compared with foreign peers, Chinese scholars are in a leading position.

In the next decade, the frontier in this field must lie in the following areas: spatio-temporal development characteristics and early identification of geological disaster chains based on multi-source heterogeneous data analysis; the clarification of the genetic mechanism and chain evolution mechanism under multiple disaster factors; the establishment of resilient and risk assessment and preventive optimization methods for geological hazard chains under extreme climate change; and the promotion of real-time monitoring, warning, and intelligent disaster prevention decision-making system development. At the same time, this front will gradually develop towards quantification, intelligence, and systematization. With increasingly harsh geological environments and frequent extreme weather conditions encountered during engineering construction and operation, this cutting-edge research achievement will be widely applied in engineering construction and safe operation, with huge development potential (Figure 1.2.9).

Table 1.2.9 Countries with the greatest output of core papers on "spatio-temporal distribution and intelligent evaluation of giant geological disaster chains"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	84	77.06	4 731	56.32	2019.7
2	Australia	14	12.84	1 124	80.29	2019.2
3	USA	14	12.84	984	70.29	2019.6
4	Italy	13	11.93	913	70.23	2019.5
5	UK	6	5.50	273	45.50	2018.2
6	Norway	4	3.67	631	157.75	2018.2
7	Iran	4	3.67	489	122.25	2020.2
8	India	3	2.75	465	155.00	2019.7
9	Vietnam	3	2.75	458	152.67	2020.0
10	France	3	2.75	135	45.00	2019.7

Figure 1.2.7 Collaboration network among major countries in the engineering research front of "spatio-temporal distribution and intelligent evaluation of giant geological disaster chains"

Table 1.2.10 Institutions with the greatest output of core papers on "spatio-temporal distribution and intelligent evaluation of giant geological disaster chains"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China University of Geosciences	23	21.10	1 901	82.65	2019.3
2	Chengdu University of Technology	15	13.76	819	54.60	2020.0
3	Nanchang University	12	11.01	941	78.42	2019.7
4	Chinese Academy of Sciences	12	11.01	548	45.67	2019.9
5	Newcastle University	11	10.09	996	90.55	2019.4
6	Tsinghua University	9	8.26	295	32.78	2020.7
7	Sichuan University	5	4.59	293	58.60	2020.0
8	Tongji University	5	4.59	201	40.20	2020.8
9	Chang'an University	5	4.59	92	18.40	2021.2
10	The Hong Kong University of Science and Technology	4	3.67	155	38.75	2020.5

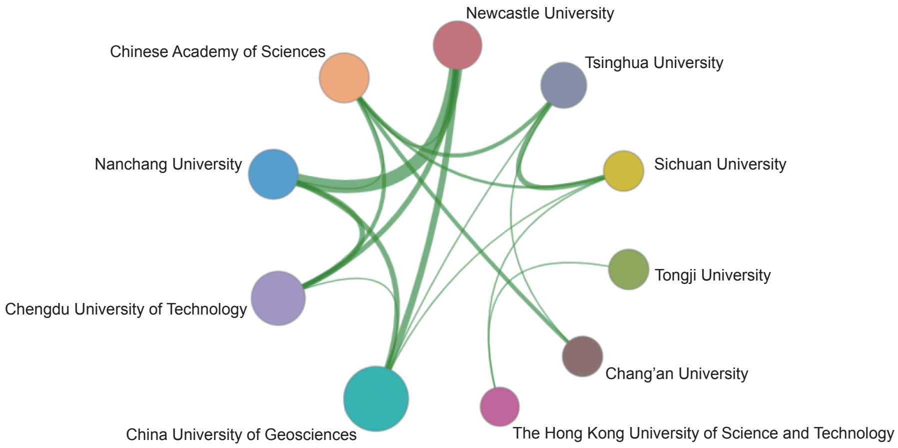

Figure 1.2.8 Collaboration network among major institutions in the engineering research front of "spatio-temporal distribution and intelligent evaluation of giant geological disaster chains"

Table 1.2.11 Countries with the greatest output of citing papers on "spatio-temporal distribution and intelligent evaluation of giant geological disaster chains"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	2 588	54.11	2021.2
2	USA	358	7.48	2020.8
3	Italy	306	6.40	2020.9
4	Iran	284	5.94	2020.7
5	India	276	5.77	2021.3
6	UK	232	4.85	2020.9
7	Vietnam	198	4.14	2020.5
8	Australia	175	3.66	2020.8
9	Germany	135	2.82	2020.8
10	Canada	117	2.45	2020.8

Table 1.2.12 Institutions with the greatest output of citing papers on "spatio-temporal distribution and intelligent evaluation of giant geological disaster chains"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	China University of Geosciences	369	20.79	2020.9
2	Chinese Academy of Sciences	350	19.72	2021.1
3	Chengdu University of Technology	253	14.25	2021.2
4	Chang'an University	129	7.27	2021.2
5	Duy Tan University	108	6.08	2020.1
6	Tongji University	104	5.86	2021.2
7	Southwest Jiaotong University	103	5.80	2021.4
8	Sichuan University	94	5.30	2021.3
9	Chongqing University	94	5.30	2021.3
10	Wuhan University	89	5.01	2021.1

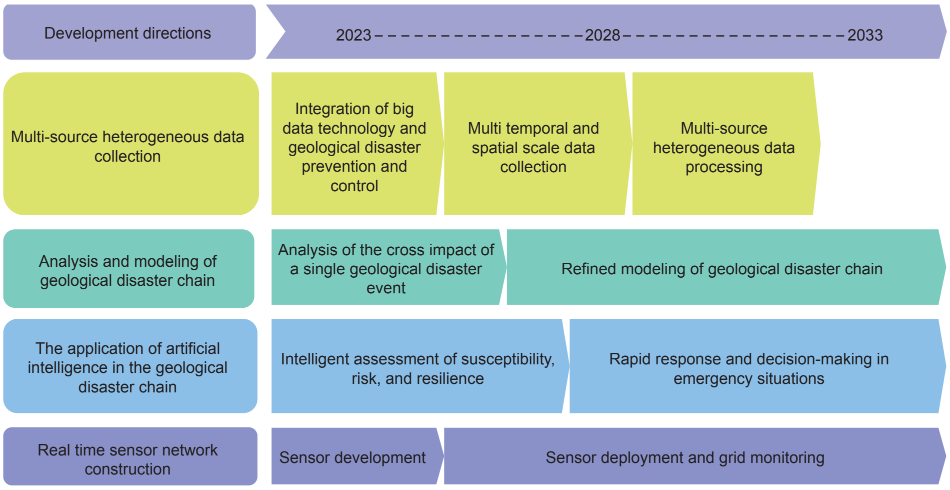

Figure 1.2.9 Roadmap of the engineering research front of "spatio-temporal distribution and intelligent evaluation of giant geological disaster chains"

