V. Civil, Hydraulic Engineering & Architecture

1 Engineering research hotspots and engineering research focus

1.1 Development trends of engineering research hotspots

The top 10 engineering research hotspots in the field of civil, hydraulic engineering and architecture are summarized in Table 1.1.1, and they cover various disciplines including architecture, structural engineering, bridge engineering, engineering mechanics, construction materials, geotechnical and underground engineering, hydraulic engineering, infrastructural engineering, and survey engineering. Among these hotspots, "Material biological remodeling" and "Mixed-pixel decomposition and spatiotemporal location big data analysis" are the emerging frontiers, while in the other aforementioned hotspots, the traditional research is extended in the fields of civil, hydraulic engineering and architecture. Table 1.1.2 presents the statistical data of publications on these hotspots from 2011 to 2016. From among the top 10 hotspots, the number of published papers is the highest in "High-performance civil, hydraulic, and building engineering structures" and "Structural defect analysis."

(1) High-performance civil, hydraulic, and building engineering structures

High-performance civil, hydraulic, and building structures are structures in key civil and hydraulic engineering and multi-functional building structural systems with high-performance in safety, serviceability, constructionability, environment-friendliness, durability, maintenance, and cost-efficiency throughout the life-cycle. This topic includes the following scientific and technological challenges: ① development of novel design principles and implementation tools for consistent compatibility of architecture (spatial arrangement), function, and structures; ② development of new concepts and methods of structural analysis and design that combine the rational optimization of the structural system and refined design; ③ development of new theories and techniques for an optimal design that takes into consideration the life-cycle and multi-performance tradeoffs while accounting for planning, design, construction, service maintenance, and demolition. To address these issues, there is a requirement for a novel concept and the revolution of the implementation

Table 1.1.1 Top 10 engineering research hotspots in civil, hydraulic engineering and architecture

No.	Engineering research hotspots	Core papers	Citation frequency	Average citation frequency	Mean year	Proportion of consistently cited papers	Patent-cited publications
1	High-performance civil, hydraulic, and building engineering structures	377	9948	26.39	2014.06	23.60%	3
2	Ultra-high performance and multi-functional cement-based composite materials	36	948	26.33	2013.78	11.10%	0
3	Methods for the analysis and simulation of complex structures	135	3699	27.40	2014.83	39.30%	2
4	Built environment and occupant behavior	34	716	21.06	2013.88	17.60%	0
5	Removal of heavy metals and other high-risk pollutants	29	1243	42.86	2012.79	20.70%	0
6	Reliability of civil engineering structures	42	1138	27.10	2013.43	23.80%	1
7	Material biological remodeling	34	1345	39.56	2012.59	20.60%	0
8	Mixed-pixel decomposition and spatiotemporal location big data analysis	95	3887	40.92	2013.31	12.60%	1
9	Structural defect analysis	30	483	16.10	2013.90	0%	0
10	Numerical simulation of fluid-structure interaction	89	2694	30.27	2012.89	7.90%	1

Table 1.1.2 Annual number of core papers belonging to each of the top 10 engineering research hotspots in civil, hydraulic engineering and architecture

No.	Engineering research hotspots	2011	2012	2013	2014	2015	2016
1	High-performance civil, hydraulic, and building engineering structures	28	37	58	73	122	59
2	Ultra-high performance and multi-functional cement-based composite materials	2	6	5	10	11	2
3	Methods for the analysis and simulation of complex structures	0	5	17	15	57	41
4	Built environment and occupant behavior	2	3	7	9	11	2
5	Removal of heavy metals and other high-risk pollutants	9	5	3	8	3	1
6	Reliability of civil engineering structures	6	6	11	7	7	5
7	Material biological remodeling	11	6	8	4	5	0
8	Mixed-pixel decomposition and spatiotemporal location big data analysis	14	12	20	32	14	3
9	Structural defect analysis	3	1	6	7	12	1
10	Numerical simulation of fluid-structure interaction	21	15	18	24	10	1

systems as well as the innovative investigations enabled by modern scientific development, which can be realized by combining physical and numerical modeling; macro-, meso- and micro-scale studies; and qualitative and quantitative synthesis. The current hot subjects are as follows: ① applications of novel materials; ② innovative structural systems; ③ refining of analysis and modeling of structures; ④ structural performance monitoring and control; and ⑤ life-cycle reliability analysis and design. From 2011 to 2016, 377 core papers were published on this hotspot, and they received a total of 9948 citations and 26.39 citations per paper.

(2) Ultra-high performance and multi-functional cement-based composite materials

Owing to the rapid development of construction technology, traditional cement-based materials with low toughness and high brittleness could not meet the high-performance demands of several special applications. Hence, ultra-high performance and multi-functional cement-based composites have become the focus of current research. Since their discovery, carbon nanotubes have been widely studied in physical, chemical, and material areas owing to their excellent performance properties. Carbon nanotubes can greatly improve the strength or toughness of materials and their conductivity. Ultra-high performance civil-engineering materials can be obtained by adding carbon nanotubes and carbon fibers into cement-based materials. The following are some common ultra-high performance civil-engineering materials: self-sensing carbon nanotube cement-based composites, multi-walled carbon-nanotubes-reinforced cement paste, and carbon-fiber-reinforced Portland cement mortar. Carbon nanomaterials in the cement matrix equip the composites with good physical and chemical properties, thus greatly enhancing the safety and reliability of concrete structures, and they can be used for high-strength intelligent cement-based materials testing. Therefore, carbon nanomaterials have broad applications in improving cement-based traditional building materials. From 2011 to 2016, 36 core papers have been published on this hotspot, and they received a total of 948 citations and 26.33 citations per paper.

(3) Methods for the analysis and simulation of complex structures

Owing to the rapid developments in computer science and technology in recent years, numerical simulations have played an increasingly important role in the study of complex structures. The two main concerns in the development of modern computational techniques are the modeling of complex material behaviors and the modeling of complex geometries. Engineering materials often sustain damage and fractures when they are subjected to external loading. The cracks could be considered as discontinuities within continuum fields. Thus, the extended finite element method (XFEM) introduces discontinuous enrichments based on the concept of the partition of unity. Owing to its mathematical accuracy and convenience in application, XFEM has been well accepted by researchers and engineers. In recent years, several researches have focused on the further development of XFEM. According to the continuum damage theory, cracks are often smeared within a certain domain and the effects of crack initiation and propagation are described by the continuum evolution of the damage variables. Damage theory is suitable for the simulation of complex structures without changing the framework of structural finite element models. The recent developments in damage models have focused on nonlocal theory based on which the issue of mesh sensitivities could be eliminated. Several new materials have been developed and designed in recent works, e.g., fiber-reinforced composites and functional graded material. The numerical methods for the simulation of newly designed materials mainly belong to the class of multi-scale methods. For structures with a rather complex geometry, the finite element meshing is quite complicated and time-consuming. In order tackle this issue, the concept of isogeometric analysis is proposed, for which the basic functions used for the geometric modeling (e.g., NURBS) are also used for the interpolation of state variables. Isogeometric analysis has been developing very quickly, and it has recently found application in the problems of vibration, buckling, and fracture. From 2011 to 2016, 135 core papers have been published on this hotspot, and they received a total of 3699 citations and 27.4 citations per paper.

(4) Built environment and occupant behavior

This hotspot involves the study of the relationship and interaction between the built environment and human comfort as well as behavior. It includes the study of the methods for meeting the psychological requirements of occupants and improving their living environment through city planning, urban design, architectural design, and building equipment system design. In addition, it includes the study of the interaction and adjustment between the occupant and environment. The main topics of research include the requirements of human comfort with respect to temperature, humidity, air velocity, radiation, and other environmental factors; the evaluation and prediction of thermal comfort based on thermal adaptation theory and dynamic thermal comfort theory; and the description and simulation of occupant adjustment to the built environment. The study of the built environment and occupant behavior comprises the following engineering science branches: outdoor microclimate and thermal comfort, thermal adaptation to climate, and adjustment to the built environment. Building environment and occupant behavior is currently a research hotspot. The traditional thermal adaptation model and design theory of the indoor air-conditioning environment have been satisfactorily developed and thoroughly investigated. In recent years, research has been focused on outdoor environmental thermal comfort, dynamic thermal comfort and thermal adaptation, thermal comfort under special environments (such as high altitudes, public transport, and aerospace environments), and interaction between thermal comfort and occupants. These topics supplement the development of existing thermal comfort and occupant behavior theory. With the improvement in the quality of life and the popularization of the concept of green and sustainable development, this subject will continue to be a research hotspot in the field of built environment and will develop new connotations based on traditional theories. From 2011 to 2016, 34 core papers were published on this hotspot, and they received a total of 716 citations and 21.06 citations per paper.

(5) Removal of heavy metals and other high-risk pollutants

Scientific and engineering methods were applied to restore water, air, or soil that had been contaminated by heavy metals and other high-risk pollutants. These methods can be used to transform the pollutants into less toxic forms or maintain their concentrations within a safe range. Heavy-metal pollution occurs when the concentrations of mercury, cadmium, lead, chromium, arsenic, and their compounds exceed their safe value in water, air, soil, or other carriers. They can cause significant harm to the environment and to lives. To prevent heavy-metal pollution, the control of the total amount of the pollutants should be combined with concentration control. Furthermore, source prevention, process disruption, cleaner production, and terminal treatment should be realized while focusing on the key prevention and control zones, key prevention and control industries, and key sources of pollution. In addition, to control the emission of heavy metals from the source, the removal of discharged metals is particularly critical, and the main technologies for achieving this presently include leaching, adsorption, ionic liquid extraction, oxidation-reduction, the electrochemical method, and photocatalytic method. Furthermore, increasing attention has been focused on the recycling field. Other high-risk pollutants in the environment include pharmaceuticals and personal care products, which can be eliminated mainly via adsorption and oxidation. Though these high-risk pollutants exist in low concentrations, long-term exposure to them is relatively risky. From 2011 to 2016, 29 core papers were published on this hotspot, and they received a total of 1243 citations and 42.86 citations per paper.

(6) Reliability of civil engineering structures

Reliability is the probability that civil structures, under normal service conditions and/or subject to disastrous conditions, satisfy the prescribed demand function and safety and durability conditions, and it also includes the theory for reliability-based structural design. The key scientific issues with respect to this reliability include the identification and modeling of uncertainty in the structural properties and actions , the structural life-cycle performance and complete process behaviors under loading, and the reliability analysis and design of structures. Since the late 1940s, structural reliability theory gradually became the core of structural design theory, and the golden epoch was from the late 1960s to early 1980s, which was enriched by the concept of performance-based design that originated in the early 1990s. Since the beginning of the 21st century, owing to the increasingly frequent effects of natural and manmade disasters, increasing importance has been attached to engineering reliability. Meanwhile, with the decreasing cost of data collection, emerging big data techniques, rapid development of the fundamental theory of mechanics and high-performance computation, and with the emerging uncertainty quantification theory in various fields, structural reliability theory is embracing new ideas. Presently, the hot subjects in this field include the modeling of uncertainty, the reduced model for engineering structures and systems, and high-efficiency stochastic analysis methods. Simultaneously, the research subjects are extended from overground structures to geotechnical and underground structures, the mathematical basis is expanded from probability theory to uncertainty modeling including the imprecise probability and interval methods, and the physical-mechanical basis is extended from simplified semi-empirical models to modern multi-scale physical mechanics. The structural reliability theory is transitioned from approximate probability to full probability and risk based decision-making, and from more mathematics-emphasized to physical-based global reliability analysis and design. From 2011 to 2016, 42 core papers were published on this hotspot, and they received a total of 1138 citations and 27.10 citations per paper.

