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, construction materials, transportation engineering, architecture, HVAC, municipal engineering, surveying and mapping engineering, and hydraulic engineering. The following research fronts were recommended by experts: "smart city and smart basin integrated sensing based on geospatiotemporal big data," "coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes," "urban spatial analysis and optimization methods based on big data," "ventilation theory for adaptive thermal comfort and indoor air quality," and "multiscale prediction of dynamic hazard evolution for underground engineering." The five remaining fronts were identified using the co-citation clustering method applied to the top 10% of highly cited papers, and they were confirmed by experts. Table 1.1.2 presents annual statistical data on the core papers published between 2014 and 2019 that are relevant to these top 10 research fronts.

(1) Smart city and smart basin integrated sensing based on geospatiotemporal big data

Integrated sensing is an important foundation for the realization of smart cities and smart basins. In smart cities and smart basins, ubiquitous smart sensors achieve the comprehensive perception of physical cities and physical watersheds and detect the core system of urban operations and watershed management in real time, thereby seamlessly connecting digital cities and digital watersheds with physical cities and physical watersheds. The real-time geospatiotemporal big data are then used to provide users with intelligent services. Developing trends in this research front include: 1) construction methods for the

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	Smart city and smart basin integrated sensing based on geospatiotemporal big data	36	924	25.67	2017.0
2	Coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes	40	1 271	31.78	2016.3
3	Urban spatial analysis and optimization methods based on big data	58	2 461	42.43	2017.1
4	Ventilation theory for adaptive thermal comfort and indoor air quality	544	16 740	30.77	2016.6
5	Multiscale prediction of dynamic hazard evolution for underground engineering	93	2 297	24.70	2017.5
6	Nano-engineered concrete materials in civil engineering	74	3 995	53.99	2017.2
7	Urban planning and design to reduce the urban heat island effect	188	6 975	37.10	2016.9
8	Performance evolution and durability design principles for materials and structures on highways and for track engineering	56	1 584	28.29	2017.5
9	Formation mechanisms and changing trends of extreme hydrologic events	238	9 287	39.02	2016.5
10	Catastrophic effects of deep energy exploitation and regulation of its mechanical behavior	105	3 319	31.61	2017.3

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 fronts	2014	2015	2016	2017	2018	2019
1	Smart city and smart basin integrated sensing based on geospatiotemporal big data	2	5	5	10	8	6
2	Coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes	11	5	4	6	8	6
3	Urban spatial analysis and optimization methods based on big data	5	5	4	20	12	12
4	Ventilation theory for adaptive thermal comfort and indoor air quality	69	97	88	102	92	96
5	Multiscale prediction of dynamic hazard evolution for underground engineering	6	7	6	19	24	31
6	Nano-engineered concrete materials in civil engineering	3	6	11	19	20	15
7	Urban planning and design to reduce the urban heat island effect	21	23	30	44	29	41
8	Performance evolution and durability design principles for materials and structures on highways and for track engineering	6	3	5	5	16	21
9	Formation mechanisms and changing trends of extreme hydrologic events	26	46	46	41	50	29
10	Catastrophic effects of deep energy exploitation and regulation of its mechanical behavior	5	14	10	22	27	27

integrated sensing infrastructure systems of smart cities and smart basins to realize the large-scale interconnection of monitoring resources and the coordination of multi-source heterogeneous sensing resources; 2) city and basin sensing methods based on integrated sensing infrastructure; and 3) integrated management and real-time analysis methods for the geographic spatial-temporal big data of smart cities and smart basins. Between 2014 and 2019, 36 core papers relevant to this research front were published. These papers received 924 citations, with an average of 25.67 citations per paper.

(2) Coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes

Offshore engineering structures such as harbor wharfs, breakwaters, oil production platforms, submarine pipelines, sea-crossing bridges and tunnels, and offshore wind power foundations confront severe operating environments and high safety risks. Under the action of winds, waves, currents, and earthquakes, the pore water pressure increases, and the effective stress decreases in the foundation of the seabed, which can lead to the strength-weakening and liquefaction of the seabed soil. At the same time, the action of waves and currents can scour the seabed foundation. Moreover, structural movements under the action of dynamic loads can also cause changes in the pore water pressure and effective stress in the seabed soil, complicating the bearing capacity of the seabed foundation. The coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes are thus a key issue for the safety and durability of offshore engineering structures. The main problems to be solved include the following: 1) the mechanism and evolution law of the strength-weakening and liquefaction of different seabed foundations (gravel, sand, soft clay, etc.) under the action of different periodic cyclic loads such as waves, earthquakes, and structural motion; 2) elastoplastic constitutive models that consider the processes of strength-weakening, liquefaction, and excess pore pressure dissipation and consolidation after the liquefaction and re-liquefaction of seabed soil under the action of cyclic loads; 3) scouring models of different seabed foundations that account for seepage effects under the action of waves and currents; 4) coupled numerical models and efficient and reliable numerical simulation methods for the nonlinear dynamic analysis of cyclic load–marine structure–seabed foundation systems; and 5) basic theory and experimental technology for physical model tests to investigate the bearing capacity of cyclic load–marine structure–seabed foundation systems. Between 2014 and 2019, 40 core papers relevant to this research front were published. These papers received 1271 citations, with an average of 31.78 citations per paper.

(3) Urban spatial analysis and optimization methods based on big data

With the development of Internet technologies, the paradigm of urban spatial analysis is being transformed by the emergence of new big data that are geo-referenced, such as cell phone data, public transport tap-in/out data, and social media check-ins. The advantages of this type of data include its large size, fine resolution, and wide coverage. These data record various human behaviors across time and space with a new level of precision, thereby forming new pipelines for us to observe, perceive, and interpret cities and their transformation. Spatial analysis and optimization based on urban big data are frontiers in urban studies and practices. The institutes leading the relevant research are located in the West in developed countries or districts, such as the United States, the United Kingdom, and the European Union, and in rapidly developing countries and areas, such as China. Developed countries typically maintain more comprehensive research systems and networks with the solid establishment of theory, methods, and applications, whereas rapidly developing countries, particularly China, are notable for the large size of their urban big data, which is attributable to their large populations, optimism toward new technologies, and good software and hardware facilities. Between 2014 and 2019, 58 core papers relevant to this research front were published, and these papers received 2461 citations, with an average of 42.43 citations per paper.

(4) Ventilation theory for adaptive thermal comfort and indoor air quality

The concept of ventilation theory for adaptive thermal comfort and indoor air quality refers to the idea that when a person is in a naturally ventilated environment, the thermal acceptability of his or her body increases due to its thermal adaptation. Because natural ventilation can provide better indoor air quality, a balance can be achieved between energy conservation and comfort. The main research directions in this front include: 1) the physiological and psychological mechanisms of human thermal adaptability in building environments; 2) effects and prediction models for thermal comfort caused by exposure experiences and thermal adaptation; 3) indoor air quality assessments in naturally ventilated environments and passive building environments; and 4) design methods for naturally ventilated environments and passive building environments. This research front has maintained a high level of activity in recent years. Extensive field surveys have been conducted in various climate zones worldwide, enriching adaptive thermal comfort theory and improving the prediction accuracy of human thermal comfort in naturally ventilated buildings. Natural ventilation, artificial airflow, and personalized comfort equipment have been used to replace traditional air conditioning and heating equipment in specific seasons and spaces in order to reduce the dependence of buildings on traditional energy and to integrate human development with nature. Between 2014 and 2019, 544 core papers relevant to this research front were published, and these papers received 16 740 citations, with an average of 30.77 citations per paper.

(5) Multiscale prediction of dynamic hazard evolution for underground engineering

At present, the construction of underground structures is developing rapidly. Many of these structures are large in scale and may encounter complex geological environments as well as hazard threats induced by strong earthquakes, active fault zones, and seismic liquefaction. Such threats pose a serious challenge to the science and technology of disaster prevention and mitigation in geotechnical and underground engineering. The multiscale prediction of dynamic hazard evolution for underground engineering is based on a combination of interdisciplinary subjects, including geotechnical earthquake engineering, structural dynamics, and multiscale science, and on the construction of multiscale dynamic analysis models that cover the macro- and meso-space scales and time effect scales. The aim is to reveal not only the integral dynamic response characteristics of underground structures at the macro-scale but also the dynamic damage mechanisms of critical joints at the meso-scale when subjected to strong earthquakes. The ultimate goal is to realize the multiscale prediction of the entire process of dynamic hazard evolution for underground engineering under high seismic intensity and adverse site conditions and thus to provide a scientific basis and technical support to improve disaster prevention and mitigation for underground structures. The main research directions in this front include: longitudinal seismic design theory for long and large tunnels, multiscale analysis methods for massive nonlinear seismic responses in underground structures, physical experimental simulations of the effects of strong earthquakes and nonuniform seismic spatial variations, dynamic response analysis of complex underground structures with sharp stiffness transitions, and dynamic hazard simulations for underground engineering in adverse sites, such as liquefaction sites and active fault zones. Trends suggest that future developments will include: the damage mechanisms of underground engineering under strong earthquakes and design countermeasures, seismic mitigation technologies and structural measures for underground structures, and rational and unified performance-based concepts for the seismic design of underground structures. Furthermore, optimizing the combination of seismic countermeasures and mitigation measures and adapting them to the seismic response characteristics of underground engineering under complex and adverse geological conditions remains one of the most challenging and urgent problems in this front. Between 2014 and 2019, 93 core papers relevant to this research front were published, and these papers received 2297 citations, with an average of 24.70 citations per paper.

(6) Nano-engineered concrete materials in civil engineering

The need for concrete materials that meet increasingly strict requirements is being expressed in modern civil engineering; however, traditional single- or multi-performance improvements at the macro-scale can barely meet this need. Multi-scale micro-nano-structure regulation and function upgrades are one of the feasible ways to improve the performance of concrete materials for modern civil engineering. Nanomaterials enable the nano-optimization of cementing gels to regulate the micro-nano-structure of concrete materials. Chemical coordination and hybridization with cement-based materials can be realized by doping organic functional groups. Moreover, nonreactive nanoparticles can regulate the early hydration progress of cement to refine its molecular structure, while some nanoparticles with reactive surface properties can be used as strong nano-bridges to coordinate and complex with cementing gels. The nano-regulation and optimization of cementing gels can significantly improve the toughness and durability of concrete materials with very low dosages. Moreover, introducing nanomaterials can provide traditional concrete materials with new functions for performance optimization. Through doping or surface infiltration, some nanomaterials can equip concrete materials with electrical conductivity and self-cleaning abilities. Piezoelectric nanoparticles can introduce intelligent perception to concrete materials, while physicochemical self-healing can be initiated by nano-functionalized healants in concrete materials. Nanomaterial-based functional improvements in concrete materials can thus meet the integrated structural and functional requirements of modern civil engineering. Theoretical analysis and numerical simulation are critical to achieving designable nano-engineered concrete materials. Nanomaterial-based optimization strategies for concrete materials can be established through computational chemistry at the nano-scale. Big data-based modeling can contribute to the elaboration of the effects of nanoparticles on concrete materials. In this way, the top-level design and rational doping theory of high-performance and multifunctional nano-engineered concrete can be achieved. Theoretical analysis, numerical simulation, and nano-dispersion technologies should be combined in order to realize nano-regulation, nano-functionalization, and nano-design in concrete. Between 2014 and 2019, 74 core papers relevant to this research front were published, and these papers received 3995 citations, with an average of 53.99 citations per paper.