2 Engineering development fronts

2.1 Trends in Top 10 engineering development fronts

The Top 10 engineering development fronts in the fields of civil, hydraulic, and architectural engineering are summarized in Table 2.1.1. These fronts cover a variety of disciplines, including municipal engineering, surveying and mapping engineering, urban planning and landscaping, architectural design and theory, transportation engineering, hydraulic engineering, construction materials, geotechnical and underground engineering, and structural engineering. The panel experts nominated the following development fronts: "intelligent detection and rehabilitation technology of drainage pipe leakage", "core technology for 1 mm level global and regional coordinate frame", and "advanced technologies for the construction and maintenance of road, rail, and airport infrastructure in extreme environments". The remaining development fronts were identified from patent maps and agreed in the expert panel meetings. Table 2.1.2 presents annual statistics on patents registered between 2017 and 2022 related to these Top 10 development fronts.

(1) Intelligent detection and rehabilitation technology of drainage pipe leakage

Drainage pipe leakage has become one of the main bottlenecks restricting the safe discharge of stormwater and complete collection and treatment of wastewater. Intelligent detection and rehabilitation technology is designed to detect, diagnose and evaluate the level of structural defects in drainage pipe, and carry out low disturbance, high quality and proactive repair, which makes the drainage pipe run safely and efficiently. Moreover, along with the development of the Internet of Things, big data and cloud computing, the leakage detection technology will shift from periodic passive detection to proactive monitoring, providing support for preventive response to potential problems in drainage pipes. The main research areas include: ① digital base technology, including a domestic geographical information system and accurate measurement under complex medium conditions; ② intelligent detection technology, including identification of hidden risks and structural health monitoring via electromagnetic and sound waves; ③ smart assessment technology, including health prediction and adaptive modeling driving by data and models; and ④ efficient early-response technology suitable for large and extra-large drainage pipes, including availability of materials suitable for long distance transportation, corrosion environment and demanding mechanical conditions. The main development trend in the future mainly focuses on precise quantitative detection technology, high strength and high adaptability early-response technology, and detection and rehabilitation quality process control technology based on mobile Internet

Table 2.1.1 Top 10 engineering development fronts in civil, hydraulic, and architectural engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Intelligent detection and rehabilitation technology of drainage pipe leakage	22	43	1.95	2020.8
2	Core technology for 1 mm level global and regional coordinate frame	55	95	1.73	2020.3
3	Digital technology for the protection and utilization of urban historical and cultural resources	19	122	6.42	2020.0
4	Generation technique for space programming of large public buildings supported by artificial intelligence	21	27	1.29	2021.1
5	Advanced technologies for the construction and maintenance of road, rail, and airport infrastructure in extreme environments	19	42	2.21	2020.4
6	*In-situ* observation technologies and equipment in complicated and extreme underwater environments	47	234	4.98	2019.8
7	The technology of preparing carbon-negative building materials from multi-source industrial byproducts	106	985	9.29	2019.5
8	Fast and accurate drilling and sensing technology in complex geological environment	258	1 257	4.87	2019.3
9	Prefabricated structures with components and modular units	286	1 694	5.92	2019.3
10	Smart irrigation and drainage technology and equipment for high productivity farmland	185	1 679	9.08	2019.4

Table 2.1.2 Annual number of core patents published for the Top 10 engineering development fronts in civil, hydraulic, and architectural engineering

No.	Engineering development front	2017	2018	2019	2020	2021	2022
1	Intelligent detection and rehabilitation technology of drainage pipe leakage	1	0	1	6	7	7
2	Core technology for 1 mm level global and regional coordinate frame	6	2	6	16	8	17
3	Digital technology for the protection and utilization of urban historical and cultural resources	3	1	3	4	2	6
4	Generation technique for space programming of large public buildings supported by artificial intelligence	1	0	4	0	3	13
5	Advanced technologies for the construction and maintenance of road, rail, and airport infrastructure in extreme environments	3	1	1	3	3	8
6	*In-situ* observation technologies and equipment in complicated and extreme underwater environments	7	8	3	8	10	11
7	The technology of preparing carbon-negative building materials from multi-source industrial byproducts	15	19	23	16	17	16
8	Fast and accurate drilling and sensing technology in complex geological environment	47	42	53	51	42	23
9	Prefabricated structures with components and modular units	37	57	52	72	65	3
10	Smart irrigation and drainage technology and equipment for high productivity farmland	35	28	33	36	27	26

technology. Between 2017 and 2022, 22 patents relevant to this research front were registered. These patents received 43 citations, with an average of 1.95 citations per patent.

(2) Core technology for 1 mm level global and regional coordinate frame

A coordinate framework is a foundation for describing changes of the Earth, including in terms of shape, expressing geospatial information. It is also a key geospatial information infrastructure for expanding human activities and promoting social development. At present, the latest international Earth reference framework cannot meet the needs of large-scale or global millimeter level Earth system dynamic change monitoring, so the core technology for millimeter level coordinate frameworks has become the forefront in this field. Development trends in this research front include the following. ① Precision spatial geodetic data processing technology determines the optimal VLBI/SLR/GNSS/DORIS data processing strategy through refined mathematical models. Based on this, global benchmark station data is uniformly reprocessed to eliminate or weaken the impact of technical system errors, providing more accurate input data for the establishment of millimeter level coordinate frameworks. ② Modeling the nonlinear motion of the reference station, aiming at the nonlinear displacement caused by geophysical effects, integrating environmental loads, thermal expansion, and other models to establish millimeter level reference station geophysical motion modeling, providing support for the establishment of a millimeter level coordinate framework. ③ A combination of spatial geodetic techniques, such as VLBI, SLR, GNSS, DORIS, etc., providing progress towards establishing a global coordinate framework; ④ Modeling of geocentric motion, combining multiple spatial geodetic techniques and geophysical models to invert geocentric motion, solves the inconsistency between the definition and implementation of the coordinate frame origin, and provides a more accurate geocentric reference framework for geodynamic research. The future development of this front involves precision spatial geodetic data processing technology, nonlinear motion modeling of reference stations, and combination of spatial geodetic technologyand geocentric motion modeling. Between 2017 and 2022, 55 patents relevant to this research front were registered. These patents received 95 citations, with an average of 1.73 citations per patent.

