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 related to the field of civil, hydraulic, and architectural engineering are summarized in Table 1.1.1. These fronts cover a variety of disciplines, including structural engineering, architectural design and theory, construction materials, urban planning, bridge engineering, underground space and tunneling, hydraulic structural engineering, photogrammetry and aerospace survey, hydrology and water resource, transportation planning, etc. Among these research fronts, "seismic analysis and safety evaluation of high dams under extreme earthquakes" was recommended by experts, and the other fronts were identified based on the top 10% of highly cited papers using the co-citation clustering method and confirmation by experts. Table 1.1.2 presents the annual statistical data on the core papers published between 2013 and 2018 relevant to the top ten research fronts.

(1) Mechanism and control of long-term performance evolution of structures

This research front refers to revelation of internal physical and chemical degradation mechanisms and realization of effective control of structural performance degradation. Under long-term environmental and mechanical loads, structural properties are degraded, and the degradation rate is controlled by the inherent physical and chemical degradation mechanisms. By grasping the above-mentioned internal mechanisms that cause structural performance degradation, targeted blocking techniques could be adopted to achieve effective control of the long-term performance of structures. Major issues concerning this research front include: 1) revelation of the physical and chemical mechanisms of structural performance evolution under long-term environmental and mechanical loads, and 2) structural performance degradation control technology based on fiber-reinforced materials and other special materials. Clearly revealing and grasping the inherent physical and chemical mechanisms of structural performance evolution contribute to the adoption of economically reasonable performance degradation control technologies. At present, detection

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	Mechanism and control of long-term performance evolution of structures	72	1707	23.71	2015.9
2	Green building design method based on the whole life cycle	184	7442	40.45	2015.6
3	Nano-modification and fiber-reinforcement of cement-based materials	75	2137	28.49	2015.6
4	Urban design and planning for reducing urban heat island effect	154	6033	39.18	2015.7
5	Large-span bridge operational smart monitoring and inspection	102	2530	24.80	2014.7
6	Lifecycle deformation prediction and control for urban and undersea tunnels	113	2895	25.62	2016.7
7	Seismic analysis and safety evaluation of high dams under extreme earthquakes	14	274	19.57	2015.6
8	Spatial-temporal fusion of multi-source satellite remote sensing images based on deep learning	40	1989	49.73	2015.4
9	Refined prediction and rapid damage assessment of river basin floods	36	1571	43.64	2016.2
10	Traffic flow modeling theory and methods for the ICV and HDV mixed traffic	186	5524	29.70	2015.7

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

No.	Engineering research front	2013	2014	2015	2016	2017	2018
1	Mechanism and control of long-term performance evolution of structures	7	11	11	11	16	16
2	Green building design method based on the whole life cycle	19	36	38	27	38	26
3	Nano-modification and fiber-reinforcement of cement-based materials	9	15	11	11	19	10
4	Urban design and planning for reducing urban heat island effect	20	23	20	35	30	26
5	Large-span bridge operational smart monitoring and inspection	32	21	17	14	10	8
6	Lifecycle deformation prediction and control for urban and undersea tunnels	7	8	13	11	16	58
7	Seismic analysis and safety evaluation of high dams under extreme earthquakes	2	3	2	2	2	3
8	Spatial-temporal fusion of multi-source satellite remote sensing images based on deep learning	6	8	7	7	6	6
9	Refined prediction and rapid damage assessment of river basin floods	3	2	8	4	9	10
10	Traffic flow modeling theory and methods for the ICV and HDV mixed traffic	19	24	40	37	37	29

and monitoring data based on the physical and chemical properties of engineering materials are used to establish prediction models for the long-term performance of structures. On this basis, structural performance improvements using fiber-reinforced polymer (FRP) and fiber-reinforced cement matrix composite (FRCM) are the research hotspots. Meanwhile, there are also some structural performance control technologies using shape memory alloy (SMA), self-healing concrete, asphalt, and new generation structural steel. Between 2013 and 2018, 72 core papers were published relevant to this research front, and these papers received 1707 citations, averaging 23.71 citations per paper.

(2) Green building design method based on the whole life cycle

The green building design method based on the whole life cycle carries out green design of buildings starting from the production, transportation, and use of the building materials and equipment, through the whole life cycle dimension of building design, construction, operation, and demolition. It aims to realize savings of energy, land, water, and material resources and to provide people with healthful, applicable, and efficient use of space. It is a design theory and method for maximizing the harmonious interaction of human and nature. The main research directions include: 1) the overall method for optimization of building space and performance combined with regional context, 2) the development and utilization of renewable and recyclable regional materials, 3) the development of a basic energy and carbon emission database for building materials and equipment over the life of a building, and 4) the development of related performance design optimization simulation software tools, etc. The trends of future development include: 1) a multi-disciplinary and whole process group collaborative design methods from single buildings to urban scale under the premise of smart, healthy, and people-oriented green building; 2) AI assisted optimization design; 3) performance-oriented digital design; 4) healthful and/or smart building design; 5) active and passive integrated devices and design; and 6) development and application of new materials. Between 2013 and 2018, 184 core papers were published relevant to this research front, and these papers received 7442 citations, averaging 40.45 citations per paper.

(3) Nano-modification and fiber-reinforcement of cement-based materials

Nano-modification and fiber-reinforcement of cement-based materials refers to the regulation of hydration and hardening properties, mechanical properties, and durability of cement-based materials by incorporating nanomaterials and fibers. At present, the research on fiber cement-based composite materials, includes single-fiber cement-based composite and hybrid fiber cement-based composite. Commonly used fibers can be divided into man-made fibers and natural plant fibers. Among them, man-made fibers mainly include such as steel fibers, glass fibers, and polypropylene fibers; whereas, natural plant fibers include such as cotton and hemp. Compared with ordinary cement-based materials, fiber cement-based composites have high tensile strength, extreme toughness, and high crack-resistance. They have good impermeability, frost resistance, and corrosion resistance, and better meet the functions of cement-based materials that the modern construction industry demands. At the same time, the application of natural plant fibers has improved the environmental value of cement-based materials and is more in line with the basic concept of sustainable development. With the rapid development of nanotechnology, nano-modification of cement-based materials has also received extensive attention. Nanomaterials with a particle size of less than 100 nm are usually used in the modification of cement-based materials, and can be classified into nano-mineral powder, nano-metal powder, and nano-oxide according to the material composition. The research on nano-modification of cement-based materials is mainly focused on the preparation of nano-modified cement-based materials, nano-modification mechanisms, and the properties of modified cement-based materials. Between 2013 and 2018, 75 core papers were published relevant to this research front, and these papers received 2137 citations, averaging 28.49 citations per paper.

(4) Urban design and planning for reducing urban heat island effect

Cities occupy 2% of the Earth's surface while their inhabitants consume almost 75% of the global energy. As a result of solar radiation and urban activities, the surface- or canopy-layer temperature in the urban areas of a city is significantly warmer than that of its surrounding areas. This effect is known as urban heat island (UHI). The UHI effect is heavily correlated to underlying surfaces, atmospheric pollution, and anthropogenic activities and it intensifies the impacts of increasing heatwaves and other extreme weather events in cities as a result of climate change. UHI affects human health by causing general discomfort, respiratory difficulties, heat cramps and exhaustion, non-fatal heat stroke, and heat-related mortality. Therefore, it is crucial and urgent to collectively act on mitigating and reducing the UHI effect to make cities sustainable. For this purpose, the design and planning strategies should cover the major factors correlated to the UHI effect, such as buildings, transportation, and greenspaces in the cities. Major research trends relevant to this topic include: 1) advance energy prediction and diagnostic models for buildings and building clusters, 2) measuring and monitoring UHI using advanced remote sensing technologies with high resolution, 3) urban greenspace patterns of spatial urban cool island effect, and 4) comprehensive strategies to mitigate UHI for large- and mega-cities. Between 2013 and 2018, 154 core papers were published relevant to this research front, and these papers received 6033 citations, averaging 39.18 citations per paper.

(5) Large-span bridge operational smart monitoring and inspection

In the process of bridge operation, local plasticity, damage, fatigue, instability, and cracking occur when the bridge interacts with the loads imposed by pedestrians, traffic flow, wind, ground motion, waves, and other operating loads. Smart operation monitoring and inspection of bridges is done to monitor the response and condition of their structures. It is done by means of smart sensing for the purpose of analysis and prediction of further deterioration behavior and operation life of the structure to provide safe and sustainable operation. The main research directions include: 1) the principles and technology of bridge smart sensing, 2) the methods for identification of the physical condition of a structure, 3) disaster early warning analysis of bridge degradation characteristics, and 4) the prediction of bridge residual life. Piezoelectric impedance, Global Position System (GPS), Satellite Aperture Radar (SAR) interferometry, acoustic emission, close-range photography, and other smart sensing methods are mainly used to monitor structural responses to strain, acceleration, displacement, as well as the overall structural physical state in the course of bridge operation. For identification of structural damage, signal processing methods such as Wavelet Transform (WT), Hilbert-Huang Transform (HHT), Kalman Filtering (KF), Least Squares (LS) are mainly used. The methods of smart reasoning such as neural networks, fuzzy reasoning, genetic algorithms, and deep learning are used to identify and evaluate the location and extent of structural damage. Disaster early warning analysis of bridge retrogression characteristics mainly involves study of the main characteristics and disaster early warning methods of non-linear and unsteady retrogression behavior of bridges under different loads. Residual life prediction mainly studies local damage propagation of damaged structures and predicts bridge failure modes and residual life. The main trend in the development of this research is a shift from the monitoring and identification of stationary, steady, and linear damage states to the monitoring and analysis of progressive, unsteady, and non-linear degradation processes. The latter provide more effective monitoring, control, and management of bridge operation. Between 2013 and 2018, 102 core papers were published relevant to this research front, and these papers received 2530 citations, averaging 24.80 citations per paper.