(7) Urban planning and design to reduce the urban heat island effect

In urban development, the temperature of the urban surface and canopy is higher than that of nearby rural areas. This phenomenon is called the urban heat island effect. The heat island effect is influenced by many factors including the urban morphology, land surface, air pollution, and anthropogenic heat. In the context of global climate change, the heat island effect further exacerbates abnormal weather phenomena, such as heat waves, and health risks to urban populations such as respiratory distress and heat stroke, resulting in adverse effects on urban climate and human comfort. Research on health-and-comfort oriented urban planning and design has been emphasized in international academic papers. The research on urban heat islands and microclimates involves the research fields of architecture, urban planning, and landscapes. The main technical measures are usually categorized as meso-scale or micro-scale. At the meso-scale are urban wind corridor planning analyses based on land use and development intensity, quantitative studies of the heat island effect based on high-resolution remote sensing technology, and green space ecological planning to mitigate the urban heat island using geographic information systems. At the micro-scale are the application of computational fluid dynamic technology for wind and heat simulation to optimize urban space planning and architectural design research and park or green space and urban street tree landscape designs to improve human comfort and mitigate heat risks. The urban block grid fineness method is a key technology for addressing the resolution reduction of the meso- and micro- scales. Other measures applied to urban heat islands include urban climate strategies, the innovation of sustainable urban developments, urban morphology, green design for heat risk management, and the prediction of the impact of urban development intensity on pollution diffusion and the energy consumption of urban agglomerations. Between 2014 and 2019, 188 core papers relevant to this research front were published, and these papers received 6975 citations, with an average of 37.10 citations per paper.

(8) Performance evolution and durability design principles for materials and structures on highways and for track engineering

Pavement material and structures are damaged by repetitive traffic loads and cyclic environmental disincentives and then deteriorate gradually over their in-service life. The concepts of behavioral evolution and durability-based design principles for pavement materials and structures refer to the evolution of pavement structures and materials and the development of fundamental design theory and methodology for durable pavement design. The main research areas in this front include: 1) using multi-scale theoretical analysis, numerical simulations, and experimental tests (both laboratory and field) to reveal the in-service behavioral evolution of pavement materials and structures and quantitatively describing their performance; 2) using modifiers to improve the durability of pavement materials; 3) considering the real stress/strain state of structures and the bimodular properties (different compression-tension properties) of materials to develop more accurate pavement design procedures; 4) developing more reliable pavement structure design models based on monitoring the long-term performance of pavement; and 5) optimizing pavement structures and conducting preventive maintenance to enhance the durability and service life of pavement. Potential research prospects include: 1) investigating the behavioral evolution of pavement materials and structures under the coupled effects of multiple factors based on the long-term performance monitoring and accelerated pavement testing; 2) developing highly efficient modifiers to improve the binder-aggregate interface bonding and the overall mechanical properties of pavement materials; and 3) developing a harmonious analysis of the mechanical properties and the structural mechanical responses of pavement materials based on the in-service behavior of pavement material and structure. Between 2014 and 2019, 56 core papers relevant to this research front were published. These papers received 1584 citations, with an average of 28.29 citations per paper.

(9) Formation mechanisms and changing trends of extreme hydrologic events

Extreme hydrologic events are hydrologic events that occur with a small probability of occurrence but a strong impact in a particular region and within a certain time scale, for which the hydrological variables deviate significantly from their normal values. Extreme hydrologic events are multi-dimensional nonlinear systems that are influenced by climate, underlying surfaces, human activities, and other factors. Their formation mechanism is therefore highly complex. In recent years, the intensity and frequency of extreme hydrologic events caused by global climate change have increased, and the consequently increased risk of flood and drought has become a major challenge for humans. The formation mechanisms and changing trends of extreme hydrologic events under the impact of global change have become top issues in current research. Main research trends include: 1) the impact of the interaction of climate–vegetation–hydrology–human activity on extreme hydrologic events; 2) trend detection, changing attributes, and future scenarios of extreme hydrologic events given the impacts of natural climate variability and human activities; 3) climate–hydrologic bidirectional coupling models and multi-scale extreme hydrologic process simulations in changing environments; and 4) risk assessment of, multi-dimensional regulation of, and comprehensive responses to extreme hydrologic events. In the future, the formation mechanisms and changing trends of extreme hydrologic events in complex environments should be investigated via a multi-disciplinary approach based on climate, hydrology, geography, management, etc., using three-dimensional total factor monitoring and scientific experiments, multi-source data fusion and assimilation, ensemble simulation of physical models with artificial intelligence (AI), and other new technologies. Between 2014 and 2019, 238 core papers relevant to this research front were published. These papers received 9287 citations, with an average of 39.02 citations per paper.

(10) Catastrophic effects of deep energy exploitation and regulation of its mechanical behavior

The rapid development of human society has produced a growing demand for energy. With improvements in all types of technical engineering systems, the exploitation of energy resources has gradually reached the deep part of the earth. In recent years, the exploitation of shale gas, hot dry rock, coalbed methane, and combustible ice have seen an upsurge. However, deep rock masses are found in complicated geological environments with high temperature and high stress, and their mechanical behaviors are more complex than those of shallow rock masses. Affected by coupled fluid–thermal–chemical–mechanical effects, the key parameters of deep rock masses, including their mechanical strength, deformation mechanisms, and permeability characteristics, are not well explained by traditional theories. Meanwhile, catastrophic problems, such as rock bursts, induced seismicity, large deformations of soft rocks, and wall instabilities in complex strata, occur frequently in deep mining. Catastrophic mechanisms thus require further investigation. To better explore the effects of deep energy mining disasters and further improve the control of the mechanical behaviors of deep rock masses, the following research aspects should be given special attention: the multi-field coupling mechanisms of complex fractured rock masses; the mechanisms, processes, and evaluation of deep, dynamic disasters; the physical and mechanical properties, deformation, and failure characteristics of deep rock masses; and the influence of deep, complex structures on the physical and mechanical properties of rock masses. Between 2014 and 2019, 105 core papers relevant to this research front were published. These papers received 3319 citations, with an average of 31.61 citations per paper.

1.2 Interpretations for three key engineering research fronts

1.2.1 Smart city and smart basin integrated sensing based on geospatiotemporal big data

Integrated sensing is an important foundation for the realization of smart cities and smart basins. In smart cities and smart basins, ubiquitous smart sensors realize the comprehensive perception of physical cities and physical watersheds and detect the core system of urban operations and watershed management in real time, thereby seamlessly connecting digital cities and digital watersheds with physical cities and physical watersheds. The real-time geospatiotemporal big data are then used to provide users with intelligent services. With the development of smart cities and smart basins, urban and basin sensing has gradually developed from isolated online sensing to multi-network integrated sensing.

Currently, the major research topics concerning smart city and smart basin integrated sensing include:

(1) Construction methods for integrated sensing infrastructure systems of smart cities and smart basins, such as 1) new technologies for the large-scale interconnection of monitoring resources between cities and river basins, including mass sensor network communication, heterogeneous sensor access, sensor network resource management, sensor network service composition, streaming data mining analysis, and geographic information interoperability; and 2) new collaborative methods for multi-source heterogeneous sensing resources, such as sensor information modeling, observation capability evaluation, collaborative monitoring, data fusion of point and surface observations, and on-demand focused services;

(2) City and basin sensing methods based on integrated sensing infrastructure, including 1) multi-scale comprehensive perception indices, common technology and standard systems, seamless spatial perception methods of urban agglomeration and watershed surface elements; 2) multi-scale intelligent light field video imaging and analysis methods; 3) fine scene space-time perception and online monitoring methods; and 4) the multi-scale synthesis of city and watershed sensing service methods; and

(3) The integrated management and real-time analysis of geographic spatiotemporal big data from smart cities and smart basins, including integrated expression methods of multi-source real-time geographic information, fusion and organization methods for real-time geographic information, flexible service methods for real-time geographic information, and deep mining methods for geographic spatial-temporal big data.

As shown in Table 1.1.1, between 2014 and 2019, 36 core papers concerning "smart city and smart basin integrated sensing based on geospatiotemporal big data" were published, with each paper being cited an average of 25.67

times. The top five countries in terms of output of core papers on this topic are China, the United States, Malaysia, Iran, and Australia (Table 1.2.1). China is one of the most active countries, having published 27.78% of the core papers. The five countries with the highest citations per paper were South Korea, the United States, Turkey, Malaysia, and Switzerland. The papers published by Chinese authors were cited 19.80 times per paper on average, which indicates that there is an opportunity for improvement by Chinese scholars on this front. As illustrated by the international collaborative network depicted in Figure 1.2.1, close cooperation was observed among the most productive top 10 countries.

The five institutions that published the most core papers were Chinese Academy of Sciences (China), China Institute of Water Resources and Hydropower Research (China), Canik Basari University (Turkey), the National University of Malaysia (Malaysia), and the University of Hong Kong (China) (Table 1.2.2). The top two institutions in terms of widely cited publications are the Chinese Academy of Sciences and the China Institute of Water Resources and Hydropower Research. Both institutions are leaders in the application of AI techniques for urban flood warning and catchment flood forecasting to prolong the leading time and increase the forecasting accuracy. As illustrated in Figure 1.2.2, the ten most productive institutions have conducted collaborative studies in this regard.