(3) Digital technology for the protection and utilization of urban historical and cultural resources

Protection and utilization of urban historical and cultural resources is an important topic of global concern, involving many fields such as urban cultural heritage, a mixture of natural and cultural heritage, and cultural landscapes. China's urban historical and cultural resources are exceptionally rich, but there are still problems in the field of resource protection and utilization, such as lagging behind others in theoretical research, insufficient systematicity and completeness of basic data, and limited scope of application of new technological methods. Along with the development of a new round of digital technology, the latest intelligent digital technology is being introduced globally into the traditional field of historical and cultural resources protection and utilization, which improves the systematization of the resource protection work and expands the breadth and depth of historical and cultural resources utilization. Thus, strengthening the development and application of the digital technology system for the protection and utilization of urban historical and cultural resources engineering development in China is of great significance for enhancing cultural self-confidence and building a strong cultural country. The forefront of research and development is primarily reflected in the following aspects: ① database construction technology for urban historical and cultural resources; ② intelligent protection technology for urban historical and cultural resources; ③ digitally empowered utilization technology for urban historical and cultural resources; and ④ integrated technology for preservation and utilization of urban historical and cultural resources. The key development directions focus on multiple data source integration, risk perception monitoring, assessment and projection, spatial planning response, value dissemination and utilization, and planning technology integration. Between 2017 and 2022, 19 patents relevant to this research front were registered. These patents received 122 citations, with an average of 6.42 citations per patent.

(4) Generation technique for space programming of large public buildings supported by artificial intelligence

Facing the urgent need to strengthen the whole-process control of large and complex construction projects, the generation technique of architectural space programming integrates multi-disciplinary and whole-process data in architectural design with the utilization of frontier development of artificial intelligence. The technique is able to make complex decisions in architectural space programming, achieving a closed-loop of data interchange from precise diagnosis, through intelligent programming, to integral design. Thus it improves the quantitative nature of decision-making in architectural design and will contribute to solving related problems, such as provision of intelligent decision-making tools for complex architectural programming, acquisition and correlation of spatial performance and human perception data, conversion and connection mechanisms for lifecycle design data, and internal mapping mechanisms between architectural programming and post-occupancy evaluation. The main technical directions include: ① uncertain and fuzzy complex decision-making technique based on graph topology; ② coupling technique of objective evaluation of spatial environment and multi-dimensional ubiquitous human perception information; ③ intelligent integral design technique throughout the building lifecycle; and ④ application of feed-forward inference technique of post-occupancy evaluation data. The major development directions of this study are as follows. Firstly, the scope of application of the technique will be expanded from architecture to full-scale urban space, shifting the focus from the form of spatial composition to places and spatial networks with an emphasis on the correlation of elements within the system. Secondly, the technique will evolve from being data-oriented to being data-driven, strengthening dynamism and connectivity of data, thereby providing powerful data support for achieving intelligent architectural space programming. Thirdly, while the aim is developing from assisting low-dimensional decision-making to solving complex high-dimensional problems, the technique will carry out intelligent technology integration demonstration applications for architectural programming and post occupancy evaluation of large construction projects with intelligence as the main path. Between 2017 and 2022, 21 patents relevant to this research front were registered. These patents received 27 citations, with an average of 1.29 citations per patent.

(5) Advanced technologies for the construction and maintenance of road, rail, and airport infrastructure in extreme environments

The objective of advanced technologies for the construction and maintenance of road, rail, and airport infrastructure in extreme environments is to address challenges posed by extreme weather conditions, geological factors, and natural disasters. These technologies employ advanced maintenance and upkeep techniques to ensure that infrastructure, such as roads, railway tracks, and airports, maintains outstanding construction quality, efficient operational performance, and long-term durability under extreme conditions. This field focuses on ensuring the reliability and stability of transportation systems under adverse environmental conditions, such as high temperatures, heavy rainfall, severe freezing and thawing, chloride salt erosion, while also addressing natural disasters like typhoons, earthquakes, and heavy rainfall to ensure safety. Key technical directions include: ① adaptation of materials and structural design for extreme environments, and development of new materials and structural designs to ensure stability and durability of road, rail, and airport facilities under extreme climate and geological conditions; ② intelligent monitoring and maintenance, with utilization of sensor technologies, monitoring systems, and other tools for real-time monitoring of the status of engineering facilities during construction and operation phases, and with early detection of anomalies to ensure high-quality construction and safe and stable operation of the facilities; ③ disaster resilience assessment and early warning, including use of data analysis and simulation techniques to assess and predict the risks of natural disasters in extreme environments, providing a scientific basis for prevention and response; and ④ emergency response and recovery, with development of emergency response plans and establishment of rapid recovery mechanisms to ensure timely repair and recovery work in the event of disasters. In the future, advanced technologies for the construction and maintenance of road, rail, and airport infrastructure in extreme environments will evolve in the following directions: 1) green and sustainable development; 2) digitalization and intelligent applications; 3) adoption of new materials and techniques; and 4) enhancement of structural resilience. Between 2017 and 2022, 19 patents relevant to this research front were registered. These patents received 42 citations, with an average of 2.21 citations per patent.

(6) *In-situ* observation technologies and equipment in complicated and extreme underwater environments

Underwater on-situ observation involves collection, analysis and display of dynamic change data such as submarine sediment, submarine geological environment and the benthic boundary layer, etc. Such data can be widely used in marine disaster warning, marine resource development and utilization, as well as marine ecological environment protection, governance and restoration, etc. Complicated and extreme marine environments, with features that may include underwater geological conditions, underwater currents, storm surges, and tsunamis, not only cause significant changes in the submarine sediment, submarine geological environment and benthic boundary layer, but also have an impact on the safety of the underwater *in-situ* observation system, on the accuracy of observation data and on the stability of information transmission. The main issues that need to be studied and solved regarding *in-situ* observation technologies and equipment in complicated and extreme underwater environment include the following: ① development of high-precision, high stability and long lifespan independent observation instruments suitable for various observation purposes in complicated and extreme underwater environments; ② development of safe and reliable autonomous mobile observation platforms suitable for complicated and extreme underwater environments, to expand the spatial scale of observations; ③ development of wide area real-time information transmission and precise time synchronization information transmission system, and building large-scale spatio-temporal scale intelligent control underwater *in-situ* observation networks; and ④ development of high energy density, long lifespan and high safety energy storage systems, to provide reliable energy and power support for systematic, collaborative and intelligent underwater *in-situ* observations. Between 2017 and 2022, 47 patents relevant to this research front were registered. These patents received 234 citations, with an average of 4.98 citations per patent.