(6) Lifecycle deformation prediction and control for urban and undersea tunnels

Urban and undersea tunnels are key parts of modern infrastructure. With more and more urban and undersea tunnels being constructed and put into operation, the lifecycle deformation prediction and control of these tunnels has drawn growing attention. The interest in the topic of lifecycle deformation prediction and control has risen with concerns about lifecycle serviceability, safety, and durability of urban and undersea tunnels. The main research areas include: 1) long-term ground deformation under cyclic loading, 2) mechanical performance degradation rules of tunnel structure and material, 3) data mining and data analysis of lifecycle monitored structure deformation, 4) structural health evaluation and serviceability assessment, and 5) fast inspection and intelligent control technologies for structural deformation. Compared with traditional tunnel structures, urban and undersea tunnels are characterized by more sensitive surrounding environments and stricter operation restrictions. To ensure the serviceability and long-term safety of such tunnel structures, it is necessary to develop fast inspection technologies to monitor structural deformation and disorders, and to obtain real-time service conditions of tunnel structures. It is also necessary to develop methodologies by combining theoretical analysis, structural tests, and long-term monitoring for analyzing tunnel health conditions and serviceabililty. This must consider interactions between a structure and all related environmental factors and serve to establish an intelligent prediction and control framework for lifecycle deformation. Among these research topics, the fast inspection technologies and intelligent analysis of the big data obtained will be important directions in the near future. Between 2013 and 2018, 113 core papers were published relevant to this research front, and these papers received 2895 citations, averaging 25.62 citations per paper.

(7) Seismic analysis and safety evaluation of high dams under extreme earthquakes

High dams are essential infrastructure for controlling river runoff and realizing the comprehensive utilization of water resources and hydropower. Their failure may cause catastrophic disasters due to uncontrolled release of reservoir water. Therefore, the safety of high dams under extreme earthquakes has attracted wide attention. To evaluate the seismic safety of high dams subject to strong earthquakes reasonably, four factors should be considered: ground motion parameters at dam sites, dynamic behavior of dam materials and foundation, seismic response of the dam-foundation-reservoir system, and safety evaluation criteria. The state-of-the-art trends for seismic analysis and safety evaluation of high dams can be summarized as follows: 1) seismic risk analysis developing from probability methods to parallel with direct numerical simulation methods, 2) seismic response analysis of high dams developing from linear elastic methods to non-linear large deformation procedures, 3) dynamic failure simulation of dam and foundation materials developing from macro-scale to meso-scale mechanical methods, and 4) safety evaluation of high dams developing from traditional safety factors to risk-based decision-making methods. Following the above-mentioned trends in development, there are still many key issues that should be solved in the future, such as 1) numerical simulation of the entire process of faulting, seismic wave propagation, and high dam response, 2) macro-scale and micro-scale dynamic failure mechanisms of dam and foundation materials, 3) ultimate seismic capacity of dam-foundation systems, 4) deformation stability of high embankment dams at risk from strong earthquakes, 5) disaster chains involving cascade high dams, 6) risk assessment considering economic investment, project design, and disaster losses, and 7) real time health monitoring of high dams, along with rapid assessment of earthquake damage and disaster relief. Between 2013 and 2018, 14 core papers were published relevant to this research front, and these papers received 274 citations, averaging 19.57 citations per paper.

(8) Spatial-temporal fusion of multi-source satellite remote sensing images based on deep learning

High-resolution spatial-temporal remote sensing images can provide rapid and accurate information on land use change, and it has a variety of applications to land use change detection, disaster mitigation, and decision-making, among others. However, due to limitations of sensor hardware, it is difficult to acquire remote sensing images directly with high temporal and spatial resolution. Spatial-temporal fusion technology can spatially and temporally fuse remote sensing image data from different sensors, scales, and phases without changing the existing observation conditions. Moreover, they produce simultaneous data interpretation with high spatial and temporal resolution, thus alleviating the “spatiotemporal contradiction” of remote sensing data. In recent years, deep network training technology has provided theoretical support for the establishment of high-low resolution image mapping relationships and multi-sensor remote sensing image data has provided a complete data base for the network learning process. The main research directions of this research front include: 1) construction of spatial-temporal integration frameworks for deep learning, including spatiotemporal convolution neural networks, countermeasure generation neural networks, deep residual learning networks, and deep dense connection networks; and 2) construction of space-time loss function of visual perception, including elastic network loss function, space-time joint-structure-similar loss function, and space-time-information residual loss function. The main development trends are as follows: 1) toward a framework of deep learning spatial-temporal fusion coupled with remote sensing physical processes, 2) the technology of deep learning spatial-temporal fusion considering large-scale scene changes, and 3) the theory and methods of spatial-temporal-spectrum integration fusion based on deep learning. Between 2013 and 2018, 40 core papers were published relevant to this research front, and these papers received 1989 citations, averaging 49.73 citations per paper.

(9) Refined prediction and rapid damage assessment of river basin floods

The refined prediction and rapid damage assessment of river basin floods is done to accurately and rapidly simulate the flood propagation process, flood damage, and flood impacts, so as to provide decision-support for flood risk management and emergency response. It is achieved by applying meteorological models, hydrological models, hydrodynamic models, flood damage assessment models, and remote sensing techniques, based on high-resolution data from meteorology, landforms, topography, structure, engineering, and socioeconomics. With the development of advanced computer technology, numerical analyses, information technology, and in-depth study of flood disaster mechanisms in recent years, it has become possible to make refined predictions and to do rapid damage assessment of river basin floods. The current development trends include: 1) high-resolution meteorological numerical prediction based on multi-source data fusion, 2) hydrological forecasting models based on physical mechanisms, 3) hydrodynamic simulation models for whole watersheds, 4) integrated basin flood simulation coupled with meteorological simulation, hydrologic, and hydrodynamic models, 5) flood damage assessment models for all types of assets, 6) artificial intelligence forecasting methods and models, and 7) desktop maneuver systems for river basin flood emergency management. Frontier key scientific and technical issues include: 1) high-resolution rainstorm prediction, 2) GPU high-performance accelerated simulation techniques for unstructured grids, 3) model parameter extraction and rapid flood damage assessment methods based on remote sensing data, 4) real-time correction technology of hydrodynamic models, 5) surface-groundwater exchange mechanisms, 6) dam-break mechanism and development-process simulation, 7) assessment of vulnerability of people and assets, damage relationships between all factors of floods (water depth, flow velocity, duration, and carrying away things and destroying assets), indirect flood damage and impact, and 8) applications of artificial intelligence technology. Between 2013 and 2018, 36 core papers were published relevant to this research front, and these papers received 1571 citations, averaging 43.64 citations per paper.

(10) Traffic flow modeling theory and methods for the ICV and HDV mixed traffic

The development of Intelligent and Connected Vehicles (ICVs) is a trend of future traffic, and the gradual deployment of ICVs in traffic will result in a transition period, in which vehicles with various levels of automation/connection and Human Driven Vehicles (HDVs) co-exist. Due to significant differences between ICVs and HDVs in terms of information acquisition, perception, response time, and interaction, and differences at the automation and connection levels among ICVs, traffic flow will manifest some new characteristics. Current research is focused on developing new traffic flow models for heterogeneous traffic and exploring the implications of mixed traffic on traffic flow and safety. The main research fields include:

1) Modeling heterogeneous driving behavior considering human factors. Proper understanding of how human drivers will respond to ICVs, and how ICVs could interact with HDVs is urgent but lacking. This lack of understanding may result in unsafe and inefficient traffic situations. Therefore,

it is necessary to explore the effects of human factors on heterogeneous driving behavior.

2) Driving behavior modeling incorporating information. “Information” is the core element for ICVs. Different types of information (e.g., descriptive information, advisory information, executive information), information content, information release forms, and information collaboration level of the drivers (e.g., willingness to cooperate, degree of collaboration) will have different effects on driving behavior. Hence, the impact of information must be incorporated into the new traffic flow model.

3) Advanced interactive driving simulator-based experiments to study the interactions between ICVs and HDVs. It is difficult to obtain sufficient empirical data on interactions between ICVs and HDVs in the real world, and limited testing data from testing fields cannot cover all interactive scenarios. Therefore, it is necessary to develop a dedicated traffic flow simulation platform, and design massive scenarios for experiments, in order to obtain sufficient operational data about the interactions between ICVs and HDVs for subsequent traffic flow research. Between 2013 and 2018, 186 core papers were published relevant to this research front, and these papers received 5524 citations, averaging 29.70 citations per paper.

1.2 Interpretations for three key engineering research fronts

1.2.1 Mechanism and control of long-term performance evolution of structures

Civil engineering structures inevitably suffer from long-term performance degradation due to the environmental and mechanical loads to which they are exposed while in service. In order to project its performance over a structure’s life cycle, it is necessary to study the internal damage evolution mechanisms of the structure. Developing long-term performance-evolution principles for concrete, steel, and masonry structures are now the focus of many scholars.

Certain structures tend to degrade prematurely owing to insufficient knowledge concerning the evolution of their structural performance. At present, from the perspective of physics and chemistry, research is being conducted on the inherent degradation mechanisms of engineering materials (e.g., carbon steel bar, concrete, steel) exposed to various loads and environments. This information will be used to provide predictive models for the long-term performance evolution of structures considering key parameters. Moreover, performance repair technologies for seriously damaged structures are being studied, thereby improving the lifetime reliability of structures and achieving the goal of effective control of structural performance.

Currently, major research topics concerning the mechanism and control of long-term performance evolution of structures include:

Establishing evaluation and prediction models for the long-term performance of structures based on long-term performance degradation data about engineering materials. The relevant research includes chloride ion penetration rate models, on-line monitoring of steel corrosion damage, optimization checks based on reliability assessments, and maintenance options.

The improvement and control of structural performance using fiber-reinforced polymer composites (FRP) and fiber-reinforced cement matrix composites (FRCM). For FRP materials, the relevant studies include external bonding technology, near-surface mounting (NSM) technology, and internal reinforcing technology. For FRCM materials, a recent research hotspot involves the strengthening technologies that use FRCMs to provide better bending, shear, and shock resistance of concrete and masonry structures.

Research on control of structural performance based on new technologies such as shape memory alloy (SMA), self-healing concrete, asphalt, and new-generation structural steel. These include, for example, improving concrete performance with nanomaterials, using shape memory alloy for strengthening steel and concrete structures, and the strengthening of structures using super-weathering steel technology.

As shown in Table 1.1.1, 72 core papers were published between 2013 and 2018 concerning “mechanism and control of long-term performance evolution of structures”, and each paper was cited an average of 23.71 times. The top five countries or regions in terms of core-paper output in this regard are Italy, the USA, Greece, China, and Switzerland (Table 1.2.1). China is one of the most active players on this topic, publishing 9.72% of core papers. The top five countries or regions receiving the highest average citations were Spain, the USA, Greece, Italy, and China. The papers published by China were each cited 22.00 times on average, which indicates that there is still room for further improvement from Chinese scholars on this front. As illustrated by the international collaborative network depicted in Figure 1.2.1, except for India, close cooperation was observed among the most productive top ten countries/regions, especially the USA and Italy.