Table 1.2.1 Countries with the greatest output of core papers on “smart city and smart basin integrated sensing based on geospatiotemporal big data”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	10	27.78%	198	19.80	2017.4
2	USA	6	16.67%	299	49.83	2016.7
3	Malaysia	5	13.89%	234	46.80	2017.0
4	Iran	5	13.89%	124	24.80	2017.2
5	Australia	5	13.89%	111	22.20	2017.2
6	UK	4	11.11%	59	14.75	2018.2
7	Turkey	3	8.33%	148	49.33	2016.0
8	South Korea	2	5.56%	148	74.00	2016.0
9	Switzerland	2	5.56%	72	36.00	2016.0
10	Iraq	2	5.56%	64	32.00	2018.0

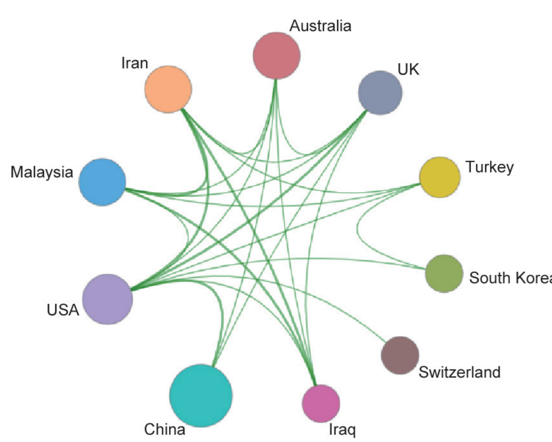

Figure 1.2.1 Collaboration network among major countries in the engineering research front of “smart city and smart basin integrated sensing based on geospatiotemporal big data”

Table 1.2.2 Institutions with the greatest output of core papers on "smart city and smart basin integrated sensing based on geospatiotemporal big data"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	3	8.33%	98	32.67	2018.0
2	China Institute of Water Resources and Hydropower Research	3	8.33%	38	12.67	2017.0
3	Canik Basari University	2	5.56%	140	70.00	2015.5
4	National University of Malaysia	2	5.56%	68	34.00	2017.0
5	University of Hong Kong	2	5.56%	54	27.00	2015.5
6	University of Tehran	2	5.56%	52	26.00	2016.5
7	Razi University	2	5.56%	49	24.50	2018.5
8	University of Southern Queensland	2	5.56%	47	23.50	2018.0
9	Islamic Azad University	2	5.56%	39	19.50	2018.5
10	Huazhong University of Science and Technology	2	5.56%	38	19.00	2018.5

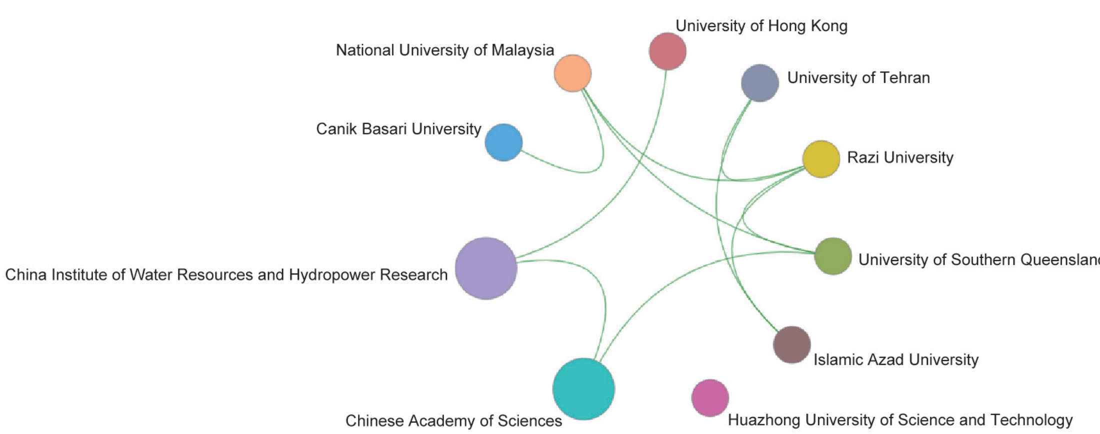

Figure 1.2.2 Collaboration network among institutions in the engineering research front of "smart city and smart basin integrated sensing based on geospatiotemporal big data"

As shown in Table 1.2.3, the five most active countries in terms of paper citations were China, Iran, the United States, Vietnam, and Australia. The top five institutions in terms of citations of core papers were Ton Duc Thang University (Vietnam), Duy Tan University (Vietnam), University of Tehran (Iran), University of Tabriz (Iran), and the University of Southern Queensland (Australia) (Table 1.2.4). China ranked first in terms of the quantity of core papers produced and the number of citations of core papers, indicating that Chinese researchers pay close attention to this topic.

Summarizing the above statistical data, in terms of research trends concerning "smart city and smart basin integrated sensing based on geospatiotemporal big data," compared with their foreign counterparts, Chinese scholars have performed well and are gradually becoming leaders in the field.

1.2.2 Coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes

Offshore engineering structures such as seaport wharfs, breakwaters, oil production platforms, submarine pipelines, cross sea bridges, subsea tunnels, and offshore wind power foundations confront severe operating environments and elevated safety risks. Under the action of wind, waves, currents, and earthquakes, the pore water pressure increases,

Table 1.2.3 Countries with the greatest output of citing papers on "smart city and smart basin integrated sensing based on geospatiotemporal big data"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	258	24.86%	2018.7
2	Iran	165	15.90%	2018.8
3	USA	151	14.55%	2018.4
4	Vietnam	84	8.09%	2019.3
5	Australia	73	7.03%	2018.8
6	India	63	6.07%	2018.5
7	South Korea	62	5.97%	2018.5
8	Turkey	50	4.82%	2018.3
9	Malaysia	47	4.53%	2018.6
10	Canada	46	4.43%	2018.7

Table 1.2.4 Institutions with the greatest output of citing papers on "smart city and smart basin integrated sensing based on geospatiotemporal big data"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Ton Duc Thang University	63	17.36%	2019.2
2	Duy Tan University	47	12.95%	2019.5
3	University of Tehran	40	11.02%	2018.3
4	University of Tabriz	33	9.09%	2018.8
5	University of Southern Queensland	31	8.54%	2018.4
6	Chinese Academy of Sciences	27	7.44%	2018.3
7	Huazhong University of Science and Technology	27	7.44%	2018.7
8	University of California, Santa Barbara	25	6.89%	2018.0
9	Hohai University	25	6.89%	2019.0
10	Ilia State University	23	6.34%	2019.1

and the effective stress decreases in the foundation of the seabed. This can lead to the strength-weakening and liquefaction of the seabed soil. At the same time, the action of waves and currents can scour the seabed foundation. In addition, structural movements under the action of dynamic loads can also change the pore water pressure and effective stress in the seabed soil, complicating the bearing capacity of the seabed foundation. The coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes are key issues for the safety and durability of offshore engineering structures.

The dynamic responses of seabed foundations and their coupling effect with structures are core problems in the coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes. There are three types of response models for seabed foundations: the Laplace, diffusion, and Biot consolidation equations. Both the Laplace and diffusion equations assume that the soil skeleton is not deformable and consider the pore fluid to be either incompressible or compressible. The coupling effect between the soil skeleton and pore fluid is not considered in either model. The Biot consolidation equation assumes that the soil skeleton is deformable, the pore fluid is compressible, and the fluid motion satisfies Darcy's law. Moreover, it considers the acceleration of both the soil skeleton and the pore fluid. Although the coupling effect of the soil skeleton and pore fluid are considered in the Biot consolidation equation, the constitutive model of the seabed soil is limited in the elastic range. In modelling the coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes, most methods apply various dynamic actions on the structure as loads and do not consider the response effect of the seabed foundations under dynamic actions.

The main topics to be addressed in this field include the following:

(1) The mechanisms and evolution of the strength-weakening and liquefaction of different seabed foundations (gravel, sand, soft clay, etc.) under the action of different periodic cyclic loads such as waves, earthquakes, and structural motions;

(2) An elasto-plastic constitutive model that accounts for the processes of strength-weakening, liquefaction, and excess pore pressure dissipation and consolidation after the liquefaction and re-liquefaction of different types of seabed soil under the action of cyclic loads;

(3) Scouring models of different seabed foundations that consider seepage effects under the action of waves and currents;

(4) Coupled numerical models for the nonlinear dynamic analysis of cyclic load–marine structure–seabed foundation systems and efficient, reliable numerical simulation methods; and

(5) Basic theory and experimental technology to test physical models to investigate the bearing capacity of cyclic load–marine structure–seabed foundation systems.

As listed in Table 1.1.1, between 2014 and 2019, 40 core papers concerning "coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes." On average, each paper was cited 31.78 times. The top five countries in terms of core-paper output were China, Australia, Denmark, the United Kingdom, and the Netherlands (Table 1.2.5). China was the most active country in this front, producing 57.50% of the core papers. The top five countries in terms of the average number of citations per paper were the Netherlands, the United States, Denmark, the United Kingdom, and Mexico. In terms of core-paper citations, papers published by Chinese authors were cited 26.87 times per paper on average, indicating that researchers in China are gradually gaining attention. As illustrated by the international collaborative network depicted in Figure 1.2.3, relatively close cooperation was observed between China, Australia, and the United Kingdom.

As listed in Table 1.2.6, the five institutions publishing the highest number of core papers were Griffith University (Australia), Technical University of Denmark (Denmark), Hohai University (China), Chinese Academy of Sciences (China), and Shanghai Jiao Tong University (China). In recent years, researchers from Griffith University have conducted in-depth, systematic studies on the dynamic responses of seabed foundations under the action of waves and currents, while researchers from the Technical University of Denmark have

Table 1.2.5 Countries with the greatest output of core papers on "coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	23	57.50%	618	26.87	2016.7
2	Australia	19	47.50%	491	25.84	2016.8
3	Denmark	12	30.00%	458	38.17	2015.7
4	UK	10	25.00%	350	35.00	2016.5
5	Netherlands	5	12.50%	230	46.00	2014.8
6	Belgium	3	7.50%	80	26.67	2017.7
7	USA	2	5.00%	79	39.50	2014.0
8	Turkey	2	5.00%	33	16.50	2017.0
9	Mexico	1	2.50%	28	28.00	2016.0
10	Norway	1	2.50%	17	17.00	2018.0

conducted research on seabed scouring around pipelines and vertical circular cylinders under the action of waves and currents. As illustrated in Figure 1.2.4, the top 10 institutions have cooperated closely.