(7) The technology of preparing carbon-negative building materials from multi-source industrial byproducts

The technology of preparing carbon-negative building materials from multi-source industrial byproducts involves preparation of carbon-negative building materials by the carbonation reaction of alkaline earth metals, e.g., Ca^{2+} and Mg^{2+}, contained in industrial byproducts. The property of the materials prepared and the energy consumed via processing can be further optimized by introducing multiple byproducts and their physical and chemical effects. This technology contributes to carbon emission mitigation in the construction sector and facilitates the recycling of waste materials. The most investigated topics in this field include: ① the carbonation reactivity of calcium (alumino-) silicate materials and approaches to enhancing the reactivity; ② the carbonation reaction, crystallography of carbonation products, and microstructural changes induced by the reaction; ③ approaches to enhancing CO_2 transportation and the carbonation reaction; and ④ industrial processing and facilities. The application of this technology relies on a balance between the materials engineering and environmental performances. For future research, breakthroughs can be made on: ① high-performance cementitious systems with multi-source byproducts; ② multiple reaction mechanisms coupling carbonation and hydration; ③ characterization of the reaction-transport processes by 3D and in-situ test methods; ④ coupling materials preparation with other industrial processes; and ⑤ standards on materials performance and the assessment of environmental impacts. Between 2017 and 2022, 106 patents relevant to this research front were registered. These patents received 985 citations, with an average of 9.29 citations per patent.

(8) Fast and accurate drilling and sensing technology in complex geological environments

“Fast and accurate drilling and sensing technology” refers to the use of advanced drilling technology and equipment to rapidly obtain underground physical data and characterize geological conditions in the face of extremely complex geological conditions during deep underground exploration and engineering construction. Through technologies such as transmission, control, information perception, and data fusion, this approach enables the perception of equipment status and geological environment, precise determination of various parameters, reliable execution of instructions, and the development of intelligent detection equipment, standardized drilling processes, controllable borehole quality, advanced accident prediction, intelligent control of process parameters, and self-assessment of geological parameters. These enhancements ultimately increase the efficiency of obtaining underground physical data and geological information in drilling projects. In deep and complex geological environments, challenges include high temperatures, high pressures, long implementation periods, and significant protocol parameters. These challenges lead to issues in drilling projects such as inadequate drilling equipment power, reduced service life of downhole tools, difficulties in controlling borehole trajectories, and the susceptibility of well-logging instruments to high-temperature failures. The primary technological directions for fast and accurate drilling and sensing technology in complex deep geological environments include: ① development of deep and intelligent automated drilling systems and drilling tools; ② multi-process efficient and high-speed drilling techniques; ③ efficient core sampling technology for complex deep formations; ④ horizontal directional drilling and in-hole comprehensive testing techniques; ⑤ in-well data measurement, transmission, intelligent drilling control based on advanced sensors; ⑥ enhancement of reliability for tools and instruments in high-temperature hard rock formations; and ⑦ advanced ahead-of-time perception technology regarding the downhole formation environment and drilling equipment status. The future development trend is towards lightweight, end-to-end, and automated drilling technology equipment upgrades, as well as the construction of advanced intelligent sensing, measurement, transmission, control, and closed-loop drilling technologies, integrating multiple sources of information from the underground environment. Between 2017 and 2022, 258 patents relevant to this research front were registered. These patents received 1 257 citations, with an average of 4.87 citations per patent.

(9) Prefabricated structures with components and modular units

Construction industrialization has an inevitable tendency by which the traditional construction industry follows the modern industrial mode of production with a purpose of improving construction efficiency, saving energy, reducing consumption, and achieving high quality development. The main characteristics may include standardized design, factory production, assembly construction, integrated decoration and information management, etc. As an efficient way to realize construction industrialization, prefabricated buildings can be assembled on-site with standardized components prefabricated by factory production lines. Therefore, it is of utmost importance for construction industrialization to research and develop effective prefabricated building structural systems, as well as corresponding building components and construction technologies. Current research focuses on: ① prefabricated building structure systems and corresponding design methods; ② prefabricated building components and modular units (including connection components) with different degrees of integration and corresponding design methods; ③ prefabricating technology for factory production of building components and assembling technology for buildings on-site; ④ integrated construction technology; and ⑤ digital and intelligent construction technology. For the ongoing research trend, prefabricated building structure systems will be developed directly from effective components with high-efficiency and high-performance instead of reasonable decomposition of traditional RC, steel or timber structure systems, i.e. using the forward design method. New research fields on intelligent disaster prevention, structural toughness improvement according to prefabricating and assembling construction logistic will develop. The building components will facilitate a high degree of integration, taking forms such as 2D panels or 3D modular units, and standardization and serialization will be emphasized to satisfy the diversity of buildings. Integrating all professionals and the whole industry is focused rather than a single integration, such as structural members with decoration, structural members with specific functions, buildings and equipment. Furthermore, product thinking for buildings and the digital twinning technology will offer wide technical support for construction industrialization and intelligentization. Between 2017 and 2022, 286 patents relevant to this research front were registered. These patents received 1 694 citations, with an average of 5.92 citations per patent.

(10) Smart irrigation and drainage technology and equipment for high productivity farmland

Smart irrigation and drainage technology and equipment refers to the integrated use of technologies such as the internet of things (IoTs), advanced sensors, remote sensing, edge computing, cloud computing, and artificial intelligence (AI) in modern agricultural production. It involves multi-dimensional perception and intelligent analysis of crop growth conditions, field water conditions, irrigation and drainage channel (pipeline) status, and environmental factors. Through intelligent equipment, the smart technology enables precise monitoring and control of the irrigation and drainage processes, coordinating field water conditions, enhancing resilience to flooding and drought disasters, meeting crop growth demands, reducing labor costs, improving management efficiency, and achieving high yields and efficiency. The main research aspects of smart irrigation and drainage technology and equipment include: ① precise diagnosis of crop water and nutrient status in irrigated farmlands, as well as intelligent decision-making technologies for efficient irrigation and drainage with enhanced water and nutrient use efficiency and reduced pollutants discharge; ② development of easy-assembly and easy-operation irrigation and drainage systems with multi-level high-performance measurement and control terminals; ③ irrigation and drainage digital twin systems with self-learning capabilities and strong timeliness; and ④ intelligent optimization technology and collaborative regulation mode for all-season distributed control of irrigation and drainage system, aiming at improving the productivity of farmland. The development trends of smart irrigation and drainage technology and equipment are as follows: ① breaking through the limitations of sensor technology by introducing diverse sensing methods to achieve the fusion analysis of multi-source and multi-modal data, providing more precise and comprehensive information for high productivity farmland systems; ② enhancing the scientific and operational performances of field decisions through the fusion and interaction of data, models, and knowledge; ③ strengthening the autonomous decision-making capabilities of irrigation and drainage equipment and systems, increasing the cloud-edge computing capability and collaborative interconnection capability of equipment, and improving overall precision and efficiency through data sharing and collaboration; and ④ innovative methods, new technologies, new equipment, and new models for irrigation and drainage, realizing unmanned, intelligent, lightweight, and end-to-end irrigation and drainage for high productivity farmland. Between 2017 and 2022, 185 patents relevant to this research front were registered. These patents received 1 679 citations, with an average of 9.08 citations per patent.