(7) Material biological remodeling

Biological materials are formed with perfect structural morphology and unique superior performance during their long evolution process. Inspired by these materials, researchers have attempted to reveal the structural features and mechanisms of the biological system, which is then applied to the design and preparation of building materials. The research on structural biomimetic materials is an important branch of bionics. Based on the study of the structural characteristics and structure-activity relationship of the biomaterials, the bionic simulations of materials, structures, and systems are performed to improve the engineering structural efficiency. Biological remodeling of materials is one of the main subjects of biomimetic research. It focuses on the non-uniform expansion and mechanical influence of gels and biomaterials on healing and strengthening during the stage of hardening deformation and biological growth. The main research includes material constitutive relations and the mechanics analysis method, the modeling of the boundary growth mechanics problem, and the solutions of static and dynamic problems. Owing to inspiration from biological materials, bionic materials will become more and more microcosmic and intelligent. Future research will focus on constructing various biomimetic micro-devices using functional materials and by assembling bionic micro systems with various structures and functions. Such studies will be widely used in the military, industries, and building. From 2011 to 2016, 34 core papers were published on this hotspot, and they received a total of 1345 citations and 39.56 citations per paper.

(8) Mixed-pixel decomposition and spatiotemporal location big data analysis

The contents of mixed-pixel decomposition and spatiotemporal location big data analysis include mixed-pixel decomposition, real-time precise point positioning, and spatiotemporal big data analysis. The breakthrough sensor spatial resolution limit in mixed-pixel decomposition depicts the true nature of the mixed-pixel distribution at sub-pixel accuracy, and high-spatial-resolution image classification results can be obtained from a coarse-spatial-resolution image by scaling down in order to improve the accuracy of extraction of the image information. The real-time precise single-point positioning method uses a precise satellite ephemeris and precise clock product to obtain higher-precision spatial location data with a pseudorange and carrier-phase observations using the global navigation satellite system (GNSS) receiver. The spatiotemporal data acquisition method is aimed at obtaining high spatial resolution and spatiotemporal position accuracy in order to achieve the acquisition, storage, and reconciliation of high-dimensional spatial-temporal big data. Spatiotemporal big data analysis techniques are used for automatically discovering and extracting the implicit, non-obvious patterns, rules, and knowledge from massive, multi-source spatiotemporal location big data and for excavating values from the volume, velocity, and variety big data. From 2011 to 2016, 95 core papers were published on this hotspot, and they received a total of 3887 citations and 40.92 citations per paper.

(9) Structural defect analysis

Various imperfections including cracks, defects, and material degradations are created in civil materials and structures during their construction and service processes, owing to the comprehensive interior and exterior factors such as changes in the service environment, fire, earthquakes, and explosion shocks. These imperfections also cause various types of serious accidents and even civil engineering disasters. Therefore, there is an urgent requirement for developing fundamental theories of fracture mechanics for bearing capacity analysis and safety assessment of civil structures with defects and diseases in the fields of civil engineering, hydraulic engineering, and construction engineering. The relevant research topics are listed as follows: crack initiation criterions and crack propagation theories for civil materials and structures; fracture analysis theories of plates and shells for civil engineering; fracture behaviors, ultimate load-bearing capacity analyses, safety assessments, plastic fatigue, and fracture failure analyses for civil components and structures with odd-shaped notches under complex loading conditions; classifications, distribution surveys, characteristics, and statistical analyses of various defects or imperfections in civil structures and their suitable simulation models; and development of various types of defective specimens for various research purposes with materials such as polymethylmethacrylate, steels, and graphite, and research on the corresponding new theories and methods for physical tests and fracture analysis. Currently, the hot research direction in the field of structural defect analysis is the development of new theories and methods for the simulation of structural fractures and failure processes. Some examples are nonlocal damage models for cracked structures that are free of challenging issues such as the effects of mesh sensitivity and size, new numerical methods such as XFEM and meshless methods that circumvent the difficulties of mesh refinement and mesh movement for the simulation of the fracture propagation process, and multiscale theories and methods that can be used for analyzing new engineering materials and structures with fiber-composite and functionally graded materials ranging from the micro to the macro scope. From 2011 to 2016, 30 core papers were published on this hotspot, and they received a total of 483 citations and 16.10 citations per paper.

(10) Numerical simulation of fluid-structure interaction

Fluid-structure interaction is the interaction of structures with the surrounding fluid flow, and it includes various mechanical behaviors of a deformable solid structure under the action of the flow field and the influences of the position and shape of a deformable structure on the flow field. Fluid flow problems comprise a large number of nonlinear phenomena, and for a fluid-structure coupling system, these problems may further involve large nonlinear geometrical deformation, nonlinear elastic-plastic materials, and nonlinear problems induced by uncertainty and coupling at the contact interfaces. Generally, fluid-structure interaction systems are often complex nonlinear systems, and they are mainly analyzed using numerical simulations. The important studies on this subject include water/air flow-structure interaction and the corresponding modeling technique. The key to the successful numerical simulation of fluid-structure interaction lies in adopting a unified coordinate system and considering the coordination problem at two-phase interfaces. In the case of nonlinear coupling problems, it is necessary to find a method for obtaining the solutions in the entire fluid and solid domain, and it is also a challenge to combine the effective methods of solving the nonlinear flow equations and the structural equations. From 2011 to 2016, 89 core papers were published on this hotspot, and they received a total of 2694 citations and 30.27 citations per paper.

1.2 Understanding of engineering research focus

1.2.1 High-performance civil, hydraulic, and building engineering structures

Civil, hydraulic, and building structures are the major material carriers in human society. The development of modern society, economy, and technology has raised the performance demands of engineering structures and has resulted in the development of new high-performance engineering structures. In general, high-performance civil, hydraulic, and building structures exist in key civil and hydraulic engineering and multi-functional building structural systems with high life-cycle performance in safety, serviceability, constructionability, environment-friendliness, durability, maintenance, and cost-efficiency. With the development of economy, society, and technology, the population is becoming increasingly concentrated, and the function and structure of civil infrastructures are becoming increasingly specific and complicated. However, the losses incurred owing to natural and manmade disasters are increasing. Therefore, superior performance is required of engineering structures for protecting human lives and property. Meanwhile, rapid developments in modern science and technology (particularly in material science, fundamental physics and mechanics, information and data science, and high-performance computing techniques) have provided unprecedented opportunities for realizing high-performance structures.

Attempts to develop high-performance engineering structures raise scientific and technological challenges: ① development of novel design principles and implementation tools for the consistent compatibility of architecture (spatial arrangement), function, and structures; ② development of new concepts and methods of structural analysis and design that combine the rational optimization of structural systems and refined design; ③ development of new theories and techniques for optimal design involving life-cycle and multi-performance tradeoffs while accounting for planning, design, construction, service-maintenance, and demolition. To resolve these issues, we require a novel concept and a revolution in the implementation systems as well as innovative investigations that are enabled by modern scientific development by combining physical and numerical modeling, macro-, meso-, and micro-scale studies, and qualitative and quantitative syntheses.

The following are presently the hot subjects in "High-performance civil, hydraulic, and building engineering structures."

(1) Applications of novel materials

The development of novel materials is one of the major forces advancing innovation in engineering structures. In the past decades, material science has transited from the traditional paradigm of material fabrication—mechanical property studies—engineering applications to the paradigm of macro-microscale unified material design—integrated material-structure design. Various demands for high-performance civil, hydraulic, and building engineering structures have given rise to the development and application of materials of unique performance or comprehensive high performance (e.g., intelligent materials, high-damping materials, high-modulus materials, and high-durability materials). However, affordability is a bottleneck of high-performance civil, hydraulic, and building structures as massive amounts of materials are required in this field. Reducing the cost and improving the comprehensive or unique performance, in particular via material modification, is an important alternative.

(2) Innovative structural system

An innovating structural system is one of the major approaches for achieving high structural performance. In recent years, appreciable advances have been made in the development of new composite structures, new disaster-resistant structures (e.g., resilient structures and intelligent structures), and auto-growing structures based on bionics and topological optimization.

(3) Refined analysis and modeling of structures

The advancement of fundamental physics and mechanics (e.g., the constitutive law of solids and soft materials) and high-performance computational facilities and techniques (e.g., smoothed particle hydraulics, mesh-free method, extended finite element method, and isogeometric analysis, large deformation and strong nonlinear analysis methods) greatly promoted the refined analysis theory and methods for complex civil, hydraulic, and building structures. In this aspect, the multi-scale physical-numerical hybrid simulation incorporating the modern experimental techniques and numerical computation is a significant direction for future investigations.

(4) Structural performance monitoring and control

Structural performance monitoring will become a routine task for maintaining important civil, hydraulic, and building structures. The new multi-parameter sensors and sensing networks with high accuracy, disturbance insensitivity, superior weather-resistance performance, long service life, low-energy-consuming and wireless or remote transfer performance; analysis and high-efficiency property extraction techniques for big data; warning, intelligent control, and resilience or even self-healing of engineering structures are the challenging frontiers.

(5) Life-cycle reliability analysis and design

The hot subjects include uncertainty quantification, theory of reduced or surrogate model, big data techniques, and life-cycle management systems. In particular, uncertainty quantification and disaster-resistant reliability of civil, hydraulic, and building structures received a great deal of attention, which resulted in various breakthroughs. The life-cycle global reliability analysis and optimal design of engineering structures that incorporates monitoring and control is a promising research direction and is supported with refined physical-mechanical models and big data.

The focus of research varies in different countries owing to their different geographical environments, development phase, economic status, scientific and technological level, and history and social thought. In the past two decades, researches conducted in the USA are transitioning from massive construction to maintenance, management, and post-disaster recovery, and thus included leading research on performance-based seismic design, structural health monitoring, and life-cycle cost evaluation. Recently, they evolved from the structure scale to the community scale. The focus of research in Europe is very different. Reliability analysis and design theory for engineering structures and systems has received a great deal of attention in Norway, Denmark, and Germany; the fundamental theory for solid mechanics analysis plays a leading role in research in France and Spain; and the experimental and theoretical investigations in disaster-resistant performance of engineering systems has gained importance in Italy. Japan leads the world in the development and applications of new disaster-resistant structural systems and devices. In the past decade, with massive infrastructure construction, the investigations into the above subjects have improved greatly in China. China now plays an important role in the study of novel materials, innovative structural systems, refined analysis theory and methods, monitoring and control of structural performance, and reliability design of structures and systems; China is expected to play a world-leading role in one or several of these subjects.

As presented in Table 1.1.1, a total of 377 core papers in “High-performance civil, hydraulic, and building structures” have been published with an average of 26.39 citations per paper. As shown in Table 1.2.1, the top five countries or regions producing the most core papers are China (excluding Taiwan of China), Italy, Australia, the USA, and Algeria, and the core papers from China account for 31.03% (the Chinese mainland 21.14%; and Hong Kong, Macau, and Taiwan 9.33%), indicating that China is an important contributor in this subject. According to the average citations, the top five countries or regions are Portugal, Algeria, Germany, China, and the USA. The number of average citations from China is 24.11, which is higher than the average value, and this indicates that Chinese researchers are receiving global attention. As indicated by the collaborative network of countries or regions shown in Figure 1.2.1, it can be observed that close collaborations exist among all the top five countries or regions except Algeria.

The top five institutions producing core papers are the Univ Djillali Liabes Sidi Bel Abbes in Algeria, University of Hong Kong, City University of Hong Kong, University of Adelaide, and Univ Roma La Sapienza. The collaborative network of the major institutions (Figure 1.2.2) indicates frequent collaborations in the same country or region.