The five countries with the most citations of core papers were China, the United Kingdom, Australia, Norway, and the United States (Table 1.2.7). The five institutions with the most citations of core papers were Hohai University (China), Shanghai Jiao Tong University (China), Griffith University (Australia), Technical University of Denmark (Denmark), and Ocean University of China (China) (Table 1.2.8). China ranked first in terms of both the number of published core papers and the number of citations of core papers, indicating that Chinese researchers have paid close attention to this research front.

Figure 1.2.3 Collaboration network among major countries in the engineering research front of "coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes"

Table 1.2.6 Institutions with the greatest output of core papers on "coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Griffith University	16	40.00%	411	25.69	2016.8
2	Technical University of Denmark	12	30.00%	458	38.17	2015.7
3	Hohai University	10	25.00%	224	22.40	2017.6
4	Chinese Academy of Sciences	7	17.50%	241	34.43	2015.6
5	Shanghai Jiao Tong University	7	17.50%	185	26.43	2016.6
6	Deltares	5	12.50%	230	46.00	2014.8
7	University of Bradford	5	12.50%	125	25.00	2017.6
8	Zhejiang University	3	7.50%	54	18.00	2018.7
9	Ningbo University	3	7.50%	52	17.33	2017.7
10	University of Dundee	2	5.00%	86	43.00	2014.5

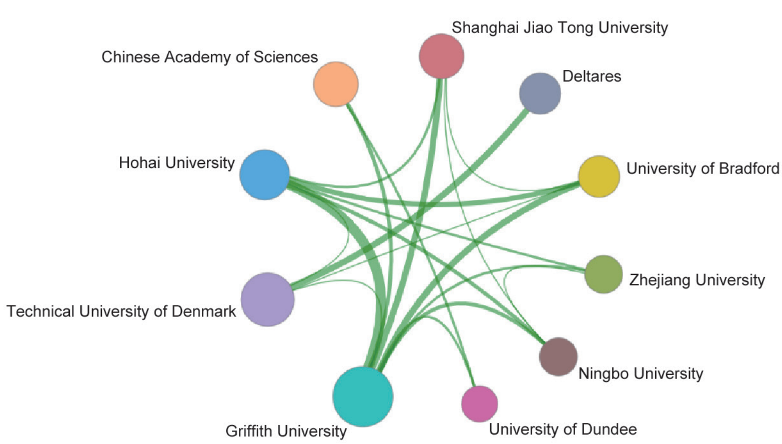

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes"

Table 1.2.7 Countries with the greatest output of citing papers on “coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes”

No.	Country	Citing papers	Proportions of citing papers	Mean year
1	China	327	38.97%	2018.3
2	UK	109	12.99%	2018.0
3	Australia	101	12.04%	2017.7
4	Norway	68	8.10%	2018.3
5	USA	62	7.39%	2018.2
6	Denmark	61	7.27%	2017.6
7	Netherlands	27	3.22%	2016.7
8	Italy	25	2.98%	2018.5
9	France	20	2.38%	2018.3
10	Spain	20	2.38%	2017.7

Table 1.2.8 Institutions with the greatest output of citing papers on “coupling response mechanisms of offshore engineering structures and seabed foundation systems under the action of wind, waves, currents, and earthquakes”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Hohai University	70	17.07%	2018.4
2	Shanghai Jiao Tong University	60	14.63%	2017.8
3	Griffith University	52	12.68%	2017.9
4	Technical University of Denmark	41	10.00%	2017.4
5	Ocean University of China	37	9.02%	2018.2
6	University of Western Australia	32	7.80%	2017.3
7	Chinese Academy of Sciences	30	7.32%	2017.4
8	Zhejiang University	26	6.34%	2018.6
9	Dalian University of Technology	24	5.85%	2017.8
10	Norwegian University of Science and Technology	20	4.88%	2018.2

1.2.3 Urban spatial analysis and optimization methods based on big data

With the development of internet technologies, the paradigm of urban spatial analysis is being transformed by the emergence of new big data that are geo-referenced, such as cell phone data, public transport tap-in/out data, and social media check-ins. The advantages of this type of data include its large size, fine resolution, and wide coverage. These data record various human behaviors across time and space with a new level of precision, thereby forming new pipelines for us to observe, perceive, and interpret cities and their transformation. Spatial analysis and optimization based on urban big data are thus frontiers for urban studies and practices.

Three domains of urban studies are involved in this front. The first is urban observation based on human behavior data, which enables our understanding of the spatial characteristics of urban elements and improves the sensitivity of the statues of various urban sub-systems, such as populations, workplaces, public service, and transport. This domain has been well explored. The second domain is urban diagnosis and performance evaluation. On the basis of human behavior data, research in this domain evaluates urban performance, including commuting and the work–life balance, population distribution, and accessibility, in terms of urban sufficiency and equality. The output of such studies is strongly related to urban optimization. Most of these efforts, however, have not yet produced applications as they have focused on problem detection and methodological developments without a convergent form for applications. The third domain is the reformation of the relevant urban theory. This reformation has been enabled by the discovery and definition of new rules of urbanization with the intelligent simulation, integration, and prediction of urban systems and their transformation. Research in this domain is still limited, but it has been widely recognized as an essential direction.

A new era of urban science and research is now being encouraged by the availability of urban big data. The main focus of current efforts is to bridge research and practice using various emerging technologies for spatial analysis and optimization. The ultimate aim of such efforts is to facilitate smart cities with theoretical innovations of the new urban science.

The institutions leading the relevant research are located in the West in developed countries or districts, such as the United States, the United Kingdom, and the European Union and in rapidly developing countries and areas, such as China. Developed countries typically maintain more comprehensive research systems and networks with the solid establishment of theory, methods, and applications, whereas rapidly developing countries, particularly China, stand out for the large size of their urban big data due to their population size, optimism regarding new technologies, and good software and hardware facilities.

The world-leading institutions in this front include the Massachusetts Institute of Technology (e.g., Media Lab), University College London (e.g., the Centre for Advanced Spatial Analysis and Urban Dynamic Lab), Swiss Federal Institute of Technology in Zurich (e.g., Future City Lab), Alan Turing Institute, Google, Twitter, and Microsoft. The leading institutes in China include Tongji University (e.g., China Intelligent Urbanization Co-creation Centre for High-Density Regions), University of Chinese Academy of Sciences, Tsinghua University, Peking University, Alibaba, Tencent, Huawei, and Jingdong. Universities are the majority among these institutes because of their interdisciplinary advantage in incorporating urban planning, geography, computer science, geographical information science, etc., in a new urban science, which has led to their dominance in this research. As a complement to this research, technology companies utilize their data sources and advanced facilities for data storage, computation, and real-time applications via their internet platforms.

Thanks to the complementary advantages of diverse sectors, the forms of cooperation on this front vary greatly. The main types include multi-sector cooperation across many universities, governments, associations, and enterprises (e.g., China Intelligent Urbanization Co-creation Centre for High-Density Regions), cross-university cooperation (e.g., Alan Turing Institute), and institute–enterprise cooperation (e.g., CAUPD-Alibaba Future City Lab).

As listed in Table 1.1.1, between 2014 and 2019, 58 core papers concerning “urban spatial analysis and optimization methods based on big data” were published, and on average each paper was cited 42.43 times. The top five countries in terms of core-paper output were China, the United States, Norway, Australia, and the United Kingdom (Table 1.2.9). As one of the leading research countries, China published 41.38% of the core papers on this research front. The top five countries in terms of the average number of citations per paper were the United Kingdom, Switzerland, Singapore, Norway, and the United States. On average, the papers published by Chinese authors received 49.54 citations per paper, which is slightly above the overall average. From the perspective of cooperation networks between countries (Figure 1.2.5), close cooperation has been observed among the most productive ten countries particularly between the United States and China.

The five institutions producing the most core papers on this front are Wuhan University (China), Norwegian University of Science and Technology (Norway), Sun Yat-Sen University (China), Peking University (China), and Arizona State University (USA) (Table 1.2.10). Wuhan University is the leader in the fields of spatial analysis with big data and the measurement, computation, and redefinition of urban structures and their transformation. The Norwegian University of Science and Technology is a pioneer in the research of environmental sensing and smart sustainable urbanization supported by the Internet of Things (IoT), information and communication technology, and other emerging technologies. From the perspective of cooperation network among the leading institutions (Figure 1.2.6), collaborative studies have been conducted by the top 10 most productive institutions on this front, except for the Norwegian University of Science and Technology.

The top five countries in terms of citations of core papers are China, the United States, the United Kingdom, Spain, and Australia (Table 1.2.11). The top five institutions in terms of

Table 1.2.9 Countries with the greatest output of core papers on "urban spatial analysis and optimization methods based on big data"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	24	41.38%	1189	49.54	2017.4
2	USA	14	24.14%	856	61.14	2016.5
3	Norway	6	10.34%	425	70.83	2017.0
4	Australia	6	10.34%	110	18.33	2018.0
5	UK	5	8.62%	704	140.80	2015.2
6	Netherlands	5	8.62%	106	21.20	2017.4
7	Spain	4	6.90%	215	53.75	2016.2
8	Japan	4	6.90%	158	39.50	2016.5
9	Switzerland	3	5.17%	244	81.33	2014.7
10	Singapore	3	5.17%	217	72.33	2016.3

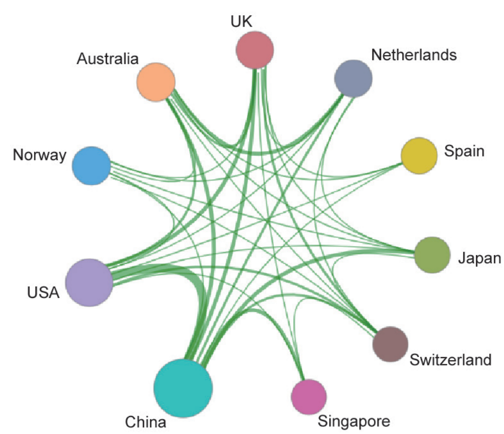

Figure 1.2.5 Collaboration network among major countries in the engineering research front of "urban spatial analysis and optimization methods based on big data"

Table 1.2.10 Institutions with the greatest output of core papers on "urban spatial analysis and optimization methods based on big data"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Wuhan University	5	8.62%	180	36.00	2017.4
2	Norwegian University of Science and Technology	4	6.90%	333	83.25	2017.5
3	Sun Yat-Sen University	4	6.90%	183	45.75	2017.2
4	Peking University	3	5.17%	172	57.33	2016.3
5	Arizona State University	3	5.17%	114	38.00	2015.3
6	Texas State University	3	5.17%	67	22.33	2017.0
7	Chinese Academy of Sciences	3	5.17%	49	16.33	2017.7
8	University College London	2	3.45%	593	296.50	2014.0
9	Kyungpook National University	2	3.45%	237	118.50	2016.5
10	Nanyang Technological University	2	3.45%	199	99.50	2016.0