2.2 Interpretations for three key engineering development fronts

2.2.1 Intelligent detection and rehabilitation technology of drainage pipe leakage

Drainage pipe leakage weakens the capacity of stormwater drainage and efficiency of wastewater treatment. It has become one of the main bottlenecks restricting the safe discharge of stormwater and complete collection and treatment of wastewater, and it induces environmental problems and safety risks of soil-underground water pollution, wastewater overflow, and road collapse. Intelligent detection and rehabilitation technology is designed to detect, diagnose and evaluate the level of structural defects in drainage pipe, and carry out low disturbance, high quality and proactive rehabilitation.

Due to the invisibility, widespread distribution, huge quantity, complex flow regime, and poor internal conditions of drainage pipes, the traditional detection technologies represent drawbacks of limited applicability, incomplete data results, and delayed prediction. In addition, the repair technologies are limited to reducing water level, excavation, and standardization. Moreover, along with the development of Internet of Things, big data and cloud computing, the leakage detection technology will shift from passive and periodic detection to proactive monitoring, providing support for proactive rehabilitation of drainage pipes.

Frontier scientific issues of intelligent detection and rehabilitation technology of drainage pipe leakage are as follows:

1) Digital base technology, including domestic geographical information system and accurate measurement of flow rate and water quality under complex medium conditions.

2) Intelligent detection technology, which includes: ① pipe external inspection technology basing on geological radar, concrete thickness detection, and rebar distribution detection; ② pipe identification technology of hidden risks via electromagnetic and sound waves; and ③ structural health monitoring technology for large-diameter and long-distance pipes.

3) Smart assessment technology, which includes: ① application of an evolutionary algorithm of pipeline services synergistically driven by data and modeling; ② failure prediction of drainage pipes influenced by multidimensional drive and multi-source data; and ③ rapid adaptive modeling of drainage pipeline networks based on the online monitoring data for crucial nodes.

4) Efficient rehabilitation technology, which includes: ① rehabilitation materials adapted to long-distance transportation, corrosive environments, and variable mechanical conditions, such as die casting pipe rehabilitation technology by using high strength and quick drying grouting materials; and ② repair technology suitable for large and extra-large pipes, such as structural strength enhancement via modular lining.

As listed in Table 2.1.1, 22 patents related to this topic were registered between 2017 and 2022, with each patent being cited 1.95 times on average. The country that registered the most patents was China (Table 2.2.1). China was at the forefront of development, contributing 100% of the patents. The citations per paper of Chinese patents was 1.95.

The five institutions that produced the most patents were Zhengzhou University, Zhengzhou Anyuan Engineering Technology

Company Limited, Hohai University, Nanjing Hohpower Information Technology Company Limited, and Guangzhou Yuntong Water Company Limited (Table 2.2.2). Cooperation among these institutions is rare (Figure 2.2.1).

The crucial development front of “intelligent detection and rehabilitation technology of drainage pipe leakage” in the coming five to ten years will focus on precise quantitative detection technology, high strength and high adaptability rehabilitation technology, and detection and rehabilitation quality process control technology based on mobile Internet technology. Precise quantitative detection technology mainly includes panoramic/laser quantitative detection technology, optical fiber leakage detection technology based on temperature and pressure, pipe residual strength detection technology based on mechanical elastic waves, pipe residual wall thickness detection technology based on ultrasonic thickness measurement, infrared camera detection method, magnetic flux leakage method, transient electromagnetic method, and pipe deformation detection technology involving calipers, laser instruments, or multi-sensors. High strength and high adaptability rehabilitation technology mainly focuses on breakthroughs in new materials, new technologies, new crafts, new equipment. Breakthroughs can not only broaden the application scenarios and quality of repair technology but also fulfill the repair needs of drainage pipes in corrosive, confined, and wet conditions. Application of mobile Internet technology for the management of detection and repair of construction enhances management effectiveness, ensures the quality of the construction process, and verifies the authenticity of the data (Figure 2.2.2).

Table 2.2.1 Countries with the greatest output of core patents on “intelligent detection and rehabilitation technology of drainage pipe leakage”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	22	100.00	43	100.00	1.95

Table 2.2.2 Institutions with the greatest output of core patents on the “intelligent detection and rehabilitation technology of drainage pipe leakage”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Zhengzhou University	3	13.64	8	18.60	2.67
2	Zhengzhou Anyuan Engineering Technology Company Limited	2	9.09	8	18.60	4.00
3	Hohai University	1	4.55	9	20.93	9.00
4	Nanjing Hohpower Information Technology Company Limited	1	4.55	9	20.93	9.00
5	Guangzhou Yuntong Water Company Limited	1	4.55	5	11.63	5.00
6	Shenzhen Qianhai Yuntong Water Company Limited	1	4.55	5	11.63	5.00
7	Henan Aibit Technology Company Limited	1	4.55	4	9.30	4.00
8	Guangzhou Lixin Electronic Technology Company Limited	1	4.55	3	6.98	3.00
9	Huazhong University of Science and Technology	1	4.55	1	2.33	1.00
10	Qingyuan Construction Safety Inspection Company Limited	1	4.55	1	2.33	1.00