As can be observed from Tables 1.2.3 and 1.2.4, the top five countries or regions producing the most citations are China, Australia, the USA, Italy, and Portugal. The citations from China account for 24.30%, and three of the top five institutions producing the most citations are from China (i.e., University of Hong Kong, City University of Hong Kong, and Wuhan University). This indicates that Chinese researchers are at the frontiers of these investigations.

In summary, China is maintaining the same pace as other countries or regions in frontier research in “High-performance civil, hydraulic, and building structures” and has the potential for playing a leading role. It is essential to allocate more funding to research on these topics in order to advance such studies and to play a leading role in the world.

Table 1.2.1 Major producing countries or regions of core papers on the engineering research focus “High-performance civil, hydraulic, and building engineering structures”

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	China	117	31.03%	2821	33.03%	24.11	31	1
2	Italy	71	18.83%	1191	13.94%	16.77	0	0
3	Australia	69	18.30%	1524	17.84%	22.09	23	0
4	USA	43	11.41%	1032	12.08%	24.00	10	0
5	Algeria	39	10.34%	1169	13.69%	29.97	5	0
6	Germany	31	8.22%	858	10.05%	27.68	6	2
7	Singapore	24	6.37%	544	6.37%	22.67	6	0
8	Portugal	20	5.31%	712	8.34%	35.60	5	1
9	France	20	5.31%	276	3.23%	13.80	0	0
10	Iran	19	5.04%	306	3.58%	16.11	4	0

Table 1.2.2 Major producing institutions of core papers on the engineering research focus “High-performance civil, hydraulic, and building engineering structures”

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Univ Djillali Liabes Sidi Bel Abbes	39	10.34%	1169	13.69%	29.97	5	0
2	Univ Hong Kong	38	10.08%	930	10.89%	24.47	14	0
3	City Univ Hong Kong	29	7.69%	790	9.25%	27.24	10	0
4	Univ Adelaide	23	6.10%	644	7.54%	28.00	8	0
5	Univ Roma La Sapienza	23	6.10%	310	3.63%	13.48	0	0
6	Lab Struct & Mat Avances Genie Civil & Travaux Pu	21	5.57%	629	7.36%	29.95	3	0
7	Wuhan Univ	20	5.31%	460	5.39%	23.00	7	0
8	Univ Sci	19	5.04%	672	7.87%	35.37	6	0
9	Bauhaus Univ Weimar	18	4.77%	620	7.26%	34.44	5	1
10	Univ Aquila	16	4.24%	256	3.00%	16.00	0	0

1.2.2 Built environment and occupant behavior

The study of “Built environment and occupant behavior” has been developed based on traditional steady state thermal comfort for approximately the past century. Its main aim is to examine the human body’s reactions in a steady state thermal environment, which can be represented using a thermal comfort model proposed by Professor P. O. Fanger of Danish Technical University. The model became the basis of the standards used by American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) and International Standardization Organization (ISO) for developing indoor thermal environments. China's thermal environment design standards generally cite these standards.

Based on the clustering analysis of keywords in core papers, the mainstream of engineering science and the branch engineering sciences focused on in this engineering research include the following: outdoor microclimate and thermal comfort, thermal adaptation to climate, and adjustment to built environments.

(1) Outdoor microclimate and thermal comfort

This includes the adjustment of outdoor micro-climate parameters, building of comfortable outdoor thermal environments, and proposing an evaluation index of safety

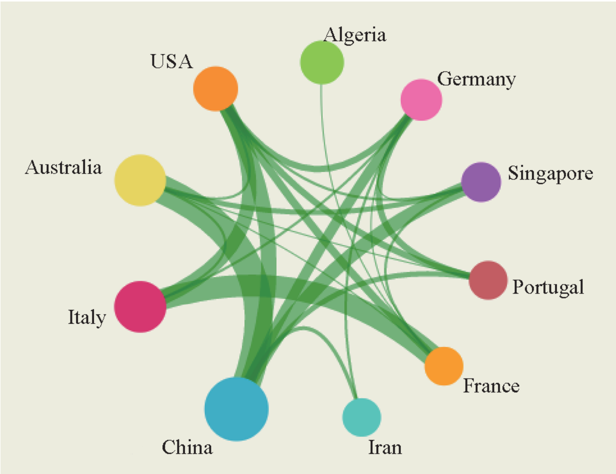

Figure 1.2.1 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "High-performance civil, hydraulic, and building engineering structures"[1]

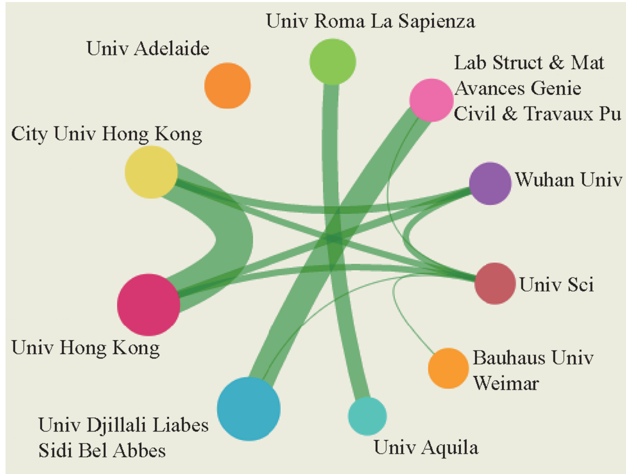

Figure 1.2.2 Collaboration network of the major producing institutions of core papers on the engineering research focus "High-performance civil, hydraulic, and building engineering structures"

Table 1.2.3 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "High-performance civil, hydraulic, and building engineering structures"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	China	87	24.30%	2014.17
2	Australia	54	15.08%	2014.11
3	USA	27	7.54%	2014.07
4	Italy	24	6.70%	2014.67
5	Portugal	16	4.47%	2013.56
6	Iran	15	4.19%	2014.93
7	Algeria	15	4.19%	2015.33
8	Germany	14	3.91%	2014.21
9	Singapore	12	3.35%	2014.42
10	Korea	8	2.23%	2013.88

and comfort for an outdoor thermal environment through methods involving building layout design, outdoor floor pavement, the application of shade parts, residential and urban greening, the use of accumulated rainwater, the use of windshields and fountains, and other technical measures. The key technologies to be solved includes: the influence of short-wave and long-wave radiation on outdoor thermal comfort; outdoor thermal comfort evaluation index and outdoor microclimate evaluation; and outdoor microclimate control measures based on thermal comfort. The currently developing trends include the development of urban-level planning theory, which is shifting from outdoor microclimate adjustment; the development of a solution for the urban heat island effect, urban ventilation corridor, and other urban-scale climate issues; the development of an index of comfort shifting from index of outdoor labor safety; efforts to meet the demand of thermal comfort in large-scale outdoor waiting areas and cultural and recreational activity areas. The key countries and regions conducting research on these subjects include

[1] In the figure, the nodes refer to the countries or regions, the size of the nodes refers to number of papers, the connecting line between nodes refers to papers published based on research cooperation, and the thickness of the connecting line indicates the number of papers based on research cooperation. These are the same in full text.

Table 1.2.4 Major producing institutions of core papers that are cited by core papers on the engineering research focus "High-performance civil, hydraulic, and building engineering structures"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Univ Hong Kong	28	5.32%	2014.61
2	City Univ Hong Kong	23	4.37%	2014.57
3	Univ Adelaide	21	3.99%	2013.86
4	Univ Sci	18	3.42%	2013.94
5	Wuhan Univ	18	3.42%	2014.61
6	Univ Djillali Liabes Sidi Bel Abbes	15	2.85%	2015.33
7	Univ Minho	12	2.28%	2013.33
8	Bauhaus Univ Weimar	10	1.90%	2014.30
9	Natl Univ Singapore	10	1.90%	2014.60
10	Hong Kong Univ Sci & Technol	9	1.71%	2013.78

Taiwan of China, Egypt, Malaysia, Singapore, Greece, the Chinese mainland, Australia, France, Argentina, Italy, and Hong Kong of China.

(2) Thermal adaptation to climate

This includes the difference of the human comfort index between non-air-conditioned naturally ventilated buildings as well as free-running buildings and the traditional air-conditioned environment; the mechanism of thermal adaptation, such as physiological acclimatization, psychological adaptation, and behavioral adjustment; and the thermal comfort prediction model reflecting thermal adaptation. In this branch of engineering science, the key issues to be resolved include the investigation of the physiological parameters reflecting the thermal adaptation; the integration of the thermal adaptation model and the traditional thermal comfort model; the investigation of the design parameters and the control measures of the indoor environment while taking into consideration the thermal adaptation. The currently developing trends include the establishment of a worldwide database of on-site surveys regarding thermal comfort and experimental results; the study of interdisciplinary relations between medical-physiological indications and thermal comfort research; the development of a thermal adaptation dynamic evaluation model and indoor environment design theory for the thermal response of occupants to various climatic zones and economic development conditions. The key countries and regions conducting research on this subject include Australia, the Chinese mainland, Hong Kong of China, Japan, India, and the USA.

(3) Thermal adjustment to built environment

This includes the driving factors of occupant adjustment behavior in a built environment, the quantitative description methods and software simulation tools of occupant behavior, and the relation between occupant behavior and environmental parameters as well as the investigation of the influence of building energy consumption for meeting the practical requirements of scientific research and engineering applications through test data acquisition, model establishment and validation, questionnaires, and case studies. The key issues to be resolved include the development of a standardized testing method of occupant behavior in a building environment, realization of parameter descriptions and regression of the occupant behavior model, and the simulation and validation of the occupant behavior model. The currently developing trends include the development of standardized testing techniques and a quantitative description of multi-person occupancy and action; the study of environmental driving factors of occupant behavior and the interaction of multiple persons; and the development of a coupled computing platform for the occupant behavior model, indoor environment parameters, and building energy consumption. The key countries and regions conducting research on this subject include the Chinese mainland, the USA, Germany, Britain, Australia, and Canada.

"Built environment and occupant behavior" is a research hotspot. The traditional evaluation model of thermal comfort and the design theory of an indoor air-conditioned environment have been satisfactorily developed and thoroughly investigated. In recent years, research has been focused on thermal comfort in outdoor environments, dynamic thermal comfort and heat adaptation, thermal comfort in special environments (such as high altitudes, public transport, and aerospace environments), and the relation between thermal comfort and occupant behavior. These hotspots are supplementary to the development of existing thermal comfort and occupant behavior theory. With the improvement in the quality of life and the popularization of the concept of green and sustainable development, this subject will continue to maintain its status as a research hotspot in the field of built environments and will develop new connotations based on traditional theories. There were 34 core papers on the field of "Built environment and occupant behavior," with 21.06 citations per paper (Table 1.1.1). The top five countries or regions with the greatest number of published core papers were Italy, the USA, India, China (excluding Taiwan of China), Japan, and Australia. Papers published by Chinese researchers accounted for 14.71% of the total core papers (8.83% by the Chinese mainland and 5.88% by Hong Kong and Macao; Table 1.2.5), marking China as one of the main countries or regions conducting research in this field. The top five countries or regions with the highest average citations are England, Taiwan of China, Germany, Japan, and India. Chinese researchers' papers were cited 16.2 times per paper on average, up to 87% of average level (Table 1.2.5), which indicates there exists an increasing possibility for Chinese researchers in this field.

In the collaborative network of countries and regions (Figure 1.2.3), the top five countries or regions with the greatest number of core papers have a close collaborative relation.

In terms of the core-paper publishing institutions (Table 1.2.6), the top three are the University of Rome La Sapienza, Roma TRE University, and Tokyo City University. However, according to the collaboration network of the top 10 publishing institutions (Figure 1.2.4), the inter-agency cooperation is not very close.