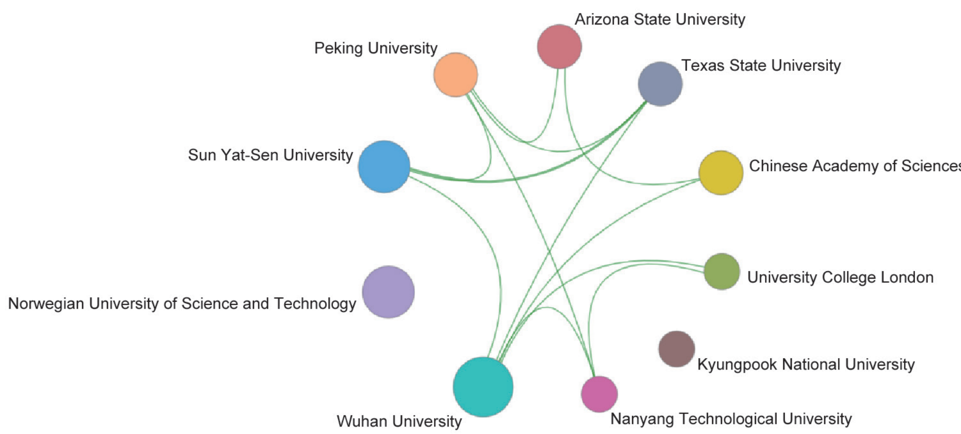

Figure 1.2.6 Collaborative network among major institutions in the engineering research front of "urban spatial analysis and optimization methods based on big data"

Table 1.2.11 Countries with the greatest output of citing papers on "urban spatial analysis and optimization methods based on big data"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	842	35.56%	2018.4
2	USA	510	21.54%	2018.1
3	UK	208	8.78%	2018.2
4	Spain	144	6.08%	2018.2
5	Australia	131	5.53%	2018.2
6	Italy	129	5.45%	2018.0
7	France	114	4.81%	2018.1
8	Germany	78	3.29%	2018.1
9	Japan	74	3.13%	2017.9
10	Canada	70	2.96%	2018.1

citations of core papers are Chinese Academy of Sciences (China), Wuhan University (China), Massachusetts Institute of Technology (USA), Sun Yat-Sen University (China), and Peking University (China) (Table 1.2.12). China ranked first in terms of the number of published core papers and citations of core papers, indicating that Chinese researchers have paid close attention to research performed on this front.

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

The top 10 engineering development fronts in the field of civil, hydraulic, and architectural engineering are summarized in Table 2.1.1. These fronts cover a variety of disciplines, including structural engineering, landscape and urban panning, transportation engineering, geotechnical and underground engineering, bridge engineering, construction materials, municipal engineering, hydraulic engineering, and geodesy and survey engineering. Among these development fronts, experts recommended the following: "planning and design technologies for public health emergency responses," "deep-water detection of latent defects and treatment technologies for water conservancy projects," "city information modeling," "regulation methodologies for the properties and microstructures of cement-based materials used in extreme environments," "regulable design of ultra-high-performance concrete," "technology and equipment

Table 1.2.12 Institutions with the greatest output of citing papers on "urban spatial analysis and optimization methods based on big data"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	101	19.77%	2018.0
2	Wuhan University	79	15.46%	2018.4
3	Massachusetts Institute of Technology	45	8.81%	2017.5
4	Sun Yat-Sen University	42	8.22%	2018.5
5	Peking University	42	8.22%	2018.3
6	University of Chinese Academy of Sciences	39	7.63%	2018.3
7	Zhejiang University	35	6.85%	2018.5
8	Tsinghua University	33	6.46%	2018.4
9	Microsoft Research Asia	32	6.26%	2016.4
10	Xidian University	32	6.26%	2018.1

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

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Planning and design technologies for public health emergency responses	38	22	0.58	2017.4
2	Intelligent construction technology and equipment for underground projects under extreme conditions	274	578	2.11	2017.5
3	Deep-water detection of latent defects and treatment technologies for water conservancy projects	90	181	2.01	2016.8
4	Design and construction technologies of earthquake-resilient structural systems	509	1 711	3.36	2016.2
5	City information modeling	150	418	2.79	2017.0
6	Regulation methodologies for the properties and microstructures of cement-based materials used in extreme environments	473	977	2.07	2016.5
7	Regulable design of ultra-high-performance concrete	15	17	1.13	2017.1
8	Precise positioning and safe navigation technology for high-speed trains	24	84	3.5	2017.0
9	Technology and equipment for leakage monitoring and in-situ repair for urban water supplies and drainage networks	177	233	1.32	2017.1
10	Earth observation and geospatial information processing technologies based on the blockchain	10	34	3.40	2018.8

for leakage monitoring and *in-situ* repair for urban water supplies and drainage networks," and "Earth observation and geospatial information processing technologies based on the blockchain." The remaining topics were identified from patent maps and then confirmed by experts. Table 2.1.2 presents annual statistical data on patents published between 2014 and 2019 related to these top 10 development fronts.

(1) Planning and design technologies for public health emergency responses

Urban planning and design can play a pivotal role in responses to public health emergencies involving space interventions since urban development has inevitable effects on human contact with infection sources, the mode of transmission and processes of infectious diseases, and the number of people who are susceptible via both ecological and social processes in the urban space. Although there are no wholly specific planning and design technologies for public health emergency responses, existing technologies for land use and urban ecology identification, the construction of the 3D urban physical space and environmental models, environmental pollution monitoring and assessment, etc. contribute to

Table 2.1.2 Annual number of patents published for the top 10 engineering development fonts in civil, hydraulic & architecture engineering

No.	Engineering development front	2014	2015	2016	2017	2018	2019
1	Planning and design technologies for public health emergency responses	2	5	3	7	8	13
2	Intelligent construction technology and equipment for underground projects under extreme conditions	15	20	31	50	76	82
3	Deep-water detection of latent defects and treatment technologies for water conservancy projects	14	17	7	11	21	20
4	Design and construction technologies of earthquake-resilient structural systems	54	57	79	90	85	95
5	City information modeling	8	15	19	29	38	33
6	Regulation methodologies for the properties and microstructures of cement-based materials used in extreme environments	62	46	77	80	87	87
7	Regulable design of ultra-high-performance concrete	2	2	3	0	1	7
8	Precise positioning and safe navigation technology for high-speed trains	3	1	1	2	3	12
9	Technology and equipment for leakage monitoring and in-situ repair for urban water supplies and drainage networks	13	13	34	28	30	53
10	Earth observation and geospatial information processing technologies based on the blockchain	0	0	0	1	0	9

isolating infection sources and blocking disease transmission routes. The effects and capabilities of these technologies can be improved in terms of their pertinence to infectious diseases, disclosure of transmission mechanisms, provision of accurate predictions, and applicability to planning and design.

Furthermore, it is necessary to promote the research and development (R&D) of technology in this field in terms of three aspects: the big data-based analysis of the spatiotemporal behavior of residents and traffic, comprehensive construction of public health units, and comprehensive spatial layout of healthcare facilities based on social equity. With efforts focused on these aspects, the capability of the urban space to respond to public health emergencies will be improved, the planning and building of healthy cities be facilitated, and more scientific and reasonable planning and design strategies be formulated. The health of urban spaces has received increased attention due to the global COVID-19 pandemic, making the development and testing of planning and design technologies for public health emergency responses imperative for better planning and building of healthy cities. Between 2014 and 2019, 38 patents relevant to this research front were published. These patents received 22 citations, with an average of 0.58 citations per patent.

(2) Intelligent construction technology and equipment for underground projects under extreme conditions

The aim of this topic is the rapid, industrialized construction of underground projects under extreme conditions with little or no human intervention. Extreme conditions include extreme natural environments and ultra-complex geological conditions, for example, high altitude, high ground temperature, high ground stress, and high water pressure. To achieve this goal, intelligent techniques (e.g., design, production and processing, construction, operation and maintenance, and R&D) and automated, intelligent equipment should be developed. In extreme natural environments, the tolerance limits of personnel and equipment and the working efficiency of mechanical equipment decreases sharply. Meanwhile, eco-environmental protection regulations have become extremely strict. Nevertheless, in extremely complex geological conditions, chain geological disasters can occur very easily, causing major accidents. For rapid construction with little or no human intervention, the industrial construction capacity under extreme conditions must be dramatically improved. Improvement can be achieved by studying the essential theory and key techniques of intelligent construction methods and by developing intelligent equipment that can coordinate with humans and engage in self-directed learning. The main research interests on this front include the following: 1) basic theories for intelligent construction that integrates the acquisition, design, and construction steps of underground engineering; 2) basic digital design platforms and integrated, intelligent design systems; 3) digital, intelligent production and processing of lining structures; 4) geological disaster prediction, intelligent construction control, and the monitoring and detection of engineering quality under extreme conditions; 5) intelligent equipment capable of coordinating with humans and learning autonomously under extreme conditions; and 6) online monitoring, intelligent diagnosis, and automatic maintenance of underground engineering under extreme conditions.

At present, the development of intelligent construction technology and equipment for underground projects is focused on three aspects: 1) forming basic theories for intelligent underground engineering construction, 2) developing geological disaster prediction techniques under extreme conditions, and 3) studying and manufacturing intelligent construction equipment suitable for extreme conditions. Between 2014 and 2019, 274 patents relevant to this research front were published. These patents received 578 citations, with an average of 2.11 citations per patent.

(3) Deep-water detection of latent defects and treatment technologies for water conservancy projects

Water conservancy projects are important for the regulation of the spatial and temporal distribution of water resources and for the optimization of the allocation of water resources. Moreover, they play an important role in control engineering systems for river floods. Due to the aging of water conservancy project structures and consequent deterioration in their performance and the impact of environmental changes coupled with earthquakes and geological disasters, dangerous situations occur occasionally. The deep-water detection of latent defects and treatment technology has become a frontier in this field. Its core consists of underwater detection equipment, diving technology, and underwater operation technology.