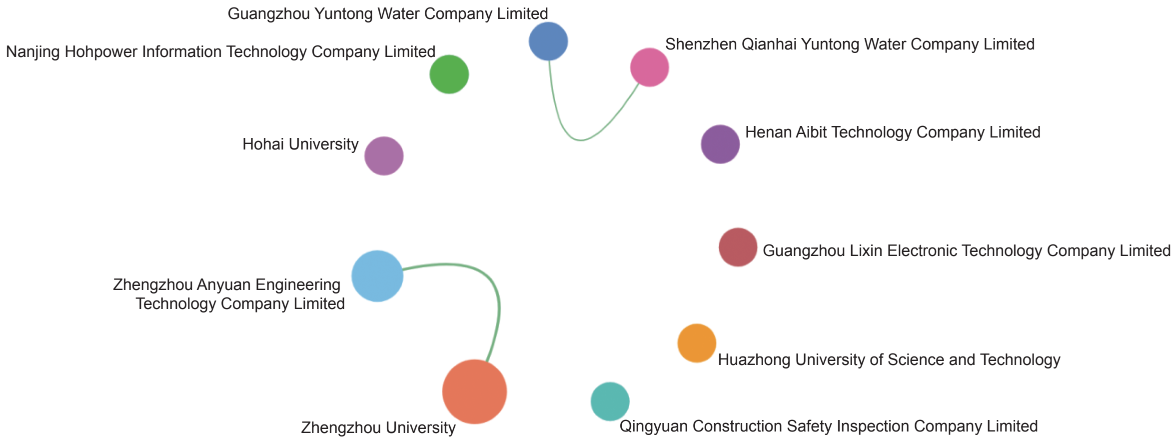

Figure 2.2.1 Collaboration network among major institutions in the engineering development front of “intelligent detection and rehabilitation technology of drainage pipe leakage”

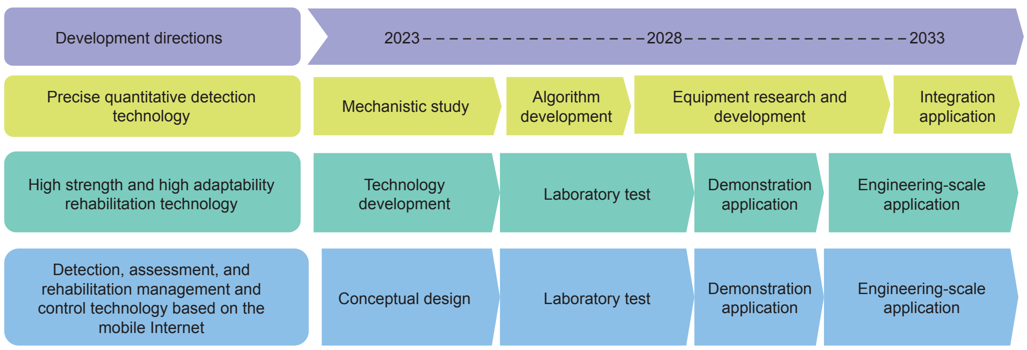

Figure 2.2.2 Roadmap of the engineering development front of “intelligent detection and rehabilitation technology of drainage pipe leakage”

2.2.2 Core technology for 1 mm level global and regional coordinate frame

The coordinate framework is a foundation for describing the shape of the Earth and changes to that, and is also a key geospatial information infrastructure for expanding human activities and promoting social development. It can provide not only basic data for deep space exploration, urban construction, disaster relief and disaster reduction, but also a unified high-precision spatial benchmark for global change detection and scientific research, such as geodynamic inversion, and earthquake, climate, and hydrological monitoring. It is a key geospatial information infrastructure for expanding human activities and promoting social development.

The existing international Earth reference framework does not meet the needs of monitoring the dynamic changes of large-scale or global millimeter scale Earth systems. Development of the core technology for a millimeter level coordinate framework has become a disciplinary goal and important challenge for the international geodetic community in the 21st century. Development trends in this research front include the following.

1) Precision spatial geodetic data processing technology to determine the optimal applications of Very-Long-Baseline Interferometry (VLBI)/Satellite Laser Ranging (SLR)/Global Navigation Satellite System (GNSS)/Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS) data processing strategy, through refined mathematical models. Based on this, global benchmark station data can be uniformly reprocessed to eliminate or weaken the impact of technical system errors, providing sufficiently precise input data for the establishment of millimeter level coordinate frameworks.

2) Modeling the nonlinear motion of the reference station, targeting the nonlinear displacement caused by geophysical effects,

integrating environmental loads, thermal expansion.

3) A combination of spatial geodetic techniques, utilizing spatial geodetic techniques such as VLBI, SLR, GNSS, DORIS, etc.

4) Modeling of geocentric motion, combining multiple spatial geodetic techniques and geophysical models to invert geocentric motion, solving the inconsistency between the definition and implementation of the coordinate frame origin, and providing a more accurate geocentric reference framework for geodynamic research.

Research institutions that produced the most papers in this field include Wuhan University, The Chinese Academy of Surveying & Mapping, and The Institute of Geodesy and Geophysics.

As listed in Table 2.1.1, 55 patents related to this topic were registered between 2017 and 2022, with each patent being cited 1.73 times on average. The three countries that registered the most patents were China, Russia, and Republic of Korea (Table 2.2.3). Among these countries, China was at the forefront of development, contributing 83.64% of the patents. The average citation frequency of Chinese patents was 1.85.

The five institutions that produced the most patents were Xi'an Applied Optics Research Institute, a certain unit of the People's Liberation Army of China, Northwestern Polytechnical University, Qianxun Location Network Company Limited, and China Electronics Technology Group Corporation (Table 2.2.4).

The future development of this front in the coming five to ten years will involve precision spatial geodetic data processing technology, nonlinear motion modeling of reference stations, combination of spatial geodetic technology, and geocentric motion modeling (Figure 2.2.3).