As can be observed from Table 1.2.7 and Table 1.2.8, the top five countries or regions by number of published core papers also have a greater number of cited papers. China has the second highest number of citations (along with India and Italy), which indicates that Chinese scholars pay close attention to and track the trends of research in this field.

Based on the above statistical analysis, in "Building environment and occupant behavior" engineering research, China is currently on par with similar researches being conducted abroad. It is recommended that China continue to increase investment in such research in order to promote the relevant research to the world-leading level.

1.2.3 Mixed-pixel decomposition and spatiotemporal location big data analysis

The *Nature* special issue on "Big Data" in 2008 and the *Science* special issue on "Dealing with Data" in 2011 pointed out the arrival of the big data era. The interdisci-

Table 1.2.5 Major producing countries or regions of core papers on the engineering research focus "Built environment and occupant behavior"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Italy	10	29.41%	164	25.04%	16.40	1	0
2	USA	6	17.65%	105	16.03%	17.50	2	0
3	India	5	14.71%	90	13.74%	18.00	1	0
4	China	5	14.71%	81	12.37%	16.20	1	0
5	Japan	4	11.76%	91	13.89%	22.75	1	0
6	Australia	4	11.76%	53	8.09%	13.25	1	0
7	Taiwan of China	3	8.82%	74	11.30%	24.67	0	0
8	Germany	3	8.82%	70	10.69%	23.33	0	0
9	England	2	5.88%	61	9.31%	30.50	0	0
10	Greece	2	5.88%	33	5.04%	16.50	0	0

Table 1.2.6 Major producing institutions of core papers on the engineering research focus “Built environment and occupant behavior”

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Univ Roma La Sapienza	7	20.59%	118	18.02%	16.86	0	0
2	Univ Roma TRE	6	17.65%	114	17.40%	19.00	0	0
3	Tokyo City Univ	4	11.76%	91	13.89%	22.75	1	0
4	Univ Calif Berkeley	4	11.76%	72	10.99%	18.00	2	0
5	Univ Tokyo	3	8.82%	61	9.31%	20.33	1	0
6	Natl Formosa Univ	2	5.88%	65	9.92%	32.50	0	0
7	Univ Freiburg	2	5.88%	56	8.55%	28.00	0	0
8	Indian Inst Technol	2	5.88%	47	7.18%	23.50	0	0
9	Univ Hong Kong	2	5.88%	37	5.65%	18.50	1	0
10	Tianjin Univ	2	5.88%	33	5.04%	16.50	0	0

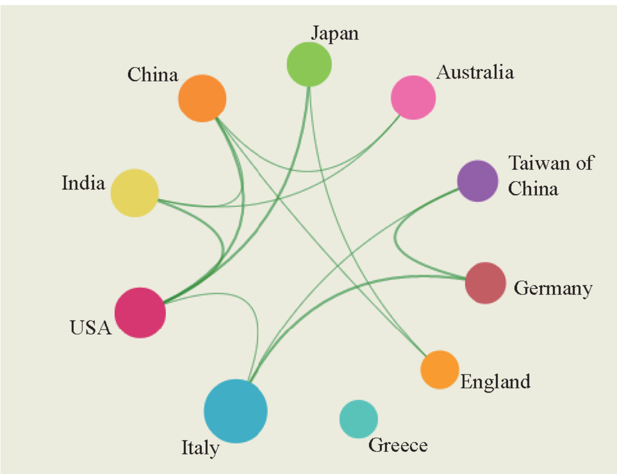

Figure 1.2.3 Collaboration network of the major producing countries or regions of core papers on the engineering research focus “Built environment and occupant behavior”

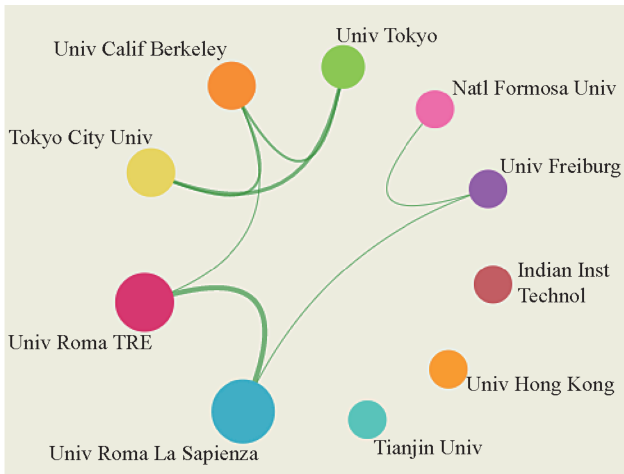

Figure 1.2.4 Collaboration network of the major producing institutions of core papers on the engineering research focus “Built environment and occupant behavior”

Table 1.2.7 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus “Built environment and occupant behavior”

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	USA	5	18.52%	2014.00
2	India	4	14.81%	2015.00
3	Italy	4	14.81%	2015.25
4	China	4	14.81%	2014.50
5	Australia	2	7.41%	2015.50
6	Japan	2	7.41%	2013.50
7	Taiwan of China	2	7.41%	2014.00
8	Argentina	1	3.70%	2015.00
9	Germany	1	3.70%	2015.00
10	Greece	1	3.70%	2014.00

Table 1.2.8 Major producing institutions of core papers that are cited by core papers on the engineering research focus “Built environment and occupant behavior”

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Univ Calif Berkeley	3	6.98%	2014.00
2	Univ Roma La Sapienza	3	6.98%	2015.33
3	Purdue Univ	2	4.65%	2014.00
4	Tianjin Univ	2	4.65%	2014.00
5	Tokyo City Univ	2	4.65%	2013.50
6	Univ Rome Tre	2	4.65%	2015.50
7	Univ Tokyo	2	4.65%	2013.50
8	Built Environm Grp	1	2.33%	2014.00
9	CEPT Univ	1	2.33%	2016.00
10	China Vanke Co Ltd	1	2.33%	2014.00

plinary fusion of surveying and mapping and information technology, is pushing the development of earth observation, perception, and cognition to multiplatform, multi-scale, multi-resolution, multi-temporal, and space-air-ground integration. The integration of various means and methods of achieving spatial data acquisition, information extraction, network management, knowledge discovery, space perception, and intelligent service location on the earth, the solid object and human activities, to provide spatial information framework, basic mathematics and information processing technique for earth science research problems, to offer reliable massive spatiotemporal information for people to fully accurate judgment and decision making.

The focus of engineering research—”Mixed-pixel decomposition and spatiotemporal location big data analysis”—presented in the retrieval results of core papers is representative of the development trend. Mixed-pixel decomposition and spatiotemporal location big data analysis include mixed-pixel decomposition, real-time precise point positioning, and spatiotemporal big data analysis. Mixed-pixel decomposition can be used to obtain high-spatial-resolution classification results from a coarse-spatial-resolution image. The real-time precise single-point positioning method makes use of a precise satellite ephemeris and precise clock product to obtain high-precision spatial location data with a pseudorange and carrier phase observations using the GNSS receiver. The aim of the spatiotemporal data acquisition method is to realize higher spatial resolution and spatial-temporal position accuracy in order to achieve the acquisition, storage, and reconciliation of high-dimensional spatial-temporal big data. Using the spatiotemporal big data analysis techniques for automatically discovering and extracting implicit, non-obvious patterns, rules, and knowledge from massive, multi-source spatiotemporal location big data, the values from the volume, velocity, and variety big data can be excavated.

(1) Decomposition of mixed pixels

Owing to the spatial resolution of the remote sensor and the complex diversity of the ground, the mixed pixels are spread widely in the remote sensing image—several different land cover types exist at a single pixel. The breakthrough sensor spatial resolution limit in mixed-pixel decomposition depicts the true nature of the mixed-pixel distribution at sub-pixel accuracy, and high-spatial-resolution image classification results can be obtained from a coarse-spatial-resolution image by scaling down in order to improve the accuracy of extraction of the image information. The key problem in mixed-pixel decomposition is to determine the land cover types and their spatial proportions. According to the interaction of various objects in the mixed pixels, the current spectral mixture model can be categorized as a linear model or nonlinear model, and the linear model is the most widely used. The development trend of mixed-pixel decomposition mainly includes the following aspects: ① research on nonlinear unmixing based on various scattering models; ② development of the endmember extraction model under spectral variability; ③ investigation into spectral unmixing combined with spatial information; ④ multi-source image fusion based on the spectral mixture model; ⑤ decomposition of mixed pixels combined with machine learning technology such as sparse decomposition and deep learning; ⑥ unmixing accuracy verification and validation problems; and ⑦ application of decomposition of mixed pixels in the fields of vegetation, water-quality survey, environmental monitoring, etc. At present, the research on pixel unmixing is more focused on the solution of the existing spectral mixture model. Because this model lacks sufficient physical basis, the testing data also have great limitations, and there thus exist some problems that are difficult to generalize in practice.

(2) Real-time precise point positioning

Precise point positioning (PPP) is an absolute position method that makes use of a precise satellite ephemeris and precise satellite clock product to obtain a precise location with a pseudorange and carrier phase observations. Compared with the multi-reference station-network real-time kinematic, real-time PPP has the advantage of a global-scale operation range, flexible station arrangement strategy, and simple operation mode. As compared with the double-difference observation data processing, the use of real-time PPP using non-difference data can improve the utilization of data. Real-time precise positioning is widely used in crustal deformation monitoring, near-real-time global positioning system (GPS) meteorology, satellite orbit determination, mobile carrier precision positioning, sea level monitoring, tsunami and earthquake monitoring, and other fields. The development of PPP mainly includes the following aspects: ① research on the estimation theory and method of developing a precise satellite clock provides real-time high-precision satellite clock products; ② study on uncalibrated phase delay and separation method for undifferenced ambiguity, fixing of the undifferenced integer ambiguity, and exploring the ambiguity fixing method at the client terminal; ③ research on PPP using multi-system integration, speeding up of the PPP of the initial time, and enhancing the reliability of the positioning results.

(3) Spatiotemporal big data analysis

Spatiotemporal big data is the result of the integration of big data and spatiotemporal data, which considers the earth as the object, and the spatiotemporal location data and activity data are acquired using a unified space-time reference. Spatiotemporal big data analysis can be used to automatically discover and extract the implicit, non-obvious patterns, rules, and knowledge from massive, multi-source spatiotemporal location big data; pay more attention to discovery rather than demonstration; put more emphasis on relationships rather than causes and effects; and focus more on prediction. The development trend of spatiotemporal big data is the study of basic theories and methods of spatiotemporal data representation, measurement, and understanding, and revealing the corresponding laws between spatiotemporal big data and real world objects, behaviors, and events.

This subject of engineering research—"Mixed-pixel decomposition and spatiotemporal location big data analysis"—has a total of 95 published core papers, and each article has been cited 40.92 times on average (Table 1.1.1). The top five countries or regions that published these core papers include China (excluding Taiwan of China), Australia, America, Germany, and the Netherlands, and the proportion of papers published by Chinese authors was 56.84% (47.37% from the Chinese mainland and 9.47% from Hong Kong and Macao; Table 1.2.9). China has the greatest proportion in the statistics and is one of the most important countries or regions in this area. The top five countries or regions producing the most core papers in this subject include Portugal, Spain, France, the USA, and Belgium, and the citation frequency of the papers published by Chinese authors is 26.3, which is approximately 60% of the average value (Table 1.2.9). This shows that Chinese scholars are increasingly focusing on this research focus. As can be observed from the cooperation network shown in Figure 1.2.5, there exists a close cooperative relation between the top five countries or regions.