As shown in Table 1.2.2, the top five institutions publishing the most core papers were the University of Padua (Italy), University of Patras (Greece), University of Bologna (Italy), Missouri University of Science & Technology (USA), and University of Miami (USA). As illustrated in Figure 1.2.2, collaborative studies were significant among the top ten most productive institutions in this regard.

As shown in Table 1.2.3, the top five most active countries or regions in terms of citing the most papers were Italy, China, the USA, the UK, and Australia. As presented in Table 1.2.4, the top five institutions citing the highest number of core papers were Lehigh University (USA), University of Bologna (Italy), Polytechnic University of Milan (Italy), University of Padua (Italy), and Missouri University of Science & Technology (USA). China ranked fourth in terms of the quantity of core papers produced and second for quantity of core papers being cited. This shows that Chinese researchers pay close attention to this research front.

Table 1.2.1 Countries or regions with the greatest output of core papers on “mechanism and control of long-term performance evolution of structures”

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Italy	29	40.28%	813	47.63%	28.03
2	USA	18	25.00%	560	32.81%	31.11
3	Greece	9	12.50%	257	15.06%	28.56
4	China	7	9.72%	154	9.02%	22.00
5	Switzerland	5	6.94%	102	5.98%	20.40
6	Canada	4	5.56%	75	4.39%	18.75
7	India	4	5.56%	23	1.35%	5.75
8	Spain	4	5.56%	146	8.55%	36.50
9	Australia	3	4.17%	45	2.64%	15.00
10	Iran	3	4.17%	52	3.05%	17.33

Table 1.2.2 Institutions with the greatest output of core papers on “mechanism and control of long-term performance evolution of structures”

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	University of Padua	9	12.50%	314	18.39%	34.89
2	University of Patras	8	11.11%	250	14.65%	31.25
3	University of Bologna	7	9.72%	175	10.25%	25.00
4	Missouri University of Science & Technology	7	9.72%	194	11.37%	27.71
5	University of Miami	6	8.33%	153	8.96%	25.50
6	Polytechnic University of Milan	5	6.94%	130	7.62%	26.00
7	Qatar University	3	4.17%	28	1.64%	9.33
8	University of Nottingham	3	4.17%	50	2.93%	16.67
9	Roma Tre University	3	4.17%	133	7.79%	44.33
10	University of Naples Federico II	3	4.17%	75	4.39%	25.00

Figure 1.2.1 Collaboration network among major countries or regions in the engineering research front of “mechanism and control of long-term performance evolution of structures”

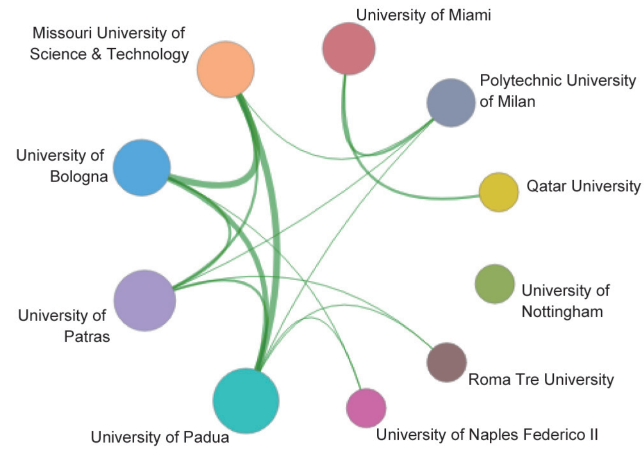

Figure 1.2.2 Collaboration network among institutions in the engineering research front of “mechanism and control of long-term performance evolution of structures”

Table 1.2.3 Countries or regions with the greatest output of citing papers on “mechanism and control of long-term performance evolution of structures”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	Italy	256	24.50%	2017.2
2	China	238	22.78%	2017.8
3	USA	181	17.32%	2017.1
4	UK	62	5.93%	2017.3
5	Australia	56	5.36%	2017.9
6	Iran	46	4.40%	2017.6
7	Poland	45	4.31%	2017.2
8	Portugal	42	4.02%	2017.5
9	Spain	41	3.92%	2017.1
10	Greece	39	3.73%	2017.3

Table 1.2.4 Institutions with the greatest output of citing papers on “mechanism and control of long-term performance evolution of structures”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Lehigh University	48	14.50%	2016.9
2	University of Bologna	40	12.08%	2017.2
3	Polytechnic University of Milan	33	9.97%	2016.8
4	University of Padua	31	9.37%	2016.7
5	Missouri University of Science & Technology	29	8.76%	2017.5
6	Roma Tre University	26	7.86%	2016.5
7	Universidade do Minho	26	7.86%	2017.1
8	University of Patras	26	7.86%	2017.1
9	University of Naples Federico II	26	7.86%	2017.5
10	University of Calabria	23	6.95%	2017.0

1.2.2 Green building design method based on the whole life cycle

In recent years, due to social and economic development, advances in science and technology, and people's pursuit of higher quality of life, the demand for green buildings has shifted from "increasing quantity" to "quality-oriented" in the sense of "people-oriented". This directly promotes the connotations of green building from the original "resource conservation" to "safe and durable", "healthy and comfortable", "convenient", and "environment livable". Therefore, in the future, it is necessary to study how to integrate safety, health, comfort, convenience, livability, and perceptibility into all stages of green building and to evaluate overall, the life cycle of structures. The development of information, energy and new technologies for materials has produced the potential for breakthroughs in key technologies in this field. The trend of future development includes: (1) a new multi-disciplinary and whole-process group-collaborative-design method from single building to urban scale under the premise of smart, healthful, and people-oriented green building, (2) AI assisted design optimization, (3) performance-oriented digital design, (4) healthful/smart building design, (5) active and passive integrated devices end design, and (6) development and application of new materials.

The institutions pursuing active research in this field within China are Tsinghua University, Xi'an University of Architecture and Technology, Chongqing University, Zhejiang University, and the China Academy of Building Research. The most active research institutions outside China are the Lawrence Berkeley National Laboratory (USA), University of Melbourne (Australia), National University of Singapore (Singapore), and the University of Perugia (Italy). In addition, there are many international architectural design software companies and architectural design companies active in this research field, such as Revit and Nikken Design. The relevant research output includes international journal articles, databases, software tools, and product patents.

As listed in Table 1.1.1, 184 core papers were published between 2013 and 2018 concerning "green building design method based on the whole life cycle", and each paper was cited 40.45 times on average. The top five countries in terms of core paper output were China, the USA, Australia, Italy, and the UK (Table 1.2.5). China was one of the most active players in this front, producing 22.83% of the core papers. The top five countries receiving the highest average citations were China, Spain, the USA, Australia, and Switzerland. In terms of core-paper citations, papers published by China were each cited 63.36 times on average, exceeding the global average number. This indicates that researchers from China are gradually gaining increasing attention. As illustrated by the international collaborative network depicted in Figure 1.2.3, relatively close cooperation was indicated between China and Australia.

As listed in Table 1.2.6, the top three institutions publishing the highest number of core papers were Hong Kong Polytechnic University (China), National University of Singapore (Singapore), Chongqing University (China), City University of Hong Kong (China), and the University of Melbourne (Australia). As illustrated in Figure 1.2.4, institutions in the same country or region cooperated, but crossover collaborations between different countries or regions were rare.

Table 1.2.5 Countries or regions with the greatest output of core papers on "green building design method based on the whole life cycle"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	China	42	22.83%	2661	35.76%	63.36
2	USA	27	14.67%	1331	17.89%	49.30
3	Australia	25	13.59%	1130	15.18%	45.20
4	Italy	15	8.15%	394	5.29%	26.27
5	UK	14	7.61%	398	5.35%	28.43
6	Singapore	10	5.43%	224	3.01%	22.40
7	Spain	9	4.89%	556	7.47%	61.78
8	Switzerland	9	4.89%	372	5.00%	41.33
9	Norway	9	4.89%	209	2.81%	23.22
10	Germany	8	4.35%	244	3.28%	30.50

Table 1.2.6 Institutions with the greatest output of core papers on "green building design method based on the whole life cycle"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Hong Kong Polytechnic University	18	9.78%	1021	13.72%	56.72
2	National University of Singapore	8	4.35%	205	2.75%	25.63
3	Chongqing University	7	3.80%	279	3.75%	39.86
4	City University of Hong Kong	5	2.72%	756	10.16%	151.20
5	University of Melbourne	5	2.72%	186	2.50%	37.20
6	Central Queensland University	5	2.72%	163	2.19%	32.60
7	University of Perugia	4	2.17%	255	3.43%	63.75
8	Norwegian University of Science and Technology	4	2.17%	134	1.80%	33.50
9	Yonsei University	4	2.17%	124	1.67%	31.00
10	Swiss Federal Institute of Technology Zurich	4	2.17%	94	1.26%	23.50

Figure 1.2.3 Collaboration network among major countries or regions in the engineering research front of "green building design method based on the whole life cycle"

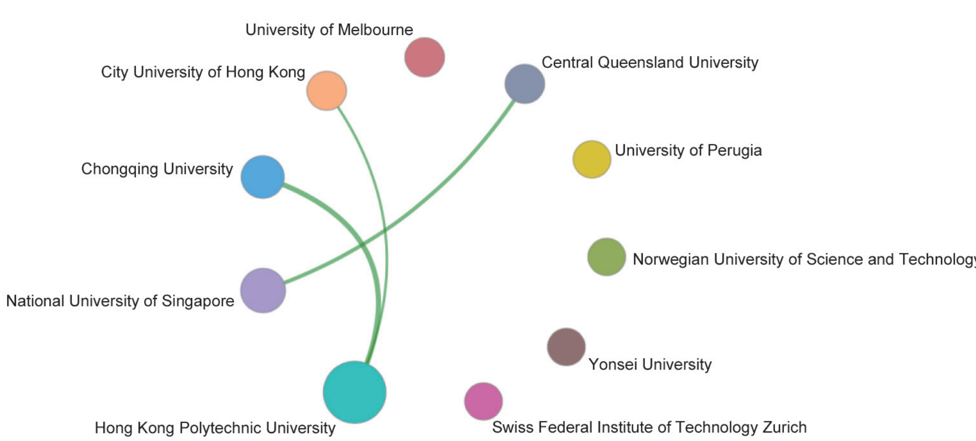

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "green building design method based on the whole life cycle"

As listed in Table 1.2.7, the top five countries/regions citing the most core papers were China, the USA, the UK, Australia, and Italy. As presented in Table 1.2.8, the top five institutions citing the most core papers were Hong Kong Polytechnic University (China), Tsinghua University (China), Chongqing University (China), Chinese Academy of Sciences (China), and National University of Singapore (Singapore). China ranked first in terms of both the number of published core papers and the number of core papers being cited, indicating that Chinese researchers pay close attention to this research front.