The deep-water detection technologies primarily address underwater leakage detection, underwater structural defect detection, metal structure detection, and underwater exploration. In this case, the technical equipment is used for carrying, testing, and working on underwater projects, and it primarily consists of manned diving technologies and related equipment, manned submersible vehicles, unmanned diving equipment (underwater robots), and equipment for underwater detection, cleaning, cutting, welding, and other special underwater tasks. Underwater latent defects treatment technologies mainly address leakage treatment, structural reinforcement and defect treatment, metal structure anticorrosion treatment, and related construction technologies. In addition, it is necessary to conduct underwater inspection and dredging, gate sealing, and other treatment processes for water discharge and conveyance during project operations and reinforcements. The main areas of development on this front include the research and development of latent defects detection equipment for water conservancy projects under complex conditions in deep-water, high-precision positioning technology for deep-water environments and underwater detection and operation, high-resolution analytical technology for low-visibility environments, and repair and reinforcing materials and processes for deep-water environments. The deep-water detection of latent defects and treatment technology for water conservancy projects are important to ensuring the long-term safety of water conservancy projects. This front serves reservoir dams, sluices, gates and embankments, long-distance water diversions, transfer projects, etc. and has broad development prospects. Between 2014 and 2019, 90 patents relevant to this research front were published, and these patents received 181 citations, with an average of 2.01 citations per patent.

(4) Design and construction technologies of earthquake-resilient structural systems

Engineering structures are the most important elements of an earthquake-resilient city, the construction of which requires that engineering structures not only resist earthquakes and prevent damage but also have the ability to recover after an earthquake. An earthquake-resilient structure transforms the material nonlinear problem of a traditional system into a geometric nonlinear problem of a resilient structure. It forms a new recoverable functional system with controllable damage, concentrated elastic–plastic deformation, greater deformation capacity, and smaller residual deformation under strong earthquakes. There are three main types of earthquake-resilient structures: structural systems with rocking members, structural systems with self-centering members, and structural systems with replaceable components. At present, the development frontiers for the design and construction of earthquake-resilient structures are mainly focused on 1) new earthquake-resilient systems with coordinated mass-stiffness damping; 2) four-level seismic fortification objectives and multi-performance indicators; 3) direct displacement-based design methods for earthquake-resilient structures; 4) earthquake resilience technologies for non-structural components; and 5) rapid construction and post-quake recovery technologies for earthquake-resilient structures. Between 2014 and 2019, 509 patents were published on this topic with 1711 patent citations and an average of 3.36 citations per patent.

(5) City information modeling

City information modeling (CIM) is a digital platform at the city level that is an advance from building information modeling (BIM). CIM extracts and fuses data from BIM at the micro level, data from a geographic information system (GIS) at the macro level, and data captured by IoT to form a 3D city model and city-integrated information body that comprehensively depicts the dynamic reality of a city. More complete data models and the integration of city information are supported by the spatial features provided by GIS, detailed building characteristics supplied by BIM, and city dynamics obtained from the IoT. In addition to the vivid visualizations offered by its 3D city models, CIM provides feature data that cover various city components and that are available anywhere, anytime.

CIM has the capability to sense, analyze, share, compute, and judge in order to effectively address issues encountered during city development. It is able to simulate city operations and regulations. Furthermore, it can evaluate development strategies based on embedded data (models). Built on top of a solid information platform and enhanced by state-of-the-art techniques, including AI, big data analysis, and 3D modeling, CIM is able to more intelligently support urban planning, urban development, and urban governance. CIM is the core and foundation of smart city development and refined urban management.

Between 2014 and 2019, 150 patents relevant to this research front were published. These patents received 418 citations, with an average of 2.79 citations per patent.

(6) Regulation methodologies for the properties and microstructures of cement-based materials used in extreme environments

The extreme service environments of engineering structures include ultra-low temperatures, ultra-high temperatures, strong corrosion, strong radiation, strong magnetic fields, ultra-high pressure, strong vacuums, and complex loads. Such extreme environmental effects can lead to serious deterioration in the performance of cement-based materials in normal service and can seriously threaten the safety of engineering structures. With the expansion of the field of human exploration and the development of construction technologies, major countries have increased demand for extreme environmental engineering construction. Cement-based materials for extreme environments therefore have broad application prospects in many future extreme environment scenarios. Hence, it is necessary to study the evolution of the mechanical properties and durability of cement-based materials in extreme environments.

The microstructure of cement-based materials is closely related to their performance. To improve the safety and service life of cement-based materials in extreme environments, the development of a common microstructure regulation technologies based on the performance requirements of cement-based materials can be effective. To fulfill this goal, advanced testing and characterization methods combined with computer simulation technology should be adopted to study the evolution of the microstructural characteristics of cement-based materials in extreme environments at multiple scales in order to reveal deep-level deterioration and damage mechanisms. Corresponding multi-scale composite structure regulation methodologies have been proposed from the perspective of raw material optimization screening, mixed proportion optimization design, and micro-structure construction and design. In view of the structural performance requirements under different extreme environments, special attention should be given to the development of hydration processes for cement-based materials, the spatialtemporal distribution regulation of hydration products, calcium-silicate-hydrate micro and nano properties, pore structure optimization, and enhancement of the interface transition zone.

Between 2014 and 2019, 473 patents relevant to this research front were published. These patents received 977 citations, with an average of 2.07 citations per patent.

(7) Regulable design of ultra-high-performance concrete

Ultra-high-performance concrete (UHPC) has been one of the most innovative cement composite materials for the last 20 years. Its design and production are mainly based on the close packing of particles, which can be achieved by reducing the porosity, improving the microstructure, increasing the homogeneity, and increasing the toughness. Compared to conventional cement-based materials, UHPC has ultra-high strength, high toughness, and excellent durability. These superior properties make UHPC a good candidate to meet the requirements of lightweight, high rises, large spans, and high durability for civil engineering construction. Thus, it has great potential applications in bridges, anti-explosion structures, thin-walled structures, architectural ornaments, marine structures, and rehabilitated and strengthening members. By changing its internal components and modifying the preparation technology, key properties, including toughness, abrasion resistance, elastic modulus, repair compatibility, and resistivity, can be controlled, enabling its application for different aspects of civil engineering. Under the premise of fully understanding its material and microstructure characteristics, the wide and precise application of UHPC in various engineering fields can be achieved according to the engineering requirements. This can significantly enhance the safety, service life, and social sustainability of the structures.

Between 2014 and 2019, 15 patents relevant to this research front were published, and these patents received 17 citations, with an average of 1.13 citations per patent.

(8) Precise positioning and safe navigation technology for high-speed trains

The railways of China have entered the high-speed era, and it is of great significance to increase the running density of high-speed trains, improve transport efficiency, and ensure transport safety. Precise positioning and safe navigation technology for high-speed trains is the primary technical means of ensuring the safety and efficiency of high-speed railway transportation. This technology uses multi-sensor fusion methods to reliably and accurately measure the real-time position, speed, acceleration, and attitude of high-speed trains in order to ensure their safe navigation and motion blocks.

The precise positioning and safe navigation of high-speed trains require accurate, real-time performance. Owing to the complex changing environment of high-speed trains, a single sensor such as global navigation satellite system (GNSS), inertial navigation system, on-board speed radar, wheel speed encoder, or response beacon cannot guarantee the precise positioning of the train with sufficient spatial and temporal resolution across an entire area. For example, the accuracy of GNSS cannot be guaranteed in canyon areas and cannot even be located in tunnels, the positioning error of inertial navigation systems accumulates over time, and the spatial resolution of transponder beacons is insufficient. To ensure that the positioning of a train meets the accuracy requirements over the whole travel area, it is first necessary to select a sensor with sufficient observation accuracy and a sufficient sampling rate. Network real-time kinematic positioning, for example, can reach centimeter-level accuracy. Second, it is necessary to conduct joint observation using the above-mentioned multiple sensors in a unified spatial and temporal reference framework. Most importantly, an effective data fusion processing method, such as Kalman filtering and its derivative methods, is needed.

The technology also needs to meet reliability requirements. To guarantee reliability redundant communication channels and observation information are required. To reliably provide precise state information about trains, it is necessary to use observation anomaly detection methods to identify sensor faults and gross errors, to perceive abnormal jumps in train position, speed, acceleration, and attitude through state anomaly detection methods, and to use robust estimation methods.

In the future, high-speed trains will travel at even greater speeds. The key research directions in this field are as follows: precision positioning that integrates multiple high-dynamic sensors; resilient positioning, navigation, and timing of high-speed trains; observation, and state anomaly detection and processing by multiple high-dynamic sensors.

Between 2014 and 2019, 24 patents relevant to this research front were published, and these patents received 84 citations, with an average of 3.5 citations per patent.

(9) Technology and equipment for leakage monitoring and *in-situ* repair for urban water supplies and drainage networks

The efficient application of technologies and equipment for leakage monitoring and *in-situ* remediation of pipelines could greatly alleviate socioeconomic stresses by reducing the average leak duration. Based on the real-time monitoring of the pressure and flowrate of water distribution networks by the supervisory control and data acquisition system, the whole scheme for leakage identifying, locating, and repairing processes could be established by model-driven and data-driven methods. The current data-driven leakage monitoring method is confronting with the challenge of accurately identifying leakages with specific supervising history data that is limited in quantity and quality, whereas the challenge to the steady or transient model-driven leakage monitoring method lies in the validation of the hydraulic model, optimization of the monitoring location, and identification of the leakage characteristics in the surveillance area. With the rapid development of the IoT and AI technology, the integration of data-driven modelling techniques and high-performance equipment for leakage detection represent the main future trend in this field. In contrast, the leakage monitoring technology for drainage systems is still in a preliminary stage and is limited by problems such as the difficulty of installation and cumbersome preservation of the monitoring devices, unstable data acquisition for tracking the level and flowrate in pipelines, and low precision of the hydraulic model. Accordingly, the key scientific research on cutting-edge technologies in this field may include the development of leakage monitoring devices, the technology of leakage identification and location via the statistical analysis of the monitoring data, and the establishment of highly accurate hydraulic models and their validation. Regarding *in-situ* remediation techniques coordinated with the pipe rehabilitation supporting measures, the main techniques include local rehabilitation, rehabilitation dominated by polyolefin material, cured-in-place pipe (CIPP), and rehabilitation with liquid solidified material. Due to the potential significant economic and social benefits, trenchless rehabilitation is gaining increasing attention.

Between 2014 and 2019, 177 patents relevant to this research front were published, and these patents received 233 citations, with an average of 1.32 citations per patent.