According to the statistics of institutions publishing these core papers (Table 1.2.10), the top five institutions include the Wuhan University, Chinese Academy of Sciences, Curtin University, University of Extremadura, and Delft University of Technology. As can be observed from the cooperation network of the top 10 paper publishing institutions shown in Figure 1.2.6, there exists a closer cooperation between foreign institutions.

According to the statistics of the cited papers (Table 1.2.11 and Table 1.2.12), the top five countries or regions that published the most core papers on this subject include China, Australia, the Netherlands, Germany, and England, and the proportion of Chinese core papers cited was 45.59% (the Chinese institutions among the top five

Table 1.2.9 Major producing countries or regions of core papers on the engineering research focus “Mixed-pixel decomposition and spatiotemporal location big data analysis”

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	China	54	56.84%	1420	41.36%	26.30	9	0
2	Australia	17	17.89%	476	13.87%	28.00	3	1
3	USA	11	11.58%	708	20.62%	64.36	0	0
4	Germany	11	11.58%	385	11.21%	35.00	1	0
5	The Netherlands	11	11.58%	266	7.75%	24.18	0	0
6	Spain	8	8.42%	1010	29.42%	126.25	1	0
7	France	7	7.37%	748	21.79%	106.86	3	0
8	Belgium	7	7.37%	315	9.18%	45.00	1	0
9	Portugal	6	6.32%	900	26.22%	150.00	1	0
10	England	6	6.32%	150	4.37%	25.00	0	0

Table 1.2.10 Major producing institutions of core papers on the engineering research focus “Mixed-pixel decomposition and spatiotemporal location big data analysis”

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Consistently cited papers	Patent-cited publications
1	Wuhan Univ	24	25.26%	618	18.00%	25.75	4	0
2	Chinese Acad Sci	13	13.68%	264	7.69%	20.31	1	0
3	Curtin Univ	11	11.58%	283	8.24%	25.73	1	1
4	Univ Extremadura	8	8.42%	1010	29.42%	126.25	1	0
5	Delft Univ Technol	8	8.42%	169	4.92%	21.13	0	0
6	Hong Kong Polytech Univ	7	7.37%	128	3.73%	18.29	1	0
7	Inst Telecomunicacoes	5	5.26%	881	25.66%	176.20	1	0
8	Inst Super Tecn	5	5.26%	850	24.76%	170.00	1	0
9	Curtin Univ Technol	5	5.26%	169	4.92%	33.80	1	1
10	Univ Toulouse	4	4.21%	661	19.25%	165.25	2	0

institutions included Wuhan University, Chinese Academy of Sciences, and Hong Kong Polytechnic University), which shows that Chinese scholars paid relatively close attention to the dynamics of this subject.

Based on the presented statistics, in the case of this engineering research subject—”Mixed-pixel decomposition and spatiotemporal location big data analysis”—Chinese scholars are keeping abreast of their foreign counterparts and gradually developing into world leaders in this research subject area. We suggest that the Chinese government should continue supplying funds to this research area in order to accelerate its development to the world-leading level.

2 Engineering development hotspots and engineering development focus

2.1 Development trends of engineering development hotspots

The top 10 engineering development hotspots in the fields of civil, hydraulic engineering and architecture are listed in Table 2.1.1, and they include “Green city and green building,” “New materials for civil engineering,” “Intelligent building construction,” “Intelligent urban transportation systems,” “Digital urban planning,” “Seismic and vibration control,” “Monitoring, inspection, and informatization of geotechnical and underground

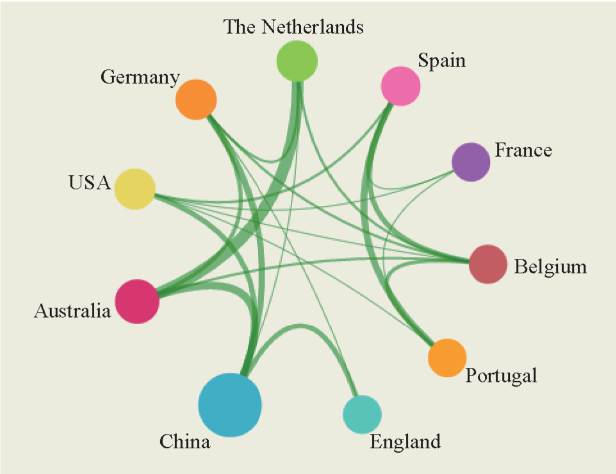

Figure 1.2.5 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Mixed-pixel decomposition and spatiotemporal location big data analysis"

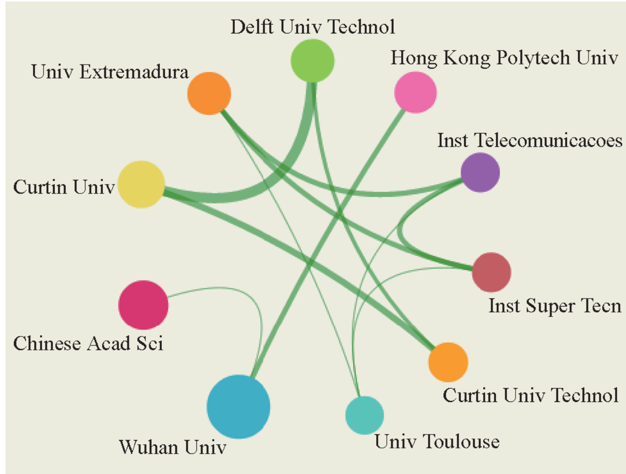

Figure 1.2.6 Collaboration network of the major producing institutions of core papers on the engineering research focus "Mixed-pixel decomposition and spatiotemporal location big data analysis"

Table 1.2.11 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Mixed-pixel decomposition and spatiotemporal location big data analysis"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	China	31	45.59%	2014.10
2	Australia	11	16.18%	2014.64
3	The Netherlands	7	10.29%	2015.14
4	Germany	7	10.29%	2014.00
5	England	3	4.41%	2014.67
6	USA	2	2.94%	2013.50
7	Belgium	1	1.47%	2015.00
8	Canada	1	1.47%	2013.00
9	Czech	1	1.47%	2014.00
10	Italy	1	1.47%	2016.00

engineering," "Global positioning navigation," "Bridge and steel structure industrialization," and "Urban rainwater flood control and utilization." The patents involved in the hotspots from 2011 to 2016 are shown in Table 2.1.2.

(1) Green city and green building

Green city and green building is the future trend of new urbanization and one of the prerequisites for realizing sustainable development. It requires the conservation of energy and resources, improvement of energy efficiency, and utilization of renewable energy while maintaining a healthy and comfortable living environment during the whole life cycle of the urban built environment. Green city and green building involves a number of research fields and is cross-disciplinary in nature. Based on the state of the art of building science and technologies, the research on this subject should explore the potential of passive energy saving strategies followed by improvement in system energy efficiency and investigations into renewable energy potential. Some of the innovative research topics include the assessment of the microclimate and energy performance of high-density urban morphology, climate-responsive and low-energy building design and optimization, smart grid and energy internet in high-density urban environments, development of passive techniques

Table 1.2.12 Major producing institutions of core papers that are cited by core papers on the engineering research focus "Mixed-pixel decomposition and spatiotemporal location big data analysis"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Wuhan Univ	15	15.63%	2014.33
2	Chinese Acad Sci	8	8.33%	2013.88
3	Curtin Univ	7	7.29%	2014.86
4	Delft Univ Technol	6	6.25%	2015.17
5	Hong Kong Polytech Univ	6	6.25%	2014.33
6	CSIRO	3	3.13%	2014.33
7	Curtin Univ Technol	3	3.13%	2014.00
8	Deutsch Zentrum Luft & Raumfahrt	3	3.13%	2013.67
9	E China Normal Univ	3	3.13%	2014.33
10	German Res Ctr Geosci GFZ	3	3.13%	2014.00

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

No.	Engineering development hotspots	Published patents	Citation frequency	Average citation frequency	Mean year
1	Green city and green building	889	5 907	6.64	2012.82
2	New materials for civil engineering	848	10 274	12.12	2012.39
3	Intelligent building construction	334	1 797	5.38	2012.91
4	Intelligent urban transportation systems	609	5 531	9.08	2012.52
5	Digital urban planning	165	1 625	9.85	2012.08
6	Seismic and vibration control	444	5 230	11.78	2012.30
7	Monitoring, inspection, and informatization of geotechnical and underground engineering	537	6 907	12.86	2012.39
8	Global positioning navigation	731	11 470	15.69	2012.50
9	Bridge and steel structure industrialization	316	2 533	8.02	2013.04
10	Urban rainwater flood control and utilization	192	310	1.61	2014.96

in challenging high-density urban environments, adaptive human comfort and behavior modeling, and integrated environment quality assessment framework. During the period from 2011 to 2016, 889 patents have been published in relation to this development hotspot, the total number of citations is 5907, and the average number of citations per patent is 6.64.

(2) New materials for civil engineering

With the increasing environmental awareness and demand for the higher performance of building materials, in contrast to traditional building materials (such as lime, cement, asphalt, concrete, reinforced concrete, and steel structures), new materials for civil engineering tend to be sustainable (such as recycled material, materials procured from waste, and energy-saving and environment-friendly materials), be functional (such as sensing or protection sound, light and magnet, etc.), and possess superior performance properties (such as lightweight, high strength, and high durability). The new materials for civil engineering mainly include green cement, sustainable cement, industrial waste cement, geopolymers (alkali-activated materials), carbon-fiber reinforcements, polymer-based materials, and ceramic materials. The key to the development and research of new materials is the long-term collaborative working of various components (for example, the coordinative working of new and old concrete, the reinforced components and the initial system, and the various components in a new type of system), low-energy-

Table 2.1.2 Annual number of core patents belonging to each of the top 10 engineering development hotspots in civil, hydraulic engineering and architecture

No.	Engineering development hotspots	2011	2012	2013	2014	2015	2016
1	Green city and green building	225	215	171	115	100	63
2	New materials for civil engineering	274	213	176	139	32	14
3	Intelligent building construction	75	78	55	70	40	16
4	Intelligent urban transportation systems	166	158	135	112	31	7
5	Digital urban planning	68	41	35	17	4	0
6	Seismic and vibration control	155	115	86	68	12	8
7	Monitoring, inspection, and informatization of geotechnical and underground engineering	153	139	150	79	11	5
8	Global positioning navigation	211	205	147	102	41	25
9	Bridge and steel structure industrialization	56	69	73	54	53	11
10	Urban rainwater flood control and utilization	0	0	0	37	125	30

consumption preparation methods, high-performance technology, and functionalized technology. The effective methods for realizing the aforementioned technologies are to explore the theory of designing long life-span civil engineering materials, to develop key materials suitable for civil construction (such as multifunctional mineral admixtures and chemical admixtures), and to explore high-efficiency and low-energy-consumption preparation methods for new materials. The new materials mentioned above can be used in several areas in civil engineering (such as housing construction, bridge tunnels, and port terminals). They have been in use and will have a wider usage in the future. From 2011 to 2016, the number of patent publications on this hotspot was 848, the total number of citations was 10 274, and the average citation frequency for each patent was 12.12.

