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Mapping the Knowledge Structure and Research Evolution of Urban Rail Transit Safety Studies

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ABSTRACT To better grasp the status quo of urban rail transit (URT) safety research and explore the knowledge base and hotspot trends, 1249 URT safety research papers from 1983-2018 were collected from the SCIE and SSCI databases of the WOS search platform as data samples. Co-occurrence analysis, burst analysis of keywords and co-citation analysis were adopted to analyze the current research situation of URT safety in the world by means of information visualization. The study found that risk analysis in the construction/operational phase, methods for predicting ground movements, and cause analyses of tunnel deformation and settlement are the knowledge bases in the field of URT safety research. Tunneling and Underground Space Technology, Safety Science, Atmospheric Environment, Lancet and Transportation Research Record are the core journals in the field. At present, the basic theory and research system of URT safety have been basically completed, but the research directions are too concentrated, and the frontier branches are too few. The research themes of URT safety were roughly grouped into three core paths: the ''health risk'' path, the ''risk analysis – safety management'' path and the ''tunnel displacement/deformation'' path. In the process of research and evolution, the research paths are refined step-by-step, and the research directions are transformed from macro to micro. The emergency evacuation of personnel in subway stations, the effects of particulate matter in subway air on human health and the use of computer technology for engineering optimization are the current frontiers of URT safety. URT safety research also tends toward risk analysis in the operational phase.

INDEX TERMS Mapping knowledge domains, evolutionary path, knowledge base, safety, urban rail transit.

I. INTRODUCTION

As the world's population increases, a large number of people are gradually flocking to cities, causing traffic congestion in large- and medium-sized cities. Urban rail transit (URT) is widely used in large- and medium-sized cities to ease traffic pressure because of its large capacity, fast speed, low energy consumption and low pollution. Due to the complexity and unpredictability of the underground, the closure of the carriage and the large passenger flow, there are risks in the construction stage and the operation stage of the URT. Once an accident occurs, it can easily cause mass casualties, major economic losses and social impacts. For example, in 2004, the collapse of the open tunnel of the Singapore Metro Loop caused four deaths. In 2008, 21 people were killed and 24 injured when the second foundation pit collapsed in the north part of Xianghu Station of line 1 of the Hangzhou subway, resulting in a direct economic loss of 49.61 million yuan. In 1995, 13 people were killed and 6,300 injured in the sarin gas attack in the Tokyo subway. In 2012, a train derailed in the 11th district of the Buenos Aires transportation hub, causing 49 deaths and more than 600 injuries. These accidents indicate that URT safety issues cannot be ignored and should attract social and scholarly attention.

In the field of safety engineering, ''safety'' and ''security'' sometimes use the same term, but to mean different things (e.g. ''incident'', an event with minor consequences in safety, and an infringement or breach in security). What's more, ''risk'' and ''safety'' occur most frequently. ''Risk'' is a quantity, which is the product of the probability of an accident occurring multiplied the severity of the accident loss. ''Safety'' is relative. it indicates a state in which the risk

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is within an acceptable range [1]. In view of the risks in the two stages of construction and operation, scholars have put forward risk analysis methods based on different principles. In the construction stage, many scholars have put forward decision-making methods based on construction safety risk analysis [2], [3]. To prevent accidents, Zhou *et al.* [4] proposed a four-dimensional risk monitoring system, and Ding *et al.* [5] designed a safety warning system. In addition, Kim *et al.* [6] designed the safety impact assessment method for South Korea's open-air underground building projects. For the operation stage, Ying *et al.* [7] and Zhang *et al.* [8] determined the precursors of accidents by analyzing accidents. Zhao *et al.* [9] established a model based on system dynamics. Some scholars used vulnerability as the entry point for studies [10]–[12]. And besides, some scholars have made relevant reviews of some different focuses in the field of URT safety, most of the research directions focus on the technical aspects. For instance, Gershon *et al.* reviewed the potential health and safety hazards related to subways [13] and the types of subway deaths in New York between 1990 and 2003 [14]. Ratnayake *et al.* [15] and Krysinska and De [16] carried out literature reviews involving epidemiological studies and subway suicide studies. There also exist reviews on the application of visualization technology in construction safety management [17], air quality inside the subway [18], subway emergency decision-making [19] and policy and management mode of URT safety in developed countries [20]. At present, there are few discussions of risk analysis methods, and there is a lack of reviews on the research fields of URT safety based on mapping knowledge domains. The reason for this lacking may be that the scope of this field is too broad, and it is therefore difficult to sort the analysis, extract the latest progress and make recommendations. At the same time, URT involves systems in which there are many risk factors and mutually influential relationships. Therefore, it is essential to illuminate the knowledge structure, research hotspots and evolution in the field of URT through describing the already achieved literature in order to shed light for the subsequent researches. To better understand the status quo and trends of URT safety research at home and abroad, we use the mapping knowledge domains method to analyze the research situation of the whole field from the perspective of bibliometrics and identify the knowledge base and hot literature of URT safety research. This study sorts the existing research theory system, explores the research frontiers and development trends, and analyzes the URT safety research theme evolution.

Bibliometrics describes the cross-science of the quantitative analysis of all knowledge carriers by means of mathematics and statistics [21]. It is a useful and effective tool to evaluate the academic productions and research evolutions in a specific research domain [22], and can visually display the development path and composition relationship of this domain. The temporal-spatial distribution characteristics of publication outputs could be obtained from related countries/regions, disciplinary categories, institutes, and journals through statistical analysis of extracted literature information. Research evolutions and trends are commonly identified by simply analyzing the most frequently used keywords, which have been used in a variety of research fields, including geopolymer application research [23], sustainable development research [24], road safety research [25] and human fatigue assessment [26]. Furthermore, co-citation analysis is an effective method to present the knowledge structures and knowledge base in a research field by analyzing the highly cited literature [27]. More recently, the co-occurrence analysis, clustering analysis and substantives in title is proved to be a more effective and comprehensive bibliometric method, which has been successfully applied to reveal the research hotspots and frontiers in the research field of risk assessment [28], ammonia oxidation [29], medical big-data research [30], infrared detection technology [31] and emergency evacuation [32].