1.2.3 Nano-modification and fiber-reinforcement of cement-based materials

With continuous improvement of living standards and the advancement of urbanization, engineering structures have been developing in the directions of high quality, durability, environmental protection, and aesthetics, which require further improvement of the performance of building materials. The fiber-reinforcement of cement-based materials can prevent the development of cracks due to bridging by the fibers and thereby improve the crack resistance of cement-based materials. With the advancement of nanotechnology, nanomaterials have also become a cement modification material with excellent performance. The incorporation of nano-materials accelerates the hydration reaction process of cement-based materials, improves their compactness, and improves the strength and durability of the materials.

The main research directions of nano-modification and fiber-reinforcement of cement-based materials are:

(1) Preparation and performance control of hybrid fiber

Table 1.2.7 Countries or regions with the greatest output of citing papers on “green building design method based on the whole life cycle”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	1429	28.43%	2017.4
2	USA	766	15.24%	2017.0
3	UK	518	10.31%	2017.1
4	Australia	502	9.99%	2017.1
5	Italy	471	9.37%	2016.9
6	Spain	333	6.63%	2017.1
7	Germany	235	4.68%	2017.2
8	Canada	205	4.08%	2017.4
9	South Korea	201	4.00%	2017.1
10	France	195	3.88%	2016.8

Table 1.2.8 Institutions with the greatest output of citing papers on “green building design method based on the whole life cycle”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Hong Kong Polytechnic University	208	21.73%	2017.3
2	Tsinghua University	104	10.87%	2017.6
3	Chongqing University	94	9.82%	2017.5
4	Chinese Academy of Sciences	81	8.46%	2017.2
5	National University of Singapore	78	8.15%	2017.2
6	City University of Hong Kong	71	7.42%	2016.4
7	Tongji University	67	7.00%	2017.4
8	Yonsei University	66	6.90%	2016.4
9	Shenzhen University	66	6.90%	2017.3
10	University of Perugia	61	6.37%	2016.3

composite cement-based materials. The fiber composites of early cement-based materials were mainly single fiber composites. With deepening research, hybrid fiber composite cement-based materials have received more attention. Hybrid fiber composite refers to the reinforcement of cement-based materials using two or more fibers of different constitutions, different sizes, and different functions. Hybrid fiber composite technology improves the comprehensive performance of cement-based materials, and at the same time, effectively reduces the cost of composite materials, making fiber-composite cement-based materials have more practical value for engineering.

(2) High performance and multi-functionality of plant-fiber-composite cement-based materials. Plant fiber has the advantages of high specific strength, high specific modulus, low density, and attractive heat insulation, along with toughness and wear resistance. It is an ecologically friendly and low-cost renewable resource. At present, research on plant fiber composite cement-based materials mainly focuses on fiber surface-modification treatment and multi-level multi-scale cracking resistance. At the same time, research has gradually been carried out on the properties of flame retardance, sound absorption, heat insulation, and vibration damping of plant-fiber-composite cement composites.

(3) Preparation of nanomaterials and nano-modified cement-based materials. The common nanomaterials for cement-based materials modification include nano-$CaCO_3$, nano carbon-tubes, nano-TiO_2, graphene oxide, nano-kaolin, nano-clay. Dispersion of nanomaterials is one of the key issues in the nano-modification technology. Common dispersion methods include: functional grouping, surfactant encapsulation, polymer encapsulation, ultrasonic dispersion and mechanical agitation dispersion. Nano-modification technology can effectively improve the compressive strength, flexural strength and durability of cement-based materials, but it has an adverse effect on the rheological properties. Therefore, the relationship among nano-materials, water-reducing agents and water used in cement-based materials is also one of the focuses of current research.

(4) Microstructure and nano-modification mechanisms of nano-modified cement-based materials. Nanomaterials can promote the cement hydration reaction and improve the early strength of cement-based materials. In addition, the nucleation effect of nanoparticles improves the orientation of CSH gels, making hydration products more compact; at the same time, nanomaterials have a filling effect on micro pores, which further reduces the porosity of cement-based materials, resulting in an increase in material density. In particular, according to market demand, the modification of some nano materials can make the cement material exhibit other functions. Examples include such as carbon-nanotube modified cement-based materials with electrical conductivity and pressure sensitivity, and nano-TiO_2 modified cement-based materials with self-cleaning performance.

As listed in Table 1.1.1, 75 core papers were published between 2013 and 2018 concerning “nano-modification and fiber-reinforcement of cement-based materials”, and each paper was cited 28.49 times on average. The top five countries/regions for core paper output were Italy, the USA, China, Greece, and Spain (Table 1.2.9). As one of the leading research countries, China published 17.33% of the core papers on this research front. The top five countries receiving the highest average citations were Spain, Brazil, Australia, China, and the USA. The papers published by Chinese authors received 30.62 citations per paper on average, which is slightly above the overall average. From the perspective of cooperation networks between major countries or regions (Figure 1.2.5), close cooperation has been observed among the most productive top ten countries or regions, particularly between the USA and Italy.

Regarding the institutions producing the most core papers (Table 1.2.10), the top five on this front are University of Patras (Greece), University of Padua (Italy), Missouri University of Science & Technology (USA), University of Bologna (Italy), and University of Miami (USA). From the perspective of cooperation networks between the leading institutions on the research front (Figure 1.2.6), the institutions of the USA, Italy, and Greece are more closely cooperating.

The top five countries or regions citing core papers are China, Italy, the USA, Australia, and the UK (Table 1.2.11). The top five institutions citing the core papers are Missouri University of Science & Technology (USA), University of Bologna (Italy), National University of Singapore (Singapore), Polytechnic University of Milan (Italy), and the University of Padua (Italy) as shown in Table 1.2.12. China ranked third in terms of the number of published core papers and first in the citing of core papers, indicating that Chinese researchers pay close attention to research performed on this front.

Table 1.2.9 Countries or regions with the greatest output of core papers on "nano-modification and fiber-reinforcement of cement-based materials"

No.	Country/Region	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	Italy	24	32.00%	672	31.45%	28.00
2	USA	22	29.33%	639	29.90%	29.05
3	China	13	17.33%	398	18.62%	30.62
4	Greece	9	12.00%	257	12.03%	28.56
5	Spain	5	6.67%	194	9.08%	38.80
6	Australia	4	5.33%	133	6.22%	33.25
7	Brazil	3	4.00%	102	4.77%	34.00
8	Canada	3	4.00%	51	2.39%	17.00
9	UK	3	4.00%	50	2.34%	16.67
10	Qatar	3	4.00%	28	1.31%	9.33

Table 1.2.10 Institutions with the greatest output of core papers on "nano-modification and fiber-reinforcement of cement-based materials"

No.	Institution	Core papers	Percentage of core papers	Citations	Percentage of citations	Citations per paper
1	University of Patras	8	10.67%	250	11.70%	31.25
2	University of Padua	8	10.67%	302	14.13%	37.75
3	Missouri University of Science & Technology	8	10.67%	239	11.18%	29.88
4	University of Bologna	7	9.33%	175	8.19%	25.00
5	University of Miami	5	6.67%	120	5.62%	24.00
6	Polytechnic University of Milan	4	5.33%	95	4.45%	23.75
7	Roma Tre University	3	4.00%	133	6.22%	44.33
8	University of Hartford	3	4.00%	144	6.74%	48.00
9	University of Nottingham	3	4.00%	50	2.34%	16.67
10	Hong Kong University of Science & Technology	3	4.00%	44	2.06%	14.67

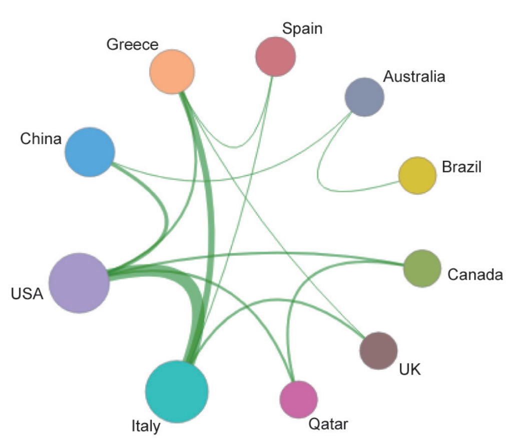

Figure 1.2.5 Collaboration network among major countries or regions in the engineering research front of "nano-modification and fiber-reinforcment of cement-based materials"

2 Engineering development fronts

2.1 Trends in top 10 engineering development fronts

The top ten 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, transportation planning, hydrology and water resources, municipal engineering, architectural design and theory, geotechnical and underground engineering, construction material, and photogrammetry and aerospace survey. Among these

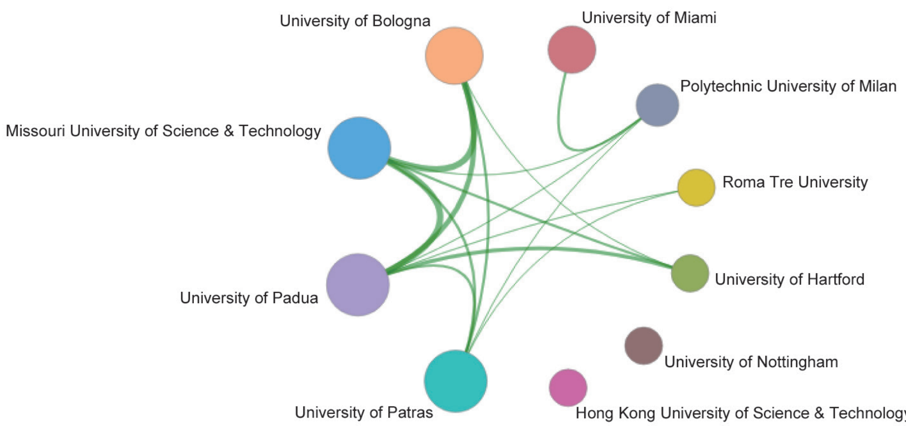

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of “nano-modification and fiber-reinforcment of cement-based materials”