(3) Intelligent building construction

As an important part of the national strategy "Made in China 2025," intelligent building construction is the necessary approach for transforming the technological revolution in the construction industry into the industrial revolution. Using building information modeling (BIM) and robotic architecture fabrication as the core and BIM-based intelligent building construction as the platform, architectural design, construction, operation, and management were integrated into the whole engineering information process. Using the combination of robotic architecture construction technology and BIM, the upgradation of the automation and information technology in construction processes will be achieved, which will promote accurate analysis and precise construction in the entire life cycle of architecture, thus encouraging the architecture industry to transform from labor-intensive to technology-, knowledge-, and management-intensive. BIM combines the Internet of Things and cloud computing technology, effectively integrates the various stages of the construction period data, processes, and resources as well as completely outlines the project, which supports intelligent building construction as a main platform and model. As the key to intelligent building construction, robotic architecture construction technology applies advanced manufacturing technology from the fields of aerospace and automotive industry into the architecture industry based on the research on "digital building equipment integration systems" and "digital construction of innovative technology." Robotic architecture construction technology contributes to solving the problems of extensive, low-efficiency manufacturing and backward technical and management methods in industry production systems. Therefore, it could be used to realize a highly flexible, customized building product for the services and production mode. Intelligent building construction plays a key role in the advancement of the construction industry and is an inevitable choice for achieving green, high-efficiency, and customized development of the architecture industry. From 2011 to 2016, the total number of patents published on this hotspot was 334, the number of citations was 1797, and the average citation frequency was 5.38.

(4) Intelligent urban transportation systems

Urban intelligent transportation systems (ITS) are defined as the real-time, precise, and highly effective comprehensive urban transportation management systems that are based on fundamental traffic flow theory and make use of advanced and modern information, communication, sensing, control, and computer technologies. The main purposes of an ITS include reducing the stochastic of traffic flow, improving the utilization and availability factors and safety level of existing transport infrastructures, and reducing the energy consumption of the whole system and the pollutant discharge. Traditional ITSs are developed around traffic signal control systems and regional guiding systems, and these two key technologies remain the hotspot of ITS research today while the integration of control and guiding has already been observed. Intelligent vehicle/autonomous driving and intelligent transportation infrastructure technologies are the emerging hot issues for modern engineering development in this field. Among these, vehicle infrastructure cooperative systems are becoming the focus of engineering development. From 2011 to 2016, there have been 609 published patents with a total number of citations of 5531 and an average citation per patent of 9.08.

(5) Digital urban planning

Digital urban planning (DUP) focuses on computer technology, multimedia technology, and large-scale storage technology as the basis and makes use of a broadband network as a link. Through the use of remote sensing, GPS, geographic information systems, telemetry, simulation and virtual reality technology, and multi-resolution, multi-time, and three-dimensional descriptions, DUP makes use of information technology to analyze the city's past, present, and future content in a digital virtual implementation over a network. Based on the virtual reality implementation, the digital planning analysis and the diagnosis and evaluation are carried out, the multi-program comparison is performed, and the public participation is taken into consideration such that the planning and decisions are made more rationally. DUP includes large data (large-scale storage), telemetry, virtual simulation, intelligent city design, smart city design, flow and operational simulation, maintaining and promoting digital change in urban planning and design and management with multidimensional sensing systems in the city, as well as government and corporate data and other large data based on the web. From 2011 to 2016, the total number of patents published on this hotspot was 165, the number of citations was 1625, and the average citation frequency was 9.85.

(6) Seismic and vibration control

Seismic and vibration control technology prevents or mitigates structural vibrations induced by earthquake excitations. Traditional seismic resisting structures dissipate energy by means of inelastic deformations of the main load resistance members. This mechanism can cause significant deformation, damage, and even collapse of the structure, and therefore compromises the structural safety level. In contrast, seismic and vibration control technology, which minimizes the damage level or controls the location of the damage, can lower the risk of collapse of structures in the case of strong earthquakes and, as a result, reduce life and economic losses. Seismic control technology often involves data collection and interventions from the perspectives of the seismic source, seismic wave propagation, and structural performance; and vibration control technology aims to decrease the input energy to the structures. The main research trends and focuses include ① dampers with various energy dissipation mechanisms, ② energy-absorbing devices, ③ seismic isolators, and ④ self-centering technology. From 2011 to 2016, 444 patents have been published, and the total number of citations of these patents was 5230. The average number of citations per patent was 11.78.

(7) Monitoring, inspection, and informatization of geotechnical and underground engineering

Based on site investigation, monitoring, and inspection, the informatization of geotechnical and underground engineering is to digitalizes, networks, intelligentializes and visualizes geotechnical and site data with spatial and temporal variability. It is one of the crucial technologies for implementing intelligent refined construction and for the operation of geotechnical and underground engineering. The obstacle faced with this important technology is the complex geotechnical environment with high spatial variability and the strong nonlinear interaction behavior between geomaterials and underground structures. The solution to this obstacle lies in the drilling techniques such as deep-ground and deep-water drilling used in peculiar environments, application of geophysical technology, micro-seismic monitoring/inspection, application of optical fiber and laser technology, signal processing, and informatization of massive data. It can be applied for site evaluation, construction monitoring, and heath inspection of geotechnical and underground engineering such as slopes, foundations, excavations, and tunnels in the design, construction, and operation stages. Current development is focused on quantitatively characterizing complex geotechnical environments and acquiring real-time information of underground structures using rapid and accurate methods. Much research will be focused on big data integration systems catering to intelligent geotechnical and underground engineering and the virtual reality technique in the future. From 2011 to 2016, the number of patents published in this field was 537, while the total number of citations was 6907 and the average number of citations was 12.86.

(8) Global positioning navigation

Global positioning navigation refers to the GNSS and the global all-weather continuous high-precision navigation positioning service. In 1989, the USA successfully launched the first GPS satellite, and by the end of 2016, there were a total of 108 navigation satellites in the sky over the earth. The global satellite navigation field comprises a pattern of coexistence of multiple systems including GPS, GLONASS, BeiDou, and GALILEO; the application of multiple systems improves the navigation positioning precision and real-time computing speed greatly. With the development of technology, the availability, continuity, reliability, positioning accuracy, and computation efficiency of global navigation and positioning will be continuously improved. Differential positioning technology, precise positioning technology, GNSS radio occultation technology, GNSS-R technology, integrated navigation technology, and all types of mobile terminal embedded application technologies are key technologies for GPS at present and in the future. The successful application of GNSS in geodesy, engineering surveying, aerial photogrammetry, vehicle navigation and control, crustal movement monitoring, engineering deformation monitoring, resource exploration, earth dynamics, and other disciplines brought a profound technological revolution to the field of surveying and mapping. From 2011 to 2016, the number of published patents on this hotspot was 731, the number of citations was 11 470, and the average number of citations per patent was 15.69.

(9) Bridge and steel structure industrialization

A bridge is a structure that spans over obstacles. Industrialization means the standardization of the design, production, construction, and management. The key technologies for bridge and steel structure industrialization include the design of large-span structure systems with flexible supports and transverse and longitudinal links, the fabrication of a high-performance steel bridge structure, bolt welding and riveting assembly and composite structure connection, fatigue-resistant vibration isolation and energy dissipation ancillary facilities, and bridge construction monitoring and control techniques. In bridge engineering, especially super-large-span bridge structure engineering, the steel structure or the steel-structure-based composite structure system is widely adopted. The industrialized manufacturing of a steel bridge includes the prefabrication of steel beams, columns, and trusses using standard steel and steel plates; the assembly of the components to form the mechanical performance optimization system of the large-span flexible structure; the connection using bolts and welding to form the structure; the monitoring and control of the bridge state in construction and in operation using optical and electrical equipment; the installation of bearings, dampers, wind barriers, and other ancillary facilities for structure disaster prevention and safety. The components of the construction include the main cable and cable net flexible support system and anchor; high-performance main truss, braces, corrugated webs, and orthotropic bridge deck precast; high-strength bolts, screws, and shear stud connections; repairable bearings, dampers, and the asphalt deck pavement; and bridge construction and operational monitoring based on BIM. From 2011 to 2016, the number of published patents on this hotspot was 316, the number of citations was 2533, and the average number of citations per patent was 8.02.

(10) Urban rainwater flood control and utilization

With the rapid development of urbanization and social economy, urban rainwater and flood issues have become increasingly critical and are mainly manifested in the increase in flood disaster risk, the loss of enormous rainwater resources, the serious urban river pollution, and the degradation of the urban ecological environment. The concept of urban rainwater flood-control and utilization has been put forward to deal with the urban rainwater and flood issues. Some measures pertaining to infiltration, storage, stagnation, purification, utilization, and drainage are taken to manage urban rainwater and runoff, thus effectively controlling urban rainwater floods and non-point source pollution at the source, halfway, or to the end. The source-control technologies include roof greening, low-elevation greenbelts, permeable pavements, rainwater gardens, grassed swales, and rain barrels. The halfway-control technologies include sewage wells, infiltration pipes and channels, and rainwater filters. The end-control technologies include rain pools, rainwater wetlands, buffer zones, ecological embankments, and biological floating islands. These technologies have been used for water resource utilization, flood control and disaster mitigation, and ecological environment protection.

In recent years, China has experienced a rapid development in urban rainwater flood-control and utilization. Some cities have attempted to build a system for rainwater flood management and to construct several demonstration projects, but the overall levels and degrees of application are still low. The transformation of rainwater and sewage diversion of the urban pipeline network is slow, the capacity of rainwater utilization facilities is too low, and there is a lack of waterlogging prevention facilities for rainstorms with intensities that exceed the drainage capacity of other existing facilities, rainwater collection facilities, underground space data, and important softwares. Thus, it is difficult to prevent urban rainwater floods in a comprehensive manner.

It is therefore necessary to speed up the construction of large-capacity drainage systems, the development of multi-scale water quantity-quality coupled simulation software and digital rainwater resources management platforms, and the study on the classification and regulation of rainwater flood resources in the future. During the period from 2011 to 2016, the number of published patents was 192, the number of citations was 310, and the average citation frequency was 1.61 for the patents concerning urban rainwater flood-control and utilization.

2.2 Understanding of engineering development focus

2.2.1 Green city and green building

Green city and green building is the future of the new type of urbanization and one of the prerequisites for realizing sustainable development. It comprises the conservation of energy and resources, improvement of energy efficiency, and utilizing of renewable energy while maintaining a healthy and comfortable living environment during the whole life cycle of the urban built environment. Green city and green building involves a number of research fields and is cross-disciplinary in nature. Based on the state of the art of building science and technologies, the research should explore the potential of passive energy-saving strategies followed by improving the system energy efficiency, and discovering the renewable energy potential. Some of the innovative research topics on this subject include the assessment of microclimate and energy performance of high-density urban morphology, climate-responsive and low-energy building design and optimization, smart grid and energy internet in high-density urban environment, innovation of passive techniques in challenging high-density urban environments, adaptive human comfort and behavior modeling, and integrated environment quality assessment framework. During the period from 2011 to 2016, 889 patents have been published. The total number of citations was 5907, and the average number of citations per patent was 6.64.

(1) Assessment of microclimate and energy performance of high-density urban morphology

Facing the challenge of increasing population density and deteriorating physical environment, contemporary urban design requires the development of climate-responsive planning and design strategies in order to lower building cooling-energy consumption, improve thermal comfort, and thus create dynamic and user-friendly urban spaces. The existing research covers the urban microclimate and building energy load. The key question in urban microclimate research is what are the critical urban morphological parameters and what are the relationships between them and the microclimate parameters in dense and complex urban areas? The studies compute and map the key morphological parameters in digital urban spaces using urban morphometric and geographical information system (GIS) spatial analyst extension tools. Empirical measurements can facilitate the establishment of empirical models that can be used to explain the relationship between the morphology and microclimate parameters. A comprehensive assessment framework that can be a useful method and tool in climate-responsive urban design will be developed.

(2) Climate-responsive and low-energy building design and optimization

During the rapid globalization process, green building design innovation inspired from regional and vernacular architecture has gained increasing attention in research. Understanding the climate and its impact on the built environment is the prerequisite for successful green building development. On one hand, one should learn from traditional architecture owing to its ecological wisdom, while on the other hand, recent advances in digital technology should be applied in the development of the methodology of green building design and research in order to manipulate urban and building morphology for optimized environmental performance.