(10) Earth observation and geospatial information processing technologies based on the blockchain

Earth observation and geospatial information processing technologies based on the blockchain are development frontiers in the field of surveying and mapping engineering. These frontiers are oriented to the distributed processing requirements of earth observation data and geospatial information. The techniques adopt a blockchain data structure, distributed node consensus algorithm, encrypted data transmission and access technology, intelligent contract data operation mode, and other core technologies, and provide a new distributed processing infrastructure and computing paradigm for earth observation data and geospatial information. The main development directions include: 1) sharing technology for remote sensing data of earth observation based on the blockchain to prevent illegal tampering and the dissemination of remote sensing images and to control and use of remote sensing images; 2) user participation based on the generation of geospatial information and updating the technology based on the blockchain; and 3) distributed geographic information service systems based on the blockchain that provide location services for vehicles and unmanned aerial vehicles.

Between 2014 and 2019, 10 patents relevant to this research front were published. These patents received 34 citations, with an average of 3.4 citations per patent.

2.2 Interpretations for three key engineering development fronts

2.2.1 Planning and design technologies for public health emergency responses

As urbanization continues, changes in habitats and high population density have increased the occurrence and spread of infectious diseases in cities. Ecological impact processes, such as changes in land use, urban heat island effects, and alterations in food production characteristics, together with social impact processes brought about by changes in the population, built environment, and lifestyle have had a decisive impact on the prevalence of infectious diseases. For spatial interventions, urban planning and design can play a pivotal role in isolating the sources of an infection, blocking transmission routes, and protecting susceptible groups.

Although at present there are no planning and design technologies specifically for public health emergency responses, existing technologies for land use and urban ecology identification, the construction of 3D urban physical spaces and environmental models, and environmental pollution monitoring and assessment can be used to isolate infection sources and block transmission routes. Nevertheless, the applicability of these technologies has yet to be further explored, and there is opportunity for improvement in their pertinence to the analysis of public health emergency responses and the scientific validity of planning and design interventions. Details for each of these technologies are as follows:

(1) Land use and urban ecology identification

At present, urban land use and urban ecology identification systems have been established based on data collection and classification, analysis and summary, and storage and monitoring. These systems can provide clues about the areas where infectious disease pathogens may exist, but their accuracy and predictive ability are still insufficient. In the future, it will be necessary to adopt machine learning to analyze the evolution of land use from the perspective of historical development. In tandem with ecological analyses, future technologies need to be applied to reveal the possible risks and impacts of pathogen exposure caused by urban expansion and habitat changes and to predict the risk of public health emergencies.

(2) Construction of 3D urban physical spaces and environmental models

The existing 3D space virtual construction technology for whole cities or specific spatial objects, such as a campus, can explicitly demonstrate multi-temporal and multi-level urban spatial forms and environmental characteristics and provide essential support for the regulation of urban activities and projects (e.g., guiding tourists, municipal projects, and fire warnings). This technology may also serve as a critical basis for the study of the transmission characteristics of infectious diseases and for the formulation of space intervention programs.

(3) Environmental pollution monitoring and assessment

The current pertinent analytical technologies focus on soil, water, and air pollution, and most are composed of modules including detection or identification, analysis, assessment, and early warning. The R&D of future technologies needs to account for key places where the risk of acquiring infectious diseases is high (such as hospitals, supermarkets, live poultry trading markets, and transportation hubs) and comprehensively consider the interactive effects of multidimensional factors, with a view to provide positive insights for spatial planning and design.

Furthermore, efforts should be made to advance the R&D of technology in terms of the following three aspects in order to improve the capability of urban spaces to respond to public health emergencies, to facilitate the planning and construction of healthy cities, and to formulate more scientific and rational planning and design strategies. 1) The big data-based analysis of the spatiotemporal behavior of residents and traffic can help predict the modes of transmission and spread of diseases under different traffic organization and management patterns, thus providing support for new urban zoning for epidemic prevention. 2) The comprehensive construction of public health units can help complete community function nodes that can play a role in both normal conditions and epidemics on the basis of the “15-minute community life circle.” 3) The comprehensive spatial layout of healthcare facilities based on social equity will emphasize care for groups susceptible to infectious diseases (such as the elderly and children) so that healthcare facilities will be reasonably equipped to best treat them.

As listed in Table 2.1.1, 38 patents related to this topic were published between 2014 and 2019. The three countries that published the most patents were China, South Korea, and Japan (Table 2.2.1), with China contributing 86.84% of the patents. The average citations per patent of the Chinese patents was 0.52, demonstrating increased attention being paid to Chinese patents.

The five organizations that produced the most patents were GEOTWO Corporation (South Korea), Xi’an University of Science and Technology (China), Sanya China Remote Sensing Research Institute (China), China National Petroleum Corporation, and Anhui Science and Technology University (China) (Table 2.2.2). GEOTWO Corporation, a South Korea-based geographic information technology company, places one of its focuses on the research and development of urban land use monitoring and assessment technology. Xi’an University of Science and Technology focuses on developing technologies of land use monitoring and urban carbon emission measurement. Specializing in the measurement of vegetation net primary productivity, Sanya China Remote Sensing Research Institute develops most of its key technologies based on remote sensing data and machine learning models. As an organization dedicated to petroleum development and transportation, China National Petroleum Corporation has developed the technology to evaluate the environmental risks brought by oil longer conveying pipeline, providing an effective method to evaluate the impacts of related accidents on eco-system. The patented technology developed by Anhui Science and Technology University on land use status can simulate the pattern succession of land use. Though none of the technologies mentioned above are designed to directly respond to public health emergencies, they can not only serve as the technical basis for planning and design interventions, but also provide solutions and references for research and development of relevant analytical methods and technological tools in the future.

Table 2.2.1 Countries with the greatest output of patents on “planning and design technologies for public health emergency responses”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	33	86.84%	17	77.27%	0.52
2	South Korea	4	10.53%	5	22.73%	1.25
3	Japan	1	2.63%	0	0.00%	0.00

Table 2.2.2 Institutions with the greatest output of patents on “planning and design technologies for public health emergency responses”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	GEOTWO Corporation	South Korea	2	5.26%	5	22.73%	2.50
2	Xi’an University of Science and Technology	China	2	5.26%	5	22.73%	2.50
3	Sanya China Remote Sensing Research Institute	China	1	2.63%	3	13.64%	3.00
4	China National Petroleum Corporation	China	1	2.63%	2	9.09%	2.00
5	Anhui Science and Technology University	China	1	2.63%	2	9.09%	2.00
6	Guangzhou Institute of Geography	China	1	2.63%	1	4.55%	1.00
7	ANA Company	South Korea	1	2.63%	0	0.00%	0.00
8	Anhui Chuanbai Technology Co., Ltd.	China	1	2.63%	0	0.00%	0.00
9	Anhui Provincial Academy of Environmental Sciences	China	1	2.63%	0	0.00%	0.00
10	Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences	China	1	2.63%	0	0.00%	0.00

2.2.2 Intelligent construction technology and equipment for underground projects under extreme conditions

In extreme natural environments, the tolerance limits of personnel and equipment and the working efficiency of mechanical equipment decrease sharply. Meanwhile, eco-environmental protection regulations have become extremely strict. Moreover, under extremely complex geological conditions, chain geological disasters can occur very easily, causing major accidents. Consider the Sichuan–Tibet railway and highway as examples. In these two projects, tunnel sections account for a large proportion of the total length and have a large burial depth, and the railway and highway pass through multiple highly active fault zones. They face significant geological problems, including high ground stress, rock burst, and the large deformation of soft rocks. These tunnel sections also have an ultra-high risk of encountering slope slides, rockfalls, and debris. Furthermore, the eco-environment along the railway and highway is sensitive and vulnerable due to particular environmental features of this region: huge changes in altitude, ultra-low temperatures on the plateaus in winter, and very high ground temperatures. The development of intelligent technology and equipment is thus urgent for their construction. The topic “intelligent construction and techniques to guarantee engineering health for the expressway into Tibet” was listed among the top 10 engineering and technical problems by the China Association for Science and Technology in 2020.

Studying and developing intelligent construction technologies and equipment for underground projects under extreme conditions are conducive to forming an intelligent industrial construction system. Such a system would encompass the entire industrial chain, including design, production and processing, construction and equipment, and operation and maintenance. It would also contribute to the promotion of new industries, new forms of business, and new modes and support the in-depth integration of industries related to underground engineering, which are cross-field, all-dimensional, and multi-level.

At present, the global underground engineering industry is developing effectively, but it faces problems such as the low level of standardization, informatization, and intelligence. A big gap remains between the underground engineering industry and advanced construction methods. With the development of a new scientific and technological revolution and ongoing industrial transformation, the new generation of information technology, represented by AI, big data, the IoT, and 5G, is accelerating in its penetration and assimilation into the underground engineering industry. To date, research interests concerning intelligent construction technology and equipment for underground engineering under extreme conditions include the following.

(1) Construction method. Traditional construction methods, such as NATM and ADECO-RS, use a dynamic feedback mechanism that continuously adjusts the construction scheme based on initial semi-empirical designs by constantly monitoring the excavation progress. Construction methods are now moving toward the integration of intelligent “acquisition–design–construction” with the development of emerging techniques for underground projects, including new sensing techniques, data transmission techniques, BIM/GIS, and information integration techniques.

(2) Design system. It comprises both digital design systems based on BIM/GIS and platforms that integrate information from the whole process, which is being developed to coordinate and unify design, manufacturing, construction, operation, and maintenance.

(3) Production and processing. Some studies are developing new production and processing techniques, including digital technical processes and the application of robots to digitalize and intellectualize the production of lining structures for underground projects. This may eventually lead to production factories with little or no human intervention.

(4) Intelligent construction. Studies on intelligent construction fall into two main categories. First, some studies have pursued detailed detection and intelligent control for geological disasters by developing intelligent prediction and control methods for geological disasters in underground projects under extreme conditions. Second, some studies focus on automating tunnel construction and reducing the number of on-site personnel and their workload with emerging techniques, such as the intelligent collection and feedback of construction site information, automatic stereo perception and positioning, digital twin platforms, expert remote diagnosis, intelligent detection, and project quality control.

(5) Intelligent equipment. Many intelligent devices are now being developed. They include intelligent equipment with man–machine coordination and an autonomous learning capacity, intelligent construction robots, automatically operational brain controllers, robotized equipment for environmental risk perception and precise operational control under extreme conditions, highly reliable intelligent and interconnected equipment, and intelligent and interconnected equipment for identifying and processing all types of geological environmental risk.

(6) Intelligent operation and maintenance. Studies of this topic include the online monitoring of the operation environment and structural health status of underground projects under extreme conditions, the intelligent diagnosis and maintenance of structural performance, accident prevention and rescue, and disaster alarms and control.