Table 1.2.11 Countries or regions with the greatest output of citing papers on “nano-modification and fiber-reinforcment of cement-based materials”

No.	Country/Region	Citing papers	Percentage of citing papers	Mean year
1	China	459	33.73%	2017.5
2	Italy	227	16.68%	2017.2
3	USA	172	12.64%	2017.4
4	Australia	82	6.03%	2017.5
5	UK	71	5.22%	2017.6
6	Iran	64	4.70%	2017.8
7	India	63	4.63%	2017.8
8	Brazil	63	4.63%	2016.9
9	South Korea	55	4.04%	2017.7
10	Portugal	54	3.97%	2017.4

Table 1.2.12 Institutions with the greatest output of citing papers on “nano-modification and fiber-reinforcment of cement-based materials”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Missouri University of Science & Technology	43	12.72%	2017.5
2	University of Bologna	40	11.83%	2017.2
3	National University of Singapore	36	10.65%	2016.4
4	Polytechnic University of Milan	30	8.88%	2017.2
5	University of Padua	29	8.58%	2016.6
6	Southeast University	29	8.58%	2017.9
7	University of Minho	28	8.28%	2017.0
8	Beijing University of Technology	27	7.99%	2017.0
9	Roma Tre University	26	7.69%	2016.5
10	University of Patras	25	7.40%	2017.1

development fronts, "comprehensive transportation planning and intelligent safety management of urban agglomeration", "ecologically friendly settlements and ecological restoration technology", and "marine surveying equipment" were recommended by experts, and the others were identified from patent maps and then confirmed by experts. Table 2.1.2 presents annual statistical data on the patents published between 2013 and 2018 related to the top ten development fronts.

(1) Technology for reinforcement, repair, and retrofitting of existing structures

Structures are inevitably subjected to function replacement, load increase, damage accumulation, performance deterioration, and characteristic loss during their service lives. Retrofitting, rehabilitation, and renovation of existing structures are therefore of great importance to ensure structural safety, enhance building functions, and maintain cultural characteristics. Under long-term effects of service

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

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Technology for reinforcement, repair, and retrofitting of existing structures	2852	1819	0.64	2016.0
2	Comprehensive transportation planning and intelligent safety management of urban agglomeration	1087	1725	1.59	2016.0
3	Technology for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans, and groundwater	506	4463	8.82	2015.5
4	Sustainable technology for resource and energy recovery from wastewater	590	2933	4.97	2015.4
5	Ecologically friendly settlements and ecological restoration technology	3717	3250	0.87	2015.7
6	Standardized construction technology for prefabricated steel structures	1552	4195	2.70	2016.0
7	Techniques and intelligent equipment for efficient and safe excavation of super tunnels	70	167	2.39	2015.6
8	3D printing cement-based materials	104	682	6.56	2016.5
9	Incident response and rapid recovery during underground space construction	1853	2245	1.21	2015.8
10	Marine surveying equipment	606	2054	3.39	2015.6

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

No.	Engineering development front	2013	2014	2015	2016	2017	2018
1	Technology for reinforcement, repair, and retrofitting of existing structures	344	367	380	428	591	742
2	Comprehensive transportation planning and intelligent safety management of urban agglomeration	139	95	148	186	239	280
3	Technology for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans, and groundwater	53	82	126	107	105	33
4	Sustainable technology for resource and energy recovery from wastewater	68	120	150	111	71	70
5	Ecologically friendly settlements and ecological restoration technology	413	534	763	702	631	674
6	Standardized construction technology for prefabricated steel structures	85	158	238	329	399	305
7	Techniques and intelligent equipment for efficient and safe excavation of super tunnels	8	9	13	13	12	13
8	3D printing cement-based materials	2	11	13	14	33	31
9	Incident response and rapid recovery during underground space construction	209	237	349	315	351	392
10	Marine surveying equipment	81	121	94	111	93	106

loads and environmental attacks, accumulation of damage, deterioration of performance, and loss of characteristics may occur to existing structures. A transient load may result in a dramatic drop in the structural performance. Renovation of existing structures is sometimes required due to function replacement, and often older structures cannot meet the requirements of modern design standards reflecting more recent developments of the social economy and technology. Therefore, a large number of existing structures need retrofitting, rehabilitation, and renovation. Major issues concerning this development front include: 1) enhancement of durability and repair of damage at the material level, 2) improvement of load bearing capacity at the component level, and 3) seismic strengthening and structural renovation at the structural level. Enhancement of durability and repair of damage at the material level mainly refer to re-alkalization of carbonized concrete, extraction of chloride ions from concrete, protective repair of the envelope materials of historical buildings, and self-healing of cracked concrete. Improvement of load bearing capacity at the component level indicates strengthening of different components and joints subjected to various loads. Seismic reinforcement and structural renovation at the structural level are generally achieved by strengthening the overall performance of the structure, improving the seismic capacity of the structure, changing the structural system, or applying seismic isolation measures to mitigate the seismic action of the superstructure. Currently, upgrading the seismic performance of traditional buildings such as timber structures and masonry structures while maintaining specific characteristics has attracted intense attention. With the development of new materials, fiber-reinforced polymer, graphene, cement-based composites, and shape memory alloys are increasingly being applied. Between 2013 and 2018, 2852 patents related to this topic were published, of which 1819 patents were cited (an average of 0.64 citations per patent).

(2) Comprehensive transportation planning and intelligent safety management of urban agglomeration

The term urban agglomeration indicates urbanized areas of concentrated residency and industry. The emergence of urban agglomeration is an obvious reflection of the growth of urbanization, as well as of engines to boost the economy. Urban agglomerations contribute to a country's balanced development across regions and enable the country to take part in international economic exchange. Different from intra-city transportation that leans heavily on commuting trips, inter-city transportation within urban agglomerations generally crosses spatial jurisdictions and shows multivariate-overlap in terms of trip purposes and demands. The iterative interplay between three components—functional structure, mobility demand, and transportation network and service—is the main concern of comprehensive transportation planning and safety management for urban agglomeration. To underpin an efficient, safe, and cost-effective passenger and cargo transportation system for city clusters, we ought to systematically design comprehensive transportation facility systems, and develop intelligent operation policies, based on informative and quantitative measures. Currently, there are five research directions within transportation planning and safety management for urban agglomeration: 1) the analysis of the correlations between spatial structure and intensity of transportation connections, 2) the planning technology for transportation corridors connecting the cities, 3) the "one-stop" passenger and cargo logistic organization plans, 4) the transportation network resilience in response to disasters and repair technology, and 5) the comprehensive active transportation intelligent safety management systems. Between 2013 and 2018, 1087 patents on this topic were published with 1725 patent citations, an average of 1.59 citations per patent.

(3) Technology for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans, and groundwater

Since the beginning of the 21st century, many countries have paid increasing attention to the protection of aquatic ecosystems while strengthening legislation and have accelerated the pace of research and development of technology for aquatic ecological environment monitoring, evaluation, and restoration. The technologies for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans, and groundwater, in particular, are defined as some of the newest and developing technologies. With the rapid development of information technology and artificial intelligence technology, there has been the rapid emergence of technologies for such as automatic sample collection and automatic water quality monitoring systems that utilize unmanned underwater and aerial vehicles, and robots that can clean water surfaces and navigate automatically. The development of technologies for monitoring and early warning for river, lake, sea, and groundwater environments have driven applications of a variety of emerging technologies.

The integration of high-precision hydrological, water quality, and ecological modeling systems has enabled building of technical systems to provide the future monitoring and early warning technologies needed for aquatic environments. Moreover, these advances are also conducive to the simulation and projection of restoration effects. In terms of the trend in the use of restoration technology, developed countries have gradually shifted from pollution control to prevention-oriented strategies, focusing more on pollution reduction at source, protecting habitat, and restoring ecosystem functions. China is currently focusing on pollution control of surface and groundwater. Between 2013 and 2018, 506 patents on this topic were published with 4463 patent citations, an average of 8.82 citations per patent.

(4) Sustainable technology for resource and energy recovery from wastewater

Sustainable technology for resource and energy recovery from wastewater involves development of efficient technologies for recovering a variety of resources (e.g., nitrogen, phosphorus, metals) and energy (e.g., biohydrogen, methane, bioelectricity) during the process of standard wastewater treatment or deep purification. This also requires the development of novel processes and green technologies with low energy consumption and low discharge, as well as carbon neutral technologies with fully internal recycling of resources and energy. The key frontier technologies include: 1) technology for cascade resource recovery from sewage/sludge, which is being systematically developed for organic carbon recovery, nitrogen/phosphorus recovery, metal recovery, and recycled water production targeting specific characteristics of sewage and various resource elements and 2) resource/energy recycling within sewage treatment systems, for which updating processes or novel technologies are explored for deep reuse of biosynthesized carbon sources in sewage, including such as extracellular polymer substrates and polysaccharides, and resource recovery from excess sludge will be applied for such as thermal hydrolysis, plasma melting, anaerobic digestion, and electricity-heat cogeneration. 3) Other frontier technologies include energy self-sufficient sewage treatment driven by renewable energy, for which technologies based on green material/energy are developed, such as microalgal-photosynthesis systems for nitrogen/phosphorus nutrient recovery, bio-electrochemical systems for energy recovery (e.g., hydrogen, methane, bioelectricity), and advanced technology for treatment of refractory pollutants based on advanced photocatalytic materials. 4) Also involved is unconventional denitrification technology with low consumption of energy and chemicals, which promotes the development of anaerobic ammonia oxidation, whole ammonia oxidation, a partial sub-digestion process combined with anaerobic ammonia oxidation, sulfur autotrophic denitrification, etc., and the development of low-carbon wastewater treatment (carbon neutral technologies), like inverted A2O and multi-stage AO processes. 5) Finally, there is intelligent control, energy saving, and reduced consumption of wastewater treatment plants, for which precise control technology based on big data analysis (such as micro-bubble aeration, energy-saving pump control, etc.), and intelligent pipeline network monitoring systems are being developed to realize the optimal utilization of resources and energy. This also involves the operation management of low-carbon processes during sewage treatment. Between 2013 and 2018, 590 patents on this topic were published with 2933 patent citations, an average of 4.97 citations per patent.