(3) Smart grid and energy internet in high-density urban environment

Massive renewable energy production based on a distributed-energy system, smart grid, and internet connection is considered to be the future of urban energy networks. The triple-E (energy, environment, and economy) system based on the GIS platform will be the pillar of green energy internet in future cities. Renewable energy sources including solar and geothermal energy will be increasingly included in urban distributed-energy systems through building-incorporated renewable-energy-system integration.

(4) Innovation of passive techniques in challenging high-density urban environments

Passive design strategies such as natural ventilation, solar heating, and daylighting are being challenged in today's high-rise high-density urban environment. Owing to mutual shading, air stagnation, and air quality degradation caused by high-density urban development, the effectiveness of the above-mentioned strategies should be re-evaluated. Re-evaluating the potential of utilizing natural energy to heat, cool, and ventilate indoor and outdoor urban spaces under a complicated and often compromised urban boundary condition requires intense research.

(5) Adaptive human comfort and behavior modeling and assessment

Adaptive comfort modeling is an important research topic in passive urban and building design. New indices including PET and UTCI have been developed to assess human thermal comfort in urban spaces, and new empirical models are being formulated based on field survey data from around the globe and especially emerging economies in sub-tropical climates. Building-occupant behavior modeling is receiving increasing attention in building-energy modeling research as this is an important but long-been-neglected factor in the determination of building energy consumption. It is important to investigate the occupant behavior while integrating qualitative approaches and data-driven quantitative approaches and employing appropriate tools to guide the design and operation of a sustainable, comfortable, and healthy urban environment.

(6) Integrated environmental quality assessment framework

Under the circumstances of climate change and increasing occurrences of extreme weather events, rapid urban development should take into consideration the consequences and impact of urbanization on the urban physical environment and carefully evaluate the measures for integrating various design intervention strategies while aiming at energy efficiency, thermal comfort, and air quality improvement. Research should be focused on investigating the effective combinations of passive and active energy-saving strategies in realizing a green city and green building and creating a synthetic-environmental quality control and assessment framework.

During the period from 2011 to 2016, 889 patents that were related to the “Green city and green building” engineering development focus were published. The total number of citations was 5907, and the average number of citations per patent was 6.64 (Table 2.1.1). The top five countries or regions in patent publication were China (excluding Taiwan of China), the USA, Korea, France, and Japan (Table 2.1.1). Among these, patent applications from Chinese institutes or individuals comprised 40.94% of the total publications, and the average number of citations per patent was 5.35, indicating that China is a key player in this field of research (Table 2.1.1). According to the corporation network of major countries or regions in the “Green city and green building” engineering focus (Figure 2.2.1), the USA is the central hub of the international corporation. The top five institutes in the publishing of core patents are Beijing University of Technology, China Construction Eighth Engineering Bureau Co., Ltd., Certain Teed Corp., Vermont Slate & Copper Services Inc., and Tianjin University. Judging from the collaboration network of major institutes in the “Green city and green building” engineering focus (Figure 2.2.2), the corporation is generally not very active.

Table 2.2.1 Major producing countries or regions of core patents on the engineering development focus "Green city and green building"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	China	364	40.94%	1946	32.94%	5.35
2	USA	329	37.01%	3084	52.21%	9.37
3	Korea	46	5.17%	228	3.86%	4.96
4	France	28	3.15%	126	2.13%	4.50
5	Japan	26	2.92%	122	2.07%	4.69
6	Germany	23	2.59%	87	1.47%	3.78
7	Canada	21	2.36%	84	1.42%	4.00
8	UK	13	1.46%	62	1.05%	4.77
9	Belgium	9	1.01%	55	0.93%	6.11
10	Australia	7	0.79%	23	0.39%	3.29

Table 2.2.2 Major producing institutions of core patents on the engineering development focus "Green city and green building"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	UYBT	23	2.59%	235	3.98%	10.22
2	CSCE	15	1.69%	76	1.29%	5.07
3	CERT	14	1.57%	140	2.37%	10.00
4	Vermont Slate & Copper Services Inc.	14	1.57%	189	3.20%	13.50
5	UTIJ	11	1.24%	57	0.96%	5.18
6	OWEN	10	1.12%	97	1.64%	9.70
7	COMP	9	1.01%	30	0.51%	3.33
8	UYQI	9	1.01%	53	0.90%	5.89
9	Huahui Eng Design Group Co., Ltd.	8	0.90%	49	0.83%	6.13
10	Jiangsu Huning Steel Mechanism Co., Ltd.	8	0.90%	34	0.58%	4.25

Note: The institute is represented by its patent holder code if it is listed in the normalized database, otherwise it is represented by its formal title. The top 10 institutes in patent publication are Beijing University of Technology, China Construction Eighth Engineering Bureau Co., Ltd., Certain Teed Corp., Vermont Slate & Copper Services Inc., Tianjin University, Owens-Corning Intellectual Capital LLC., Compagnie de Saint-Gobain (Saint-Gobain Glass, France), Tsinghua University, Huahui Engineering Design Group Co., Ltd., and Jiangsu Huning Steel Mechanism Co., Ltd. A patent holder code may represent a number of institutes and only the major one is listed here.

2.2.2 Intelligent urban transportation systems

The development of urban intelligent transportation systems (ITSs) began between the 1950s and 1960s. The early systems only included road transportation and mainly about sporadic product development on automatic vehicle control and electronic route guidance. During the next 30 to 40 years, several countries and regions invested much capital and manpower in this field, thus resulting in the rapid development of traditional ITSs, especially traffic signal control systems and regional guiding systems. Traditional ITSs are aimed at aiding authorities in intelligentizing transportation management through key technologies such as traffic guidance, regional traffic control, and congestion management. The integration technology of control and guidance will be the future direction of traditional ITSs.

(1) Intelligent vehicle/autonomous driving and intelligent transportation infrastructure technology

As the emerging development hotspot in this field, vehicles and infrastructure are becoming the intelligent elements in transportation systems owing to advanced technologies of electronic sensing, communication and smart materials, etc. The development of technologies in this field has entered the phase of scaled on-site testing.

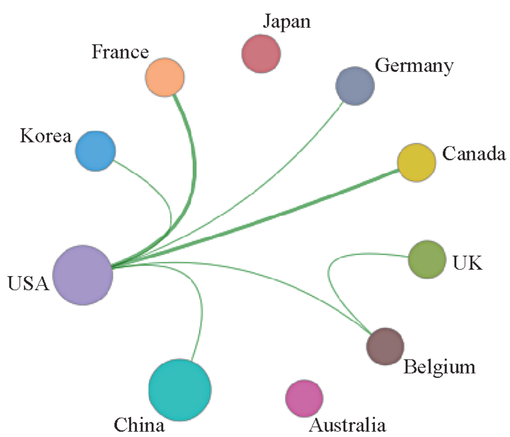

Figure 2.2.1 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Green city and green building"

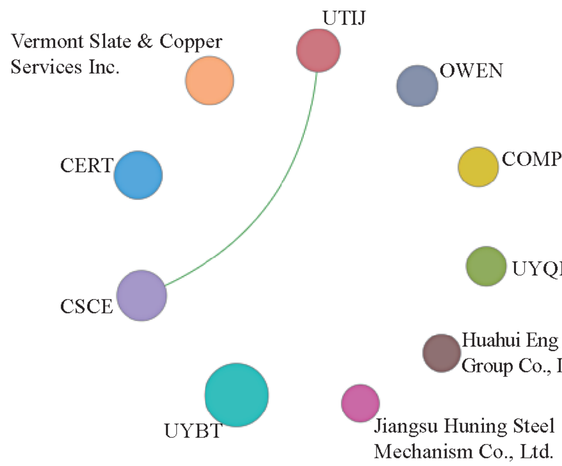

Figure 2.2.2 Collaboration network of the major producing institutions of core patents on the engineering development focus "Green city and green building"

The development of intelligent vehicle/autonomous driving and intelligent transportation infrastructure technology has brought a huge challenge to traditional ITSs. In recent years, intelligent vehicle/autonomous driving and intelligent transportation infrastructure technology have comprised the cutting edge of ITSs. Since its official proposal in 2011, the research and development of intelligent vehicle/autonomous driving have been continuously promoted by automobile enterprises, internet enterprises, etc. and have become dominant in ITS development strategies in several countries. The content involves important technologies such as automatic environment perception, vehicle-to-vehicle communication (V2V), and vehicle-to-infrastructure (V2I) communication.

(2) Vehicle-to-infrastructure (V2I) communication technology and system

Following the trends of emerging technologies, V2I systems are becoming a hotspot in ITSs. V2I technology integrated traditional ITS technology and modern intelligent vehicle/autonomous driving/intelligent infrastructure technology and utilized them in the whole process of urban transportation data collection, smart analysis, and scientific decision-making with the main purpose of building a brand-new comprehensive urban transportation system that could both fit and lead emerging technologies. V2I technologies utilize and integrate the advantages of both emerging technologies and traditional ITS technologies to achieve cooperation between vehicles and infrastructure, thus building a new comprehensive urban transportation system. V2I, which includes the technology of the Internet of Things and cloud computing, is a hot issue in ITS research.

(3) Technologies of intelligent environmental perception of transportation infrastructure, damage repair, energy harvesting, and pollution absorption

With the rapid development of both traditional and emerging ITS technologies, the trend of the integration of the two technologies became apparent; V2I technology was invented, and it grew into a major direction of ITS in several countries. Therefore, the technologies of intelligent perception, damage repair, energy harvesting, and pollution absorption were inspired. The number of published core patents in the engineering development of ITSs was 609 with an average number of citations of 9.08 (Table 2.1.1). The top five countries or regions in the publishing of core patents on this subject are China (excluding Taiwan of China), the USA, Japan, Germany, and Korea. Among these patents, 55.34% were obtained by institutions or persons from China, which makes China one of the main researching countries in this area. The average number of citations from China was 8.19 (Table 2.2.3). It can be observed that the USA is at the core position in the collaboration network between countries or regions (Figure 2.2.3). From Table 2.2.4, it can be observed that the institutions ranking among the top five are Yamanashi Toyota Jidosha KK from Japan, Southeast University from China, Dalian Shuangdi Innovative Technology Inc., INRIX Inc. from the USA, and Robert Bosch GmbH from Germany.

Table 2.2.3 Major producing countries or regions of core patents on the engineering development focus “Intelligent urban transportation systems”

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	China	337	55.34%	2759	49.88%	8.19
2	USA	122	20.03%	1806	32.65%	14.80
3	Japan	55	9.03%	354	6.40%	6.44
4	Germany	34	5.58%	190	3.44%	5.59
5	Korea	21	3.45%	125	2.26%	5.95
6	Canada	6	0.99%	56	1.01%	9.33
7	UK	5	0.82%	28	0.51%	5.60
8	Austria	4	0.66%	37	0.67%	9.25
9	The Netherlands	4	0.66%	24	0.43%	6.00
10	Taiwan of China	4	0.66%	63	1.14%	15.75

Table 2.2.4 Major producing institutions of core patents on the engineering development focus “Intelligent urban transportation systems”

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	TOYT	19	3.12%	117	2.12%	6.16
2	UYSE	18	2.96%	172	3.11%	9.56
3	Dalian Shuangdi Innovative Technology	15	2.46%	72	1.30%	4.80
4	Inrix Inc.	9	1.48%	275	4.97%	30.56
5	BOSC	8	1.31%	35	0.63%	4.38
6	AMTT	6	0.99%	51	0.92%	8.50
7	Beijing CenNavi Technologies Co., Ltd.	5	0.82%	45	0.81%	9.00
8	GOOG	5	0.82%	44	0.80%	8.80
9	HOND	5	0.82%	42	0.76%	8.40
10	IBMC	5	0.82%	68	1.23%	13.60

Note: Top 10 ranking institutions in publishing patents are Yamanashi Toyota Jidosha KK, Southeast University, Dalian Shuangdi Innovative Technology, INRIX Inc., Robert Bosch GmbH, AT&T Intellectual Property I LP (AT&T Mobility II LLC), Beijing CenNavi Technologies Co., Ltd., Google Inc., Honda Motor Co., Ltd., and International Business Machines Corp.