As listed in Table 2.1.1, 274 patents related to this topic were published between 2014 and 2019. The three countries that published the most patents were China, the United States, and Canada (Table 2.2.3). China contributed 91.97% of the patents. The average citations per patent of the Chinese patents was 1.62. As depicted in Figure 2.2.1, international cooperation on this topic has been rare among the top 10 core patent-output countries.

The five organizations that produced the most patents were the China Railway Group Limited, China University of Mining and Technology-Beijing, China Communications Construction Company Limited, State Grid Corporation of China, and Shandong University (China) (Table 2.2.4). Cooperation among these organizations is rare (Figure 2.2.2).

2.2.3 Deep-water detection of latent defects and treatment technologies for water conservancy projects

The research and development of deep-water detection and operation technologies originated in the field of marine engineering, to which they have been applied on a large scale. The traditional industrial powers are leaders in the research, development, and industrial production of such equipment.

The application environment of technologies such as deep-water detection, underwater operation, and repair of water conservancy projects differs substantially from the marine environment. The underwater detection, repair, and reinforcement techniques that are applicable to the marine environment cannot simply be transplanted and applied to newly introduced technologies. It is therefore necessary to

Table 2.2.3 Countries with the greatest output of patents on "intelligent construction technology and equipment for underground projects under extreme conditions"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	252	91.97%	408	70.59%	1.62
2	USA	15	5.47%	170	29.41%	11.33
3	Canada	2	0.73%	11	1.90%	5.50
4	Brazil	1	0.36%	0	0.00%	0.00
5	Japan	1	0.36%	0	0.00%	0.00
6	South Korea	1	0.36%	0	0.00%	0.00
7	Saudi Arabia	1	0.36%	0	0.00%	0.00

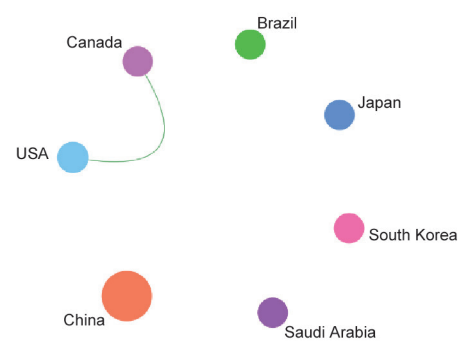

Figure 2.2.1 Collaboration network among countries in the engineering development front of "intelligent construction technology and equipment for underground projects under extreme conditions"

Table 2.2.4 Institutions with the greatest output of patents on "intelligent construction technology and equipment for underground projects under extreme conditions"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China Railway Group Limited	China	19	6.93%	16	2.77%	0.84
2	China University of Mining and Technology-Beijing	China	9	3.28%	12	2.08%	1.33
3	China Communications Construction Company Limited	China	7	2.55%	7	1.21%	1.00
4	State Grid Corporation of China	China	6	2.19%	6	1.04%	1.00
5	Shandong University	China	5	1.82%	12	2.08%	2.40
6	China University of Mining and Technology-Xuzhou	China	5	1.82%	10	1.73%	2.00
7	Southeast University	China	4	1.46%	16	2.77%	4.00
8	China Coal Technology & Engineering Group Corp	China	4	1.46%	5	0.87%	1.25
9	Chang'an University	China	4	1.46%	3	0.52%	0.75
10	Tongji University	China	3	1.09%	12	2.08%	4.00

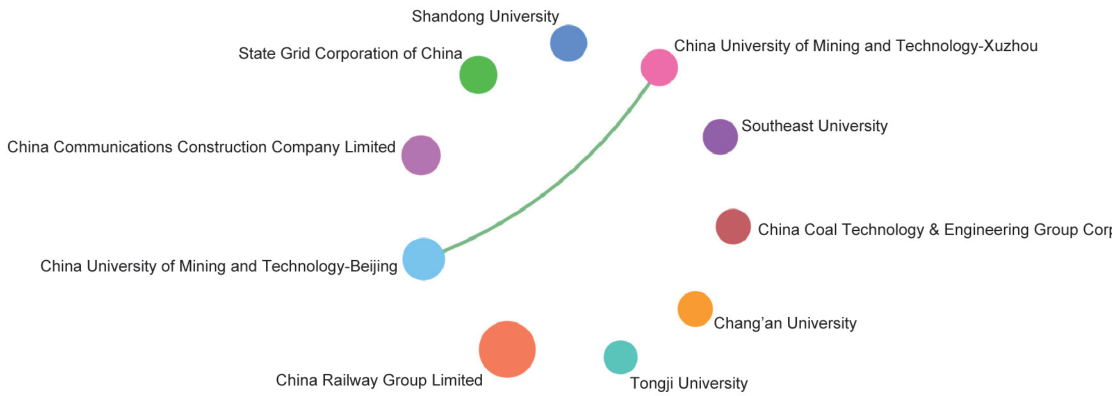

Figure 2.2.2 Collaboration network among institutions in the engineering development front of "intelligent construction technology and equipment for underground projects under extreme conditions"

produce renovations, improvements, and innovations in R&D according to the special water environments and boundary conditions of reservoir dams.

As one of the main tools for the exploration of the deep sea environment, remote-operated vehicles (ROVs) have played an important role in the exploitation of marine resources and scientific exploration of the deep sea and have long been a research focus of numerous countries. In recent years, ROVs have been used for search, dam detection, and safety inspections in reservoirs. Due to the special nature of the reservoir environment, the main application of ROVs to the water conservancy industry is observation class ROVs.

Abnormal leakages are a common issue in the operation of water conservancy projects. The existing underwater leakage detection and positioning technologies are mostly being applied experimentally in water conservancy projects. These technologies are applied in a limited manner with low accuracy, and at present they are the primary technical hurdle in the research on detection technologies for water conservancy projects.

Artificial diving operations are an irreplaceable means of underwater repair and reinforcement. The maximum depth of conventional air-diving operations is only 60 m, which does not meet the depth requirements of underwater operations for water conservancy projects. Although the most advanced conventional artificial diving can realize underwater detection and operation at depths of 100 m in deep-water environments, the artificial operation is inefficient, costly, and risky. Conventional artificial diving operations at depths exceeding 120 m remain impractical in terms of efficiency and cost, so saturated diving technologies have been adopted. To date, experiments have only been conducted at one high dam in Switzerland, and breakthroughs in adaptive equipment technology are urgently needed. It has become a priority to use ROVs, manned submersible vehicles, and other deep-water working platforms to develop unmanned operation technologies that can meet the needs of various underwater projects or to develop specialized saturated diving technologies that are suitable for the particular water environment of water conservancy projects with higher diving work efficiency, lower costs, and lower safety risks.

In environments with deep water, high head, and high flow velocity, work operations are difficult with low efficiency and high costs; moreover the applicability of underwater grouting and repair materials is poor, the process is complex, and it is difficult to guarantee the quality, inevitably affecting the repair efficacy. The research and development of new underwater repair materials and construction techniques that are convenient for underwater operations, reliable in quality, and rational in economy according to the special conditions and applications of the deep-water environment are therefore the main frontier areas that should be urgently developed. The problem of silting in front of deep-water dams resulting from the long-term operation of water conservancy projects or sudden disasters introduces great difficulties to the detection, care, and maintenance of underwater structures as well as the repair, opening, and closing of sluice gates. The existing desilting and dredging equipment and technologies domestically and abroad are mainly applicable to the clearing of sediment or small-particle aggregates in wide water areas at relatively shallow depths. It is difficult to effectively use them in narrow work environments, such as gates upstream of dams and flow channels with complex silt sediments. It is thus necessary to develop multi-functional desilting equipment and technologies suitable for water depths of over 100 m that can operate in narrow spaces and clean up complex siltation in layers (sedimentation) so as to ensure the long-term safe operation of water conservancy projects.

As listed in Table 2.1.1, 90 patents related to this topic were published between 2014 and 2019. The five countries that published the most patents were China, the United States, Brazil, the United Kingdom, and Norway (Table 2.2.5). Among these countries, China was at the forefront of development, contributing 90% of the patents. The average citations per patent of the Chinese patents was 2.21, demonstrating that Chinese patents are receiving increasing attention.

The five organizations that produced the most patents were the Power Construction Corporation of China, China National Offshore Oil Corporation, Shanghai Qere Ecological Technology Co., Ltd. (China), Zhejiang Institute of Hydraulics and Estuary (China), and Shandong University (China) (Table 2.2.6). Among the above organizations, the Power Construction Corporation of China is the only comprehensive construction corporation in China that provides water conservancy and electric power engineering and infrastructure planning, surveying and design, consulting and supervision, construction management, and investment and operation, and it has adopted “deep-water exploration and treatment technology for hidden hazards in water conservancy projects” as its core technology. China National Offshore Oil Corporation has applied deep-water exploration and operation technology to the field of marine engineering on a large scale.

Table 2.2.5 Countries with the greatest output of patents on “deep-water detection of latent defects and treatment technologies for water conservancy projects”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	81	90.00%	179	98.90%	2.21
2	USA	2	2.22%	0	0.00%	0.00
3	Brazil	2	2.22%	0	0.00%	0.00
4	UK	1	1.11%	1	0.55%	1.00
5	Norway	1	1.11%	1	0.55%	1.00
6	Japan	1	1.11%	0	0.00%	0.00
7	Mexico	1	1.11%	0	0.00%	0.00

Table 2.2.6 Institutions with the greatest output of patents on “deep-water detection of latent defects and treatment technologies for water conservancy projects”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Power Construction Corporation of China	China	4	4.44%	6	3.31%	1.50
2	China National Offshore Oil Corporation	China	3	3.33%	3	1.66%	1.00
3	Shanghai Qere Ecological Technology Co., Ltd.	China	2	2.22%	8	4.42%	4.00
4	Zhejiang Institute of Hydraulics and Estuary	China	2	2.22%	6	3.31%	3.00
5	Shandong University	China	2	2.22%	3	1.66%	1.50
6	China Communications Construction Company Limited	China	2	2.22%	1	0.55%	0.50
7	Shanghai Ocean University	China	2	2.22%	0	0.00%	0.00
8	Hohai University	China	2	2.22%	0	0.00%	0.00
9	Maoming Jinyang Tropical Pearl Boat Breeding Co., Ltd.	China	1	1.11%	14	7.73%	14.00
10	Guangdong Meixian Meiyan Mining Co., Ltd.	China	1	1.11%	12	6.63%	12.00

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