(5) Ecologically friendly settlements and ecological restoration technology

With the continuous acceleration of urbanization, the need to conduct ecological restoration in intensively developed urban settlements is inevitable. A large number of existing communities have suffered declines in quality of life due to ecological damage. Under such circumstances, it is necessary to establish a technological system for complete ecological restoration by means of reusing and recycling the spatial elements, space, energy, and materials of the affected communities. Such a process should employ passive climate control technology and follow the principles of “ecology first, entirety first, and environment first”. Specific ecological restoration strategies include such as landscape integration, water circulation, surface infiltration, and site remodeling. The research on ecological settlements and ecological restoration technology includes: 1) the ecological damage and degradation status of high density neighborhoods and the application status of ecological restoration technology (involving the degree of ecological damage and degradation), the ecological restoration ability of urban settlements, etc., and 2) engineering problems and technical methods for ecological restoration in high-density neighborhoods, involving key technologies of environmental restoration in high-density neighborhoods and methods for ecological restoration based on climate response. This body of research aims to form an ecological settlement system, and to build human habitats that meet the standard of resource-saving and environmental-friendliness. Ecological restoration is an urgent, fundamental imperative in terms of ecological engineering, and a research field of great world-wide concern. The research provides systematic principles, technical methods and design strategies for environmental restoration of urban settlements, establishes design strategies for ecological restoration of high-density settlements based on climate-responsive methods, fills the gap in ecological evaluation and strategy systems in the regeneration of old towns, and improves the mechanism for innovation of ecology-friendly cities. Between 2013 and 2018, 3717 patents on this topic were published with 3250 patent citations, and an average of 0.87 citations per patent.

(6) Standardized construction technology for prefabricated steel structures

Prefabricated steel structures refer to steel buildings integrated with industrialized facades, furniture, facilities, and pipeline systems. Prefabricated steel structures also refer to infrastructure such as steel bridges and facilities that employ ancillary systems of prefabricated members and components. The concept of standardized construction for prefabricated steel structures is closely related to life-cycle sustainability, and it involves standardized design, industrialized production, assembled construction, integrated decoration, information-based management, and intelligent application. In this way, the overall performance and quality of the construction can be improved, and the construction efficiency can be significantly enhanced. In addition, the work required on-site can be greatly reduced, and energy saving and emission reduction can be further promoted. Focusing on the function of the construction object, the standardized construction technology for prefabricated steel structures incorporates the idea of system integration in various stages (i.e., planning, design, manufacturing, transport, construction, and maintenance), so as to realize whole-process synergy. In particular, the following aspects should be ensured. 1) Serialization and diversification of the products should be enhanced by conforming to the design principles of fewer specifications and more combinations according to the requirements of generalization, modularization, and standardization. 2) Construction efficiency should be enhanced by reducing on-site welding and concrete pouring, and also by developing weld-free bolted connections, prefabricated facades and floors, and prefabricated seismic mitigation technology. 3) It is also necessary to establish a well-developed production quality management system, and improve the accuracy of manufacturing. 4) Use various specialties for a construction assembly organization scheme, so as to improve labor efficiency. 5) Carry out integrated design of non-structural systems and other parts. 6) The Building Information Model (BIM) should be used to realize professional and whole-process information management. 7) Artificial intelligence and the Internet of Things technology should be used to realize safe, convenient, comfortable, and environment-friendly systems. With the in-depth development of construction industrialization, the trend in future development is to achieve technological innovation and improvement of construction quality through multidisciplinary research and development in fields that include construction, civil engineering, computers, mechanics, telecommunications, materials, and management. Between 2013 and 2018, 1552 relevant patents were published with 4195 patent citations, averaging 2.7 citations per patent.

(7) Techniques and intelligent equipment for efficient and safe excavation of super tunnels

A super tunnel generally refers to a tunnel project with very large engineering scale (more than 15 kilometers in length or 15 meters in maximum section size). The longest tunnel in the world is more than 50 kilometers in length and the largest tunnel section exceeds 20 meters in diameter. Super-tunnel engineering is mostly used to cross mountainous or water areas with a wide range and complex environments. The construction, operation, and maintenance processes involve great technical problems and challenges. The main technical directions include: 1) high-precision detection and dynamic feedback of deep geological hydrology information in ultra-complex environments, 2) load and structural dynamic design methods in ultra-large-scale tunnels, 3) new intelligent materials and structural forms for super long and ultra-deep buried tunnels, 4) new technology and equipment for tunnel construction under high stress, high ground temperature, and high water-pressure conditions, 5) safety early warning and intelligent construction equipment for ultra-long-distance tunnels in complex environments, 6) new technology and equipment for waterproof and water controlled ultra-deep tunnel construction, operation, and maintenance, 7) intelligent sensing, maintenance technology, and equipment for ultra-long tunnel safety and service performance,

8) operation security, intelligent disaster prevention, and rescue technology for ultra-long and ultra-deeply buried tunnels, and 9) dynamic risk management and monitoring of the entire process for construction of ultra-long and ultra-deep tunnels. Between 2013 and 2018, 70 patents on this topic were published, with 167 patent citations, an average of 2.39 citations per patent.

(8) 3D printing cement-based materials

The technology for 3D Printing has drawn increasing attention in the field of automated construction, and 3D printing cement-based materials have become hot topics of research in recent years. These 3D printing cement-based materials are cement-based materials that allow the 3D printing performance required for 3D printing construction technology. Presently, major research trends relevant to this front include printable performance control, interlayer adhesion performance enhancement, and high-strength high-toughness materials. Printing performance control and mechanism research is crucial to establish design theories and to realize the printing and application of 3D printing cement-based materials. Enhancement of interlayer adhesion performance and knowledge of its mechanism are keys to the safety of 3D printed components and buildings. Development of high-strength and high-toughness cement-based materials for 3D printing is an effective means to achieve 3D printing construction without reinforcement. Developing long-life 3D printing cement-based materials, exploring the environmental sensitivity of cement-based materials for 3D printing, and the evolutionary development and mechanism of 3D-printed cement-based materials in extreme environments are expected to be important research issues in the future. Between 2013 and 2018, 104 patents on this topic were published with 682 patent citations and an average of 6.56 citations per patent.

(9) Incident response and rapid recovery during underground space construction

Disasters often occur during construction and operation of underground spaces due to the difficult ground conditions as well as to internal and external influences on the underground structures. Despite the variety of underground space construction methods and maintenance technologies used, the disasters that still happen in underground spaces mainly include water leakage, instability of underground structures, and excessive ground deformation caused by underground space construction, which also affect environmental safety. Groundwater is the most common factor causing disasters in underground structures. The ground must be strengthened while controlling the stability of the underground structure to repair underground structures after disasters in any emergency. The stability of the surrounding ground is the key to ensuring the long-term stability of the underground structure. The most effective methods commonly used in the stabilization of underground structures during emergency processes are grouting, defect repair, and structural reinforcement. The improvement of the ground can be achieved by means of grouting and anchor reinforcement. To control groundwater leakage, the most effective technical means is to precisely detect the location of the leakage and apply grouting rapidly to stop the inflowing water. Due to the increasingly complex environmental and geological conditions of underground space development and the aging of the underground structures already operating, the safety risks in the development and utilization of underground spaces have increased significantly. Under such conditions, rapid repair technology for imminent emergencies is critical. New materials with high-strength properties that can be realized rapidly, as well as new equipment that can be used in limited underground spaces, are the keys to realizing rapid repair of underground structures in emergencies. Between 2013 and 2018, 1853 patents on this topic were published, with 2245 patent citations and an average of 1.21 citations per patent.

(10) Marine surveying equipment

Marine surveying equipment is one of the development fronts in the field of surveying and mapping engineering, which provides basic support for the surveying of marine geospatial elements. Marine surveying equipment includes marine surveying platforms and professional surveying instruments for tasks that include such as seabed topographic surveying, marine gravity surveying, marine magnetic surveying, and marine seismic surveying. In recent years, ocean survey platforms have evolved from traditional ship-borne platforms to multi-dimensional data-acquisition systems for space, aviation, ground, surface, and underwater applications. Correspondingly, key technical issues relevant to this field include autonomous underwater vehicles, unmanned surface vehicles, unmanned ships, positioning and navigation equipment related to platforms, and towing devices and other ancillary equipment. Regarding professional surveying instruments, the major technical challenges concerning this development front include new sensors and their control. Data processing technologies are the main technical direction at present and include such technologies as ocean array sensors (from single probes to multiple probes) and geometric control methods of towed geophysical sensor arrays. Between 2013 and 2018, 606 patents on this topic were published with 2054 patent citations: an average of 3.39 citations per patent.

2.2 Interpretations for three key engineering development fronts

2.2.1 Technology for the reinforcement, repair, and retrofitting of existing structures

Owing to rapid industrialization, large-scale infrastructure construction has been undertaken in many countries since the middle of the twentieth century. This infrastructure may be subjected to sudden or transient disasters, such as earthquakes, fires, winds, or explosions, leading to catastrophic loss. Since the twentieth century, earthquake disasters have frequently occurred, causing serious damage to structures and major casualties. Existing structures that were built in previous decades, have a variety of structural configurations and consequently, a variety of seismic performance. In addition to the research on enhancement of the seismic performance of existing structures of different ages regarding structural configurations and materials, it is necessary to conduct symmetric research on retrofitting, rehabilitation, and renovation of structures with seismic damage.

Under the long-term effects of service loads and environmental attacks, the performance of existing structures generally degrades due to deterioration of materials, corrosion of steel, and accumulation of damage. Besides the investigation of rehabilitation techniques of materials themselves (e.g., masonry, timber, concrete, and steel) which exhibit degradation and cracking, deteriorated properties of the materials should also be taken into consideration in repair, reinforcement, and modification of components and structures.

Different from practices with typical existing structures, there are often conflicts or contradictions between reasonable protection of detailed features and spatial forms of historical buildings and retrofitting, rehabilitation, and renovation of such structures. There is still a lack of systematic research on compatible repairs at the material level, recoverable retrofitting at the component level, and system-based controllable strengthening at the structural level for historical buildings.

Major issues concerning this development front include:

(1) Techniques for the repair of materials have rapidly developed in recent years, including repair of carbonized concrete, chloride-ion-eroded concrete, weathered brick masonry, decayed wood, and corroded steel, and rehabilitation of cracked concrete, steel, masonry, and wood (especially the self-healing techniques for cracked concrete).

(2) Retrofitting of structural components generally shifts from static loads to fatigue loads, impacts, or explosions, from intact elements to damaged ones, from short-term to long-term performance, and from deterministic to random analysis.