2.2.3 Seismic and vibration control

The main research trends and focuses related to the seismic and vibration control technology include ① dampers with various energy-dissipation mechanisms, ② energy absorbing devices, ③ seismic isolators, and ④ self-centering technology.

(1) Energy dissipation dampers

Energy dissipation dampers are devices that facilitate the reduction of vibration responses of structures in the case of earthquakes. Depending on the energy-dissipation mechanism, dampers can be categorized into two types, namely, displacement-dependent dampers and velocity-dependent dampers. Displacement-dependent dampers include metal dampers and friction dampers. Metal dampers use the satisfactory plastic deformation abilities of low-carbon steel under cyclic loading to dissipate energy, and friction dampers dissipate energy by means of friction caused by the relevant displacement of two blocks that are firmly in contact with each other. In contrast, velocity-dependent dampers mainly include fluid viscous dampers (walls) and viscoelastic dampers. These dampers often allow an increase in the damping ratio with little influence on the initial stiffness of the structure, but it should be noted that some of the damping materials may provide a certain level of stiffness. Fluid viscous dampers (walls) dissipate energy by taking advantage of the viscose

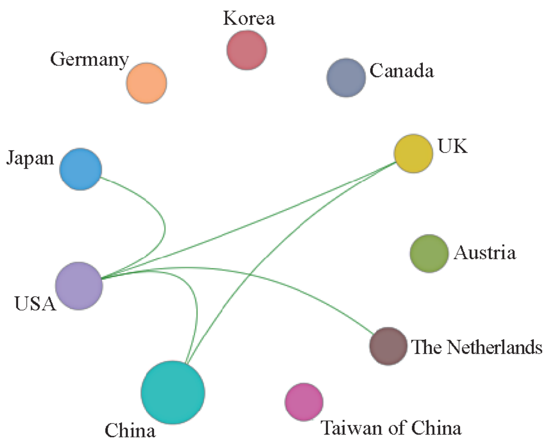

Figure 2.2.3 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Intelligent urban transportation systems"

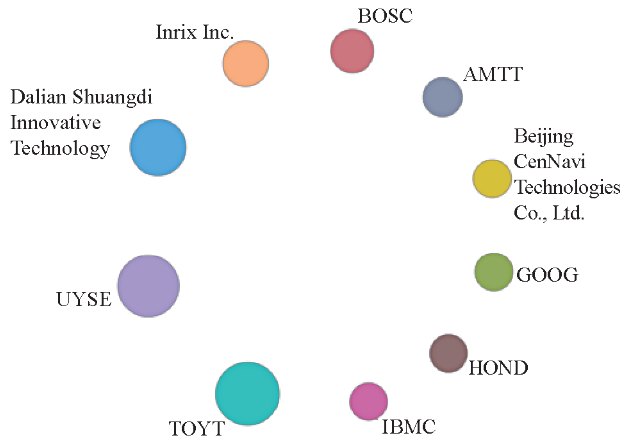

Figure 2.2.4 Collaboration network of the major producing institutions of core patents on the engineering development focus "Intelligent urban transportation systems"

property of the fluid. Viscoelastic dampers comprise viscoelastic materials and restraining plates, and these components are attached using a vulcanization process. The viscoelastic material dissipates energy by means of large shear deformations. The current research interests and future research trends of energy dissipation dampers include the principle of high-durability dampers, fatigue responses, special-purpose dampers, and smart materials and dampers.

(2) Energy absorbing devices

Energy absorbing devices aim to reallocate the energy that is transferred into the structure by incorporating a substructure that absorbs dissipated energy, thus reducing the vibration response of the main structure. When the main structure vibrates under external excitations, the relative motion of the substructure tends to apply an inertia force onto the main structure, and if the inertia force is properly controlled, the vibration response of the main structure can be effectively reduced. Common energy absorbing devices include tuned mass dampers (TMDs), tuned liquid dampers (TLDs), and suspension mass pendulum dampers (SMPDs). A TMD comprises a spring system, damping system, and mass block, and when its natural period matches that of the building, an optimal controlling effectiveness can be achieved. A TLD comprises a rigid container that is filled with liquid and is mounted on a structure to realize passive control. An SMPD consists of a pendulum system that swings and provides inertia forces to control the structural vibration. The current research interests and future research trends of energy absorbing devices include innovative energy absorbing mechanisms and active-passive hybrid energy absorbing technology.

(3) Seismic isolation technology

Seismic isolation technology is aimed at establishing an isolation layer between the superstructure and the foundation, such that the superstructure is separated from the ground, and thus, the energy input is significantly reduced. Currently, most of the seismic isolation technologies focus on horizontal seismic actions, where the lateral stiffness of the isolation layer is significantly smaller than that of the superstructure. Thus, the natural period of the structures equipped with the seismic isolation devices can be prolonged, and the induced acceleration is effectively reduced. Seismic isolation devices commonly include rubber bearings, roller bearings, and friction bearings. Rubber bearings employ a number of rubber layers and steel shim plates placed in alternation, and the appropriate anti-corrosion measures are often taken. Generally, rubber bearings are supposed to have sufficient stiffness in order to resist wind loads, and under extreme conditions, exhibit degraded stiffness that helps increase the natural period of the structure. Roller bearings employ a series of rollers between the superstructure and the foundation in order to enable smooth slippage and thus an increase in the natural period of the structure. Similarly, friction bearings use the friction that is generated between the plates mounted at the superstructure and the foundation. Static friction can provide sufficient lateral stiffness against wind loads, and sliding friction can promote energy dissipation. The commonly used friction materials include sliding layer coating and silt layer coating. The current research interests and future research trends of seismic isolation technology include durability design, degradation behavior under corrosive environments, smart materials and base isolators, and multi-function base isolators.

(4) Self-centering structures

Self-centering structures are innovative structural systems that exhibit limited residual deformation after earthquakes. Self-centering technology has become one of the most attractive strategies for structural resilience design. From the perspective of the self-centering driving mechanism, two approaches have been widely investigated, namely, the post-tension (PT) approach and shape memory alloy (SMA) approach. The PT approach uses post-tensioned reinforcement or cables to enable a self-centering tendency, in which case, energy dissipative devices are often used in parallel. The SMA approach uses the superelastic property that enables a recoverable strain of up to 10%, and thus, hysteresis loops are induced, which are inherent damping characteristics of the SMA material. From an implementation point of view, self-centering members can be categorized into self-centering connections, self-centering bracings, self-centering column feet, and self-centering shear walls. Both the PT and SMA approaches are suited to the first three member types, whereas the last type often requires the PT approach. The current research interests and future research trends of self-centering technology include self-centering construction technology, self-centering maintenance strategy, fiber-reinforced post-tension bars, a low-cost SMA approach, and hybrid self-centering technology.

In relation to the engineering development focus "Seismic and vibration control," 444 core patents have been published, and the average number of citations per patent is 11.78 (Table 2.1.1). The top five countries or regions in publishing patents on this subject are China (excluding Taiwan of China), the USA, Germany, Japan, and France. China is the most active country in this area of research, and Chinese organizations or individuals contributed to 49.55% of the total patents, with an average number of citations of 11.23 per patent (Table 2.2.5). From Figure 2.2.5, it can be observed that extensive collaborations exist among various countries. From the perspective of the number of patents shown in Table 2.2.6, the top five institutions are CGG Services SA, Baker Hughes Corp., Schlumberger Canada Ltd., Westerngeco LLC., and Beijing University of Technology. According to the network information shown in Figure 2.2.6, there are limited collaborations between various organizations.

Table 2.2.5 Major producing countries or regions of core patents on the engineering development focus "Seismic and vibration control"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	China	220	49.55%	2471	47.25%	11.23
2	USA	129	29.05%	2000	38.24%	15.50
3	Germany	23	5.18%	205	3.92%	8.91
4	Japan	22	4.95%	212	4.05%	9.64
5	France	21	4.73%	129	2.47%	6.14
6	UK	14	3.15%	115	2.20%	8.21
7	Canada	9	2.03%	37	0.71%	4.11
8	The Netherlands	9	2.03%	77	1.47%	8.56
9	Norway	7	1.58%	53	1.01%	7.57
10	Korea	6	1.35%	45	0.86%	7.50

Table 2.2.6 Major producing institutions of core patents on the engineering development focus "Seismic and vibration control"

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	CGGV	16	3.60%	105	2.01%	6.56
2	BAKO	14	3.15%	278	5.32%	19.86
3	SLMB	14	3.15%	178	3.40%	12.71
4	WGSC	11	2.48%	168	3.21%	15.27
5	UYBT	10	2.25%	125	2.39%	12.50
6	CNPC	9	2.03%	86	1.64%	9.56
7	ESSO	9	2.03%	159	3.04%	17.67
8	HALL	8	1.80%	235	4.49%	29.38
9	China Univ Petroleum	8	1.80%	92	1.76%	11.50
10	PGSG	7	1.58%	66	1.26%	9.43

Note: The top 10 organizations in patent publishing are CGG Services SA, Baker Hughes Corp., Schlumberger Canada Ltd., GECO Technology B.V., Beijing University of Technology, China National Petroleum Corp., Exxonmobil Upstream Research Company (Exxonmobil Research & Engineering Co.), Halliburton Energy Services Inc., China University of Petroleum, and PGS Geophysical AS.

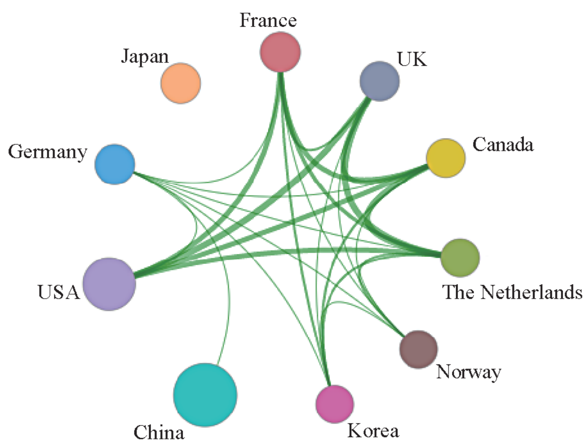

Figure 2.2.5 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Seismic and vibration control"

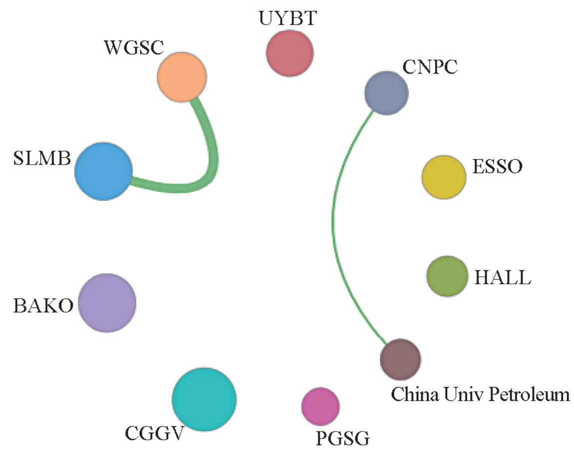

Figure 2.2.6 Collaboration network of the major producing institutions of core patents on the engineering development focus "Seismic and vibration control"

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