Table 2.2.3 Countries with the greatest output of core patents on "core technology for 1 mm level global and regional coordinate frame"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	46	83.64	85	89.47	1.85
2	Russia	6	10.91	4	4.21	0.67
3	Republic of Korea	1	1.82	4	4.21	4.00
4	France	1	1.82	2	2.11	2.00
5	Poland	1	1.82	0	0.00	0.00

Table 2.2.4 Institutions with the greatest output of core patents on "core technology for 1 mm level global and regional coordinate frame"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Xi'an Applied Optics Research Institute	4	7.27	16	16.84	4.00
2	A certain unit of the People's Liberation Army of China	3	5.45	1	1.05	0.33
3	Northwestern Polytechnical University	2	3.64	6	6.32	3.00
4	Qianxun Location Network Company Limited	2	3.64	5	5.26	2.50
5	China Electronics Technology Group Corporation	2	3.64	4	4.21	2.00
6	Beijing Institute of Environmental Features	2	3.64	0	0.00	0.00
7	Satellite Surveying and Mapping Application Center NASG	1	1.82	12	12.63	12.00
8	Wuhan University	1	1.82	5	5.26	5.00
9	Beihang University	1	1.82	4	4.21	4.00
10	Institute of Electronics, Chinese Academy of Sciences	1	1.82	4	4.21	4.00

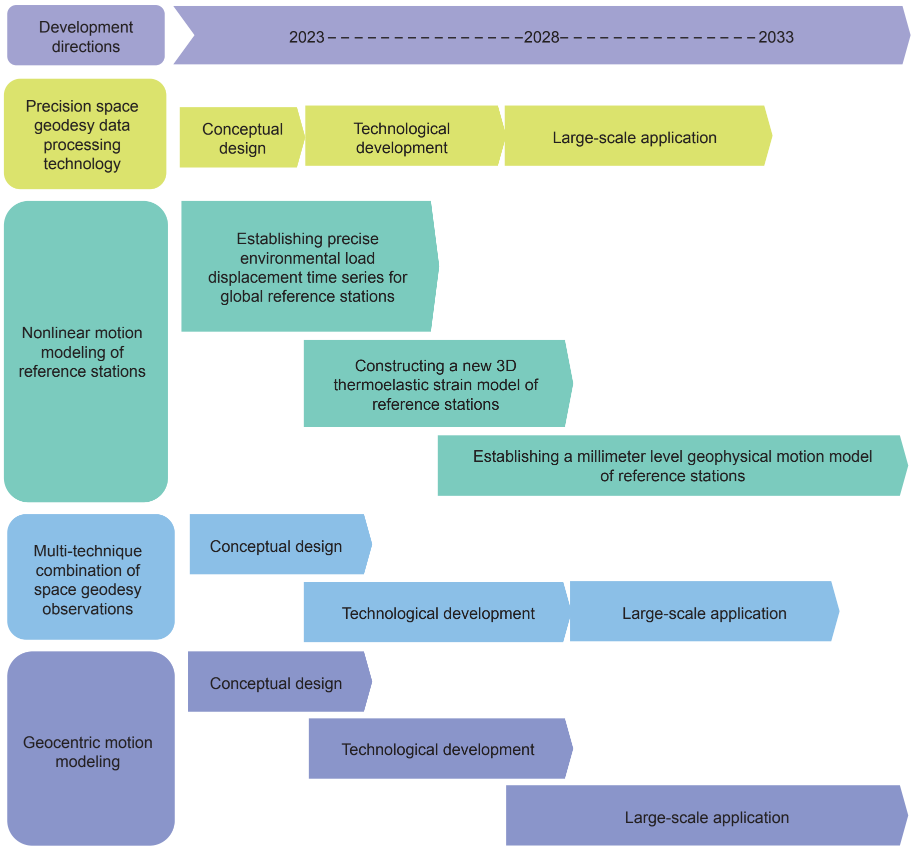

Figure 2.2.3 Roadmap of the engineering development front of “core technology for 1 mm level global and regional coordinate frame”

2.2.3 Digital technology for the protection and utilization of urban historical and cultural resources

The core of the digital technology for the preservation and utilization of urban historical and cultural resources lies in enabling a coordinated approach through digital technology. This transforms preservation from static and passive methods to dynamic and proactive strategies, fully realizing the important value that historical and cultural resources hold for urban space and societal development. The forefront of research and development is primarily reflected as follows.

1) Database construction technology for urban historical and cultural resources: Creating a digital archive of historical and cultural resources is fundamental for achieving comprehensive resource preservation. This not only supports the restoration and protection of cultural heritage but also serves as a carrier for heritage value dissemination and the need for coordinated management of various resources. However, historical and cultural resources vary in type, including tangible heritage, intangible heritage, and movable and immovable cultural artifacts. Moreover, the tangible resources vary significantly in spatial scale. Key to addressing this challenge is the development of technology for integrating diverse and heterogeneous data from multiple sources and ensuring seamless data connectivity across various scales.

2) Intelligent protection technology for urban historical and cultural resources: The safety of urban historical and cultural resources is influenced by both natural hazards (such as climate change and natural disasters) and human activities (such as resource utilization and development). Digital technology provides technical feasibility for establishing an interactive, dynamic, and intelligent proactive protection mechanism that incorporates “perception monitoring-dynamic assessment-risk warning-measure response” linkages to address various risks.

3) Digitally empowered utilization technology for urban historical and cultural resources: Digitization of urban historical and cultural resources serves not only to preserve historical information but is also a crucial means for value generation. Several

European countries have initiated digital museum projects, enhancing interactive experiences through technologies like virtual reality. They have developed applications for devices such as smartphones and have integrated urban historical and cultural resources into emerging digital industries like electronic gaming.

4) Integrated technology for preservation and utilization of urban historical and cultural resources: Through integrated technology, the three major phases of "database construction-risk assessment, response-resource utilization, and value dissemination" are interconnected, promoting mutual enhancement through the empowerment of digital technology. Additionally, preservation and utilization of urban historical and cultural resources should not remain an isolated technology. It should be integrated into the broader technical framework of land and spatial resource preservation and utilization, fostering horizontal coordination with other urban resource management efforts and vertical integration across spatial levels within the broader land and spatial context to ultimately achieve comprehensive, all-encompassing, and full-cycle land and spatial resource management.

As listed in Table 2.1.1, 19 patents related to this topic were registered between 2017 and 2022, with each patent being cited 6.42 times on average. The three countries that registered the most patents were China, Romania, and Republic of Korea (Table 2.2.5). Among these countries, China was at the forefront of development, contributing 78.95% of the patents. The average citation frequency of Chinese patents was 7.60.

The five institutions that produced the most patents were Central South University, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, China University of Geosciences (Wuhan), Dingchen Construction Management Company Limited, and Korean Advanced Institute of Science and Technology (Table 2.2.6).