(3) Seismic retrofitting and renovation at the structural level mainly rely on improvement of the seismic capacity of structures or mitigation of the seismic action of the superstructure by applying seismic isolation measures. The former generally includes strengthening the overall performance of the structure, changing the structural system, providing the desirable bearing capacity of loaded members, and enhancing the stiffness of joints. The latter is normally achieved by providing vibration isolation devices and installing dampers, as well as buckling-restrained brace members.

(4) Rehabilitation and maintenance technologies of historical buildings have been developed continuously, including the compatible repair of typical materials of historical buildings (e.g., lime, white marble, raw earth wall and bricks), enhancement of the ultimate load-bearing capacity and performance of damaged components and joints of traditional timber and masonry structures, as well as theory and methods for system-based structural retrofitting.

(5) With the development of materials science, many new high-performance materials such as fiber-reinforced polymer materials, graphene, cement-based composite materials, and shape memory alloys, have been recognized by researchers and applied to structural retrofitting, rehabilitation, and renovation.

As listed in Table 2.1.1, 2852 patents were published on this topic between 2013 and 2018. The top five countries or regions publishing the most patents were China, Japan, South Korea, Russia, and the USA (Table 2.2.1), and China contributed more than 59.71% of the patents. As depicted in Figure 2.2.1, international cooperation is rare among the top ten patent-output countries or regions in this regard.

As listed in Table 2.2.2, the top five organizations producing the most patents were the China State Construction Engineering Corporation (China), Takenaka Komuten KK (Japan), Shimizu Construction Co., Ltd. (Japan), Taisei Construction Co., Ltd. (Japan), and Luoyang Institute of Science and Technology (China). Cooperation among these organizations is rare (Figure 2.2.2).

2.2.2 Comprehensive transportation planning and intelligent safety management of urban agglomeration

An urban agglomeration is an urbanized area of concentrated residency and industry. The emergence of urban agglomerations is the obvious reflection of the growth of urbanization, as well as of engines to boost the economy. Urban agglomerations contribute to a country's balanced development across

Table 2.2.1 Countries or regions with the greatest output of patents on "technology for the reinforcement, repair, and retrofitting of existing structures"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	1703	59.71%	1248	68.61%	0.73
2	Japan	570	19.99%	248	13.63%	0.44
3	South Korea	323	11.33%	113	6.21%	0.35
4	Russia	59	2.07%	24	1.32%	0.41
5	USA	45	1.58%	100	5.50%	2.22
6	Germany	22	0.77%	11	0.60%	0.50
7	Colombia	11	0.39%	3	0.16%	0.27
8	Italy	9	0.32%	11	0.60%	1.22
9	France	9	0.32%	6	0.33%	0.67
10	Poland	9	0.32%	2	0.11%	0.22

Table 2.2.2 Institutions with the greatest output of patents on "technology for the reinforcement, repair, and retrofitting of existing structures"

No.	Institution	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	CSCE	China	62	2.17%	68	3.74%	1.10
2	TKEN	Japan	53	1.86%	15	0.82%	0.28
3	SHMC	Japan	40	1.40%	13	0.71%	0.33
4	TAKJ	Japan	38	1.33%	15	0.82%	0.39
5	LUOY	China	27	0.95%	21	1.15%	0.78
6	DWHO	Japan	23	0.81%	6	0.33%	0.26
7	UYSE	China	22	0.77%	29	1.59%	1.32
8	SHCG	China	22	0.77%	26	1.43%	1.18
9	CMEG	China	22	0.77%	12	0.66%	0.55
10	RJI	Japan	21	0.74%	7	0.38%	0.33

CSCE: China State Construction Engineering Corporation; TKEN: Takenaka Komuten KK; SHMC: Shimizu Construction Co., Ltd.; TAKJ: Taisei Construction Co., Ltd.; LUOY: Luoyang Institute of Science and Technology; DWHO: Daiwa House Industry Co., Ltd.; UYSE: Southeast University; SHCG: Shanghai Construction Group Co., Ltd.; CMEG: China Metallurgical Group Corporation; RJI: Retrofitting Japan Inst.

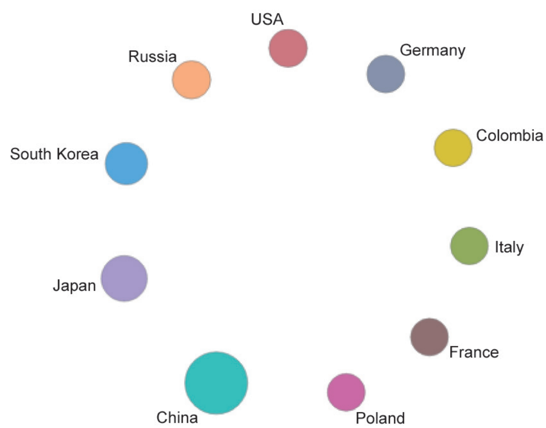

Figure 2.2.1 Collaboration network among countries or regions in the engineering development front of “technology for the reinforcement, repair, and retrofitting of existing structures”

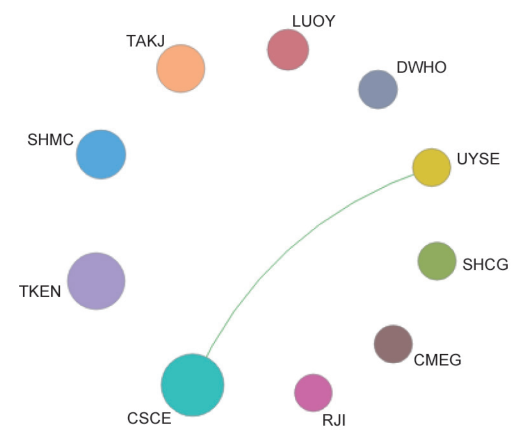

Figure 2.2.2 Collaboration network among institutions in the engineering development front of “technology for the reinforcement, repair, and retrofitting of existing structures”

regions and enable the country to take part in international economic exchange. Different from intra-city transportation that leans heavily on commuting trips, inter-city transportation within urban agglomerations generally crosses spatial jurisdictions and exhibits multivariate overlap in terms of trip purposes and demands. The iterative interplay between three components—functional structure, mobility demand, and transportation network and service—is the main concern of comprehensive transportation planning and safety management for urban agglomeration.

To underpin an efficient, safe, and cost-effective passenger and cargo transportation system for city clusters, we ought to design comprehensive transportation facility systems systematically and develop intelligent operation policies based on informative and quantitative measures.

Currently, there are five research directions for transportation planning and safety management for urban agglomeration:

(1) Analysis of the correlations between spatial structure and intensity of transportation connections. Based on flow space, using multi-source big data such as city-to-city passenger and freight transportation, location-based population migration, nighttime lighting, etc., spatial analysis and social network analysis methods are used to reveal the population mobility of cities between city clusters, and to identify the spatial scale and structure of a city cluster.

(2) Planning technology for transportation corridors connecting the cities. The level of passenger and freight transportation corridors is defined according to the spatial connection intensity of a city cluster. In a transportation corridor, transportation facilities such as roads, tracks, and other backbone facilities, road passenger transportation, and railway passenger transportation, are synergistically integrated to build a multi-channel, multi-mode, and multi-operation mode composite corridor to promote the intensification and synergy of passenger and freight transportation.

(3) One-stop passenger and freight organization method for urban agglomerations. This is about utilizing information technology such as big data, cloud computing, and mobile Internet to integrate efficiently the infrastructure (corridors, hubs) with operational organizations. It promotes the direct communication of supply and demand information, and builds a “one ticket” passenger service system and “one order” freight service system within the urban agglomeration.

(4) Transportation network cascade invulnerability assessment and repair technology for urban agglomerations. This is to construct a cascading failure model of an urban-agglomeration composite transportation network, and to propose criteria for evaluation of network vulnerability. The aim is to identify critical channels and nodes using optimization, simulation, and other technical means, and to format the channel and node capacity repair methods for different damage scenarios to improve resilience in the urban agglomeration transport system.

(5) Comprehensive, proactive, intelligent traffic safety management systems for city clusters. First, it is necessary to

develop holographic detection and proactive identification technologies and equipment to determine the multi-source operation risk within the comprehensive transportation network. Then, cutting-edge research is needed to establish operation risk pre-warning and dynamic-control technical systems. With the traffic risk control domain knowledge graph and information distribution approaches, the remaining frontiers are conducting elaborate and accurate safety management for both city-cluster comprehensive transportation networks and for key traffic operators.

As listed in Table 2.1.1, 1087 patents were published on this topic between 2013 and 2018. The top five countries/regions publishing the most patents were China, South Korea, the USA, Japan, and India (Table 2.2.3); China contributed more than 91.17% of the patents. As depicted in Figure 2.2.3, international cooperation is rare among the top ten core patent-output countries or regions in this regard.

As listed in Table 2.2.4, the top five institutions producing the most patents were Southeast University (China), Jilin University (China), Jiangsu University of Technology (China),

Table 2.2.3 Countries or regions with the greatest output of patents on "comprehensive transportation planning and intelligent safety management of urban agglomeration"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	991	91.17%	1468	85.10%	1.48
2	South Korea	29	2.67%	21	1.22%	0.72
3	USA	19	1.75%	121	7.01%	6.37
4	Japan	11	1.01%	8	0.46%	0.73
5	India	8	0.74%	14	0.81%	1.75
6	Russia	5	0.46%	0	0.00%	0.00
7	Germany	4	0.37%	2	0.12%	0.50
8	Netherlands	3	0.28%	49	2.84%	16.33
9	Australia	2	0.18%	13	0.75%	6.50
10	Canada	2	0.18%	3	0.17%	1.5

Table 2.2.4 Institutions with the greatest output of patents on "comprehensive transportation planning and intelligent safety management of urban agglomeration"

No.	Institution	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	UYSE	China	10	0.92%	32	1.86%	3.20
2	UYJI	China	10	0.92%	14	0.81%	1.40
3	JIAA	China	9	0.83%	2	0.12%	0.22
4	HPT	China	8	0.74%	8	0.46%	1.00
5	ADICSS	China	8	0.74%	7	0.41%	0.88
6	ZTEC	China	7	0.64%	27	1.57%	3.86
7	SHCG	China	7	0.64%	10	0.58%	1.43
8	UCHA	China	6	0.55%	10	0.58%	1.67
9	WBDIT	China	5	0.46%	27	1.57%	5.40
10	UYQI	China	5	0.46%	24	1.39%	4.80

UYSE: Southeast University; UYJI: Jilin University; JIAA: Jiangsu University of Technology; HPT: Hangzhou Pule Technology Co., Ltd.; ADICSS: Anhui Dar Intelligent Control System Stock Co., Ltd.; ZTEC: ZTE Corporation; SHCG: Shanghai Urban Traffic Design Institute Co., Ltd.; UCHA: Chang'an University; WBDIT: Wuxi Big Dipper Information Technology; UYQI: Tsinghua University.