Table 2.2.5 Countries with the greatest output of core patents on "digital technology for the protection and utilization of urban historical and cultural resources"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	15	78.95	114	93.44	7.60
2	Romania	3	15.79	0	0.00	0.00
3	Republic of Korea	1	5.26	8	6.56	8.00

Table 2.2.6 Institutions with the greatest output of core patents on "digital technology for the protection and utilization of urban historical and cultural resources"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Central South University	1	5.26	40	32.79	40
2	Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences	1	5.26	35	28.69	35
3	China University of Geosciences (Wuhan)	1	5.26	11	9.02	11
4	Dingchen Construction Management Company Limited	1	5.26	11	9.02	11
5	Korea Advanced Institute of Science and Technology	1	5.26	8	6.56	8
6	Chengdu University of Technology	1	5.26	6	4.92	6
7	Institute of Urban Environment, Chinese Academy of Sciences	1	5.26	4	3.28	4
8	Shenyang University of Technology	1	5.26	3	2.46	3
9	Suzhou Planning and Design Research Institute Company Limited	1	5.26	2	1.64	2
10	Xi'an Zhongke Xiguang Aerospace Technology Company Limited	1	5.26	2	1.64	2

The key development directions for the “digital technology for the protection and utilization of urban historical and cultural resources” project in the next 5–10 years will focus on multiple data source integration, risk perception monitoring, assessment and projection, spatial planning response, value dissemination and utilization, and planning technology integration (Figure 2.2.4).

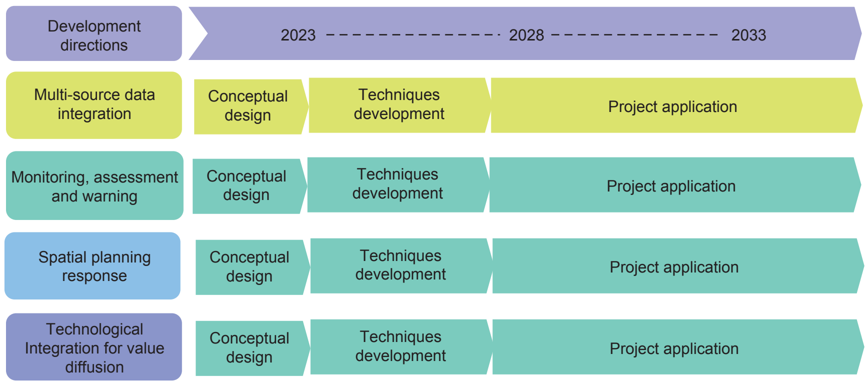

Figure 2.2.4 Roadmap of the engineering development front of “digital technology for the protection and utilization of urban historical and cultural resources”

Participants of the Field Group

Leaders

CUI Junzhi, NIE Jianguo, ZHU Hehua, GU Xianglin

Members of the expert group

Academicians:

CUI Junzhi, OU Jinping, WANG Hao, YANG Yongbin, ZHANG Jianyun, LIU Jiaping[1], MIAO Changwen, LI Jiancheng, DU Yanliang, GUO Renzhong, HU Chunhong, NIU Xinqiang, PENG Yongzhen, ZHENG Jianlong, WANG Fuming, KONG Xianjing, CHEN Xiangsheng, ZHANG Jianmin, WU Zhiqiang, YUE Qingrui, LI Huajun, LV Xilin, CHEN Jun, MA Jun, FENG Xiating, ZHU Hehua, DU Xiuli, WANG Mingyang, LIU Jiaping[2], HAO Hong, XING Feng, TONG Xiaohua

Experts:

CAI Chunsheng, CAI Yi, CAI Yongli, CHEN Jun, CHEN Peng, CHEN Qing, CHEN Qiuwen, CHEN Xin, CHEN Yonggui, CHENG Yuning, FAN Jiansheng, FAN Lingyun, FAN Yue, FENG Dianlei, GAO bo, GAO Jun, GAO Liang, GE Yaojun, GU Chongshi, GUO Jinsong, GUO Ronghuan, HAN Jie, HE Pengfei, HE Ruimin, HUANG Jiesheng, HUANG Tinglin, HUANG Yong, JIA Liangjiu, JIANG Chao, JIANG Jinyang, JIANG Zhengwu, JIN Junliang, LENG Hong, LI Chen, LI Xiangfeng, LI Yinong, LI Zao, LI Zhengrong, LI Zhi, LIN Bolong, LING Jianming, LIU Chao, LIU Cuishan, LIU Fang, LIU Helin, LIU Jing, LIU Renyi, LIU Shuguang, LIU Yanling, LU Andong, NIU Xinyi, PENG Jinqing, REN Weixin, SHAO Yisheng, SHI Beiling, SHI Caijun, SHI Tiemao, SHU Zhangkang, SU Ping, SUN Jian, SUN Lijun, SUN Zhi,

1 Xi’an University of Architecture and Technology.
2 Southeast University.

TAN Guangming, TAN Gangyi, TIAN Bo, TIAN Li, WANG Fang, WANG Han, WANG Jieqiong, WANG Shuangjie, WANG Aijie, WANG Benjin, WANG Guoqing, WANG Hui, WANG Jianhua, WANG Lan, WANG Wei, WANG Yayi, WANG Yuanzhan, WANG Zhiwei, WU Yongfa, WU Faquan, XIA Shengji, XIAO Feipeng, XIE Hui, XU Bin, XU Feng, XU Junzeng, YAN Jinxiu, YAN Yu, YANG Bin, YANG Dawen, YANG Junyan, YANG Liu, YANG Zhongxuan, YAO Junlan, YAO Yangping, YE Wei, YE Yu, YU Zhongbo, YU Haitao, YUAN Feng, YUAN Yanping, YUE Zhongqi, ZENG Peng, ZHANG Chen, ZHANG Feng, ZHANG Yunsheng, ZHAO Miaoxi, ZHEN Feng, ZHENG Bailin, ZHENG Gang, ZHENG Xi, ZHOU Xiang, ZHOU Zhengzheng, ZHUANG Xiaoying, ZHUO Jian

Report writers

MA Jun, ZHUANG Weimin, TONG Xiaohua, CHEN Peng, CHEN Xin, CHENG Guanghua, CUI Dongjin, FAN Yue, FENG Chengyou, GAO Liang, HUANG Yu, JIA Liangjiu, LI Chen, LI Yuanqi, LIU Chao, LIU Fang, LIU Helin, LIU Yanling, LU Chunhui, NI Huayong, PAN Yue, QU Zhang, SONG Dianlan, SU Jingwen, SUN Chengyu, WANG Han, WANG Benjin, WANG Dalei, WANG Fawu, WANG Rui, WANG Xin, WANG Yuanzhan, WU Jixiu, WU Jinsheng, WU Jiang, XIAO Feipeng, XIAO Yang, XU Junzeng, YAO Junlan, ZENG Peng, ZHANG Chen, ZHANG Qing, ZHAO Yunmei, ZHENG Fang, ZHUO Jian