Hangzhou Pule Technology Co., Ltd. (China), and Anhui Dar Intelligent Control System Stock Co., Ltd. (China). Cooperation among these organizations is rare (Figure 2.2.4).

2.2.3 Technology for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans, and groundwater

Since the mid-1980s, based on reflection of the consequences of large-scale urbanization and industrialization, many countries have increased research and development of river, lake, ocean, and groundwater remediation engineering technologies to achieve precise governance and remediation. Concurrently, monitoring and evaluation technology were also developed. The Water Framework Directive (WFD) promulgated by the European Union (EU) in 2000 has proven to be a successful model for global management of water resources. The EU's laws on water resource management have changed from protecting public water quality and regulating pollution sources in the last century to focusing on integrated water resource management at the beginning of this century. Since 2010, the EU approach has shifted to focusing on performance and paying more attention to the protection of water ecosystems. In Japan, the River Law was revised again in 1997, which integrates the protection of water ecology, safeguarding of water resources, and disaster prevention into a complete countermeasure system. The 17 sustainable development goals formally adopted at the United Nations Summit on Sustainable Development in September 2015 also focused on ecosystems and protection of underwater biology. It can be seen that after entering the 21st century, developed countries such as the European countries, the United States, and Japan have paid more attention to the research and development of technology for monitoring, evaluation, and restoration of aquatic ecological environments. Developed countries have also played a leading role in the governance and protection of the global water ecological environment.

Monitoring is done to determine the current status and changing trends through continuous investigation and observation. With evaluation, more attention is directed to the development of efficient evaluation-model systems, using a variety of monitoring data to simulate the prediction and impact assessment of possible trends. Through evaluation, we are able to understand the principles of the complex, unseen processes behind appearances. These are the principles upon which we can propose effective environmental management strategies and integrate the hydrology, water quality, and ecological model systems with high precision to achieve the simulation and prediction of the restoration effects. Restoration is the application of various engineering means to repair a damaged water environment. Because artificial restoration often requires a great deal of resources and time, it is particularly important to develop an appropriate and orderly restoration plan based on full consideration of the environmental capacity and natural restoration potential.

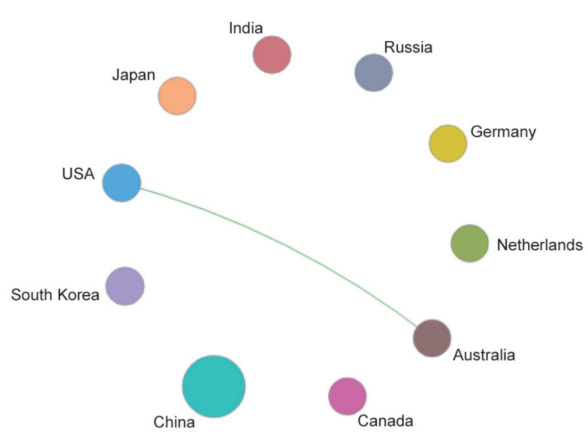

Figure 2.2.3 Collaboration network among countries or regions in the engineering development front of "comprehensive transportation planning and intelligent safety management of urban agglomeration"

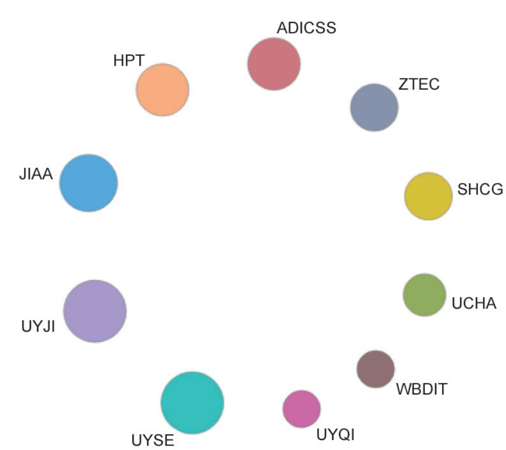

Figure 2.2.4 Collaboration network among institutions in the engineering development front of "comprehensive transportation planning and intelligent safety management of urban agglomeration"

Developed countries have gradually shifted from pollution control to prevention-oriented strategies. For pollution-source control, ecological engineering methods such as natural restoration are used extensively, and the objectives of pollution source reduction, habitat protection, and ecological function restoration are achieved by building green infrastructure. At present, China mainly concentrates on the pollution control of surface and groundwater. However, with the rapid development of information technology and artificial intelligence technology, associated technologies have also developed. These include provisions for automatic measurement, automatic sample collection, automatic water-quality-monitoring systems, automatic algae filtering and cleaning systems, and autonomous navigation for surface garbage cleaning and surface cleaning robots. These develop and utilize unmanned aerial vehicles and unmanned aerial vehicles are emerging endlessly, showing a trend of running parallel to the progress in developed countries.

As listed in Table 2.1.1, 506 patents were published on this topic between 2013 and 2018. The top five countries were China, the USA, South Korea, Japan, and France (Table 2.2.5). Among them, China was one of the key countries at the forefront of development, contributing 91.11% of the patents. The average frequency of Chinese patent citation was 6.62, which indicates that Chinese patents are getting more and more attention. Analysis of the proportion of international patents shows that although the average frequency of patent citation in China was 28.75, which is lower than that of the USA in the period (i.e., 81.79), it was significantly higher than that in developed countries such as South Korea and Japan. This indicates that in China, international competitiveness and awareness of independent intellectual property protection are increasing. In this area, there was no cooperation between countries or regions shown in the cooperation network between countries/regions producing patents (Figure 2.2.5).

As listed in Table 2.2.6, the top five organizations producing the most patents were Hohai University (China), Suzhou Feichi Environmental Technology Co., Ltd. (China), Shenzhen DJI Technology Co., Ltd. (China), Zhejiang Ocean University (China), and Tianjin University (China). Among the top ten institutions regarding patent-output in China, scientific research institutes and enterprises were balanced in number, indicating that Chinese enterprises have a strong sense of independent innovation in the field of technological development against a background of strategies for ecologically sustainable civilization. The top ten cooperation networks of patent producers (Figure 2.2.6), showed no cooperation among these organizations.

Table 2.2.5 Countries or regions with the greatest output of patents on "technology for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans and groundwater"

No.	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	461	91.11%	3051	68.36%	6.62
2	USA	22	4.35%	1196	26.80%	54.36
3	South Korea	6	1.19%	36	0.81%	6.00
4	Japan	3	0.59%	48	1.08%	16.00
5	France	3	0.59%	40	0.90%	13.33
6	Denmark	2	0.40%	28	0.63%	14.00
7	Canada	2	0.40%	22	0.49%	11.00
8	Russia	2	0.40%	6	0.13%	3.00
9	Germany	1	0.20%	18	0.40%	18.00
10	Netherlands	1	0.20%	8	0.18%	8.00

Table 2.2.6 Institutions with the greatest output of patents on "technology for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans and groundwater"

No.	Institution	Country/Region	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	UYHO	China	11	2.17%	61	1.37%	5.55
2	SFET	China	11	2.17%	52	1.17%	4.73
3	DJII	China	9	1.78%	257	5.76%	28.56
4	UYZO	China	7	1.38%	40	0.90%	5.71
5	UTIJ	China	6	1.19%	57	1.28%	9.50
6	CNPW	China	6	1.19%	19	0.43%	3.17
7	WDMM	China	6	1.19%	7	0.16%	1.17
8	CRHK	China	5	0.99%	41	0.92%	8.20
9	UYCR	China	5	0.99%	22	0.49%	4.40
10	UQT	China	4	0.79%	52	1.17%	13.00

UYHO: Hohai University; SFET: Suzhou Feichi Environmental Technology Co., Ltd.; DJII: Shenzhen DJI Technology Co., Ltd.; UYZO: Zhejiang Ocean University; UTIJ: Tianjin University; CNPW: POWERCHINA Water Environment Management Technology Co., Ltd.; WDMM: Wuxi Dagong Machine Manufacturing Co., Ltd.; CRHK: Chinese Research Academy of Environmental Sciences; UYCR: China Three Gorges University; UQT: Qingdao Technological University.

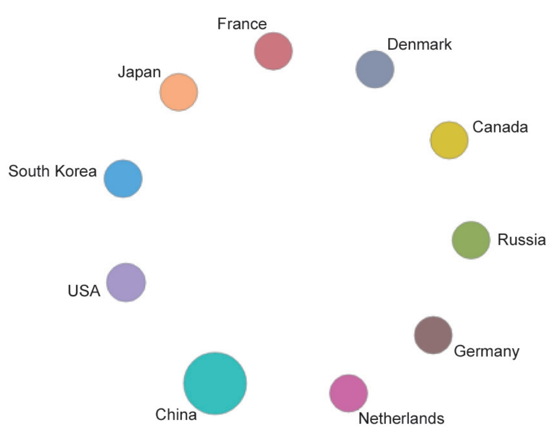

Figure 2.2.5 Collaboration network among countries or regions with the greatest output of patents in the engineering development front of "technology for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans and groundwater"

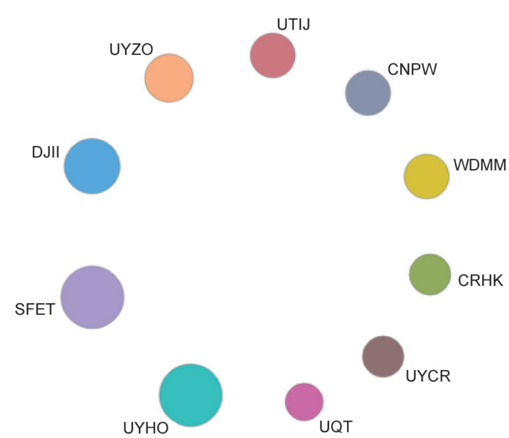

Figure 2.2.6 Collaboration network among institutions in the development front of "technology for monitoring and rehabilitation of eco-water environments in rivers, lakes, oceans and groundwater"

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