In this paper, the bibliometrics softwares (CiteSpace and VOSviewer) were used to sort the temporal-spatial distribution, core literature analysis, author contribution analysis, co-citation analysis and keyword co-occurrence analysis of the literature on URT safety research in the SCI-E and SSCI search platforms of the Web of Science core database over nearly 35 years to explore the basic rules of research in this field, grasp the research frontiers and hot issues, and clarify the evolution path and development trends of URT safety research.

II. DATA AND METHODS

A. DATA SOURCE

SCI-E and SSCI of the Web of Science (WOS) core database were selected as the target databases to search for source literature. The retrieval formula was set as TS = (''urban rail transit ''OR metro OR'' underground railway ''OR subway) AND TS = (safety OR security OR risk). The retrieval time was from 1983 to 2018 (as of 2018-12-31), and 1249 retrieval records were finally obtained.

TABLE 1. Types of retrieved documents.

Type of Document	Frequency	Proportion/%
Article	1209	96.80
Proceedings Paper	50	4.00
Review	27	2.16
Meeting Abstract	7	0.56
Book Review	3	0.24
Editorial Material	3	0.24

There were 6 literature types among the 1249 references. Table 1 lists the 6 literature types, along with the corresponding numbers and proportions. Among the results, there were 1209 articles, accounting for 96.8% of the total literature, which was the most frequent literature type. Proceedings papers ranked second, with 50 papers (4%). The other four document types are listed separately as follows:

"Review" (27), "Meeting Abstract" (7), "Editorial Material" (3), and "Book Review" (3).

B. METHODS AND TOOLS

The co-occurrence analysis, clustering analysis, co-citation analysis and betweenness centrality calculation of the 1249 exported literatures were carried out using the visualization software VOSviewer and CiteSpace through bibliometric and visualization analysis methods. The theoretical basis is as follows [33], [34]:

The construction of the co-occurrence matrix is the basis of cluster analysis. By counting the times that any two keywords appear in the same article, n keywords can be used to construct an $n \times n$ matrix S:

$$S = \left(s_{ij}\right) \tag{1}$$

where $S_{ij} \geqslant 0$ is a similarity vector, $S_{ij} = S_{ji}, i, j \in \{1, 2, \ldots, n\}$

$$S_{ij} = \frac{c_{ij}}{w_i w_j} \tag{2}$$

Refer to (2), S_{ij} is the similarity vector of i and j, C_{ij} represents the co-occurrence times of i and j, and W_i and W_j represent the appearance times of i and j, respectively. The distance between clusters is determined by (3):

$$E(X; S) = \sum\nolimits_{i<j} S_{ij} \left\| X_i - X_j \right\|^2 \tag{3}$$

Refer to (3), $\| \cdot \|$ is the Euclidean norm, and the distance between similar nodes is maintained by (4) :

$$\sum\nolimits_{i<j} \left\| X_i - X_j \right\| = 1 \tag{4}$$

Centrality in the Citepace menu means betweenness centrality, which is an index of the importance of the measured nodes in the network, called centrality for short. The calculation formula is as follows:

$$BC_i = \sum\nolimits_{s \neq i \neq t} \frac{n_{st}^i}{g_{st}} \tag{5}$$

In (5) g_{st} is the shortest path number from node s to node t, and n^i_{st} is the shortest path number through node i in the shortest path from node s to g_{st} of node t.

The Links is mainly used to calculate the correlation strength of the network nodes. The software uses the Cosine method to calculate the formula as follows:

$$\mathrm{Cos}\,ine(c_{ij}, s_i, s_j) = \frac{c_{ij}}{\sqrt{s_i s_j}} \tag{6}$$

In equation (6), c_{ij} is the co-occurrence number of s_j and s_i, s_i is the frequency at which i appears, and s_j is the frequency at which j appears. The algorithm proposed by Kleinberg has been used for burst detection in Citespace software [35].

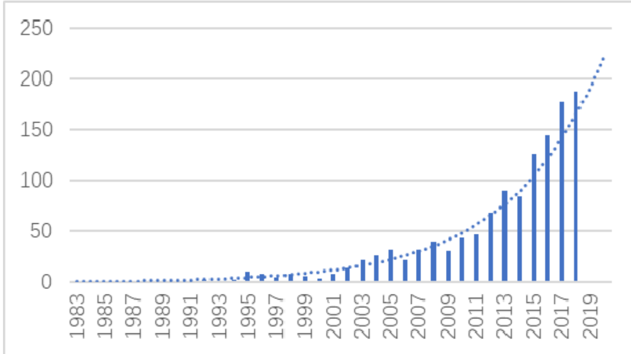

FIGURE 1. Publication growth trend around the world.

III. RESULTS AND DISCUSSION

A. TEMPORAL DISTRIBUTION MAP OF THE LITERATURE

1) TEMPORAL DISTRIBUTION OF WORLD LITERATURE

A total of 1249 papers related to research on URT safety was retrieved from the Web of Science core collection database. From 1983 to 2018, the annual documentary distribution and polynomial trend lines are shown in Fig. 1. It can be seen from the figure that the development of world URT safety research can be roughly divided into three stages.

Initial phase (1983-2002): From 1983 to 2002, the amount of annual literature in this field was small, with the highest number of only 14 articles published within a year. This shows that the relevant research was just starting in this stage. In this stage, the themes of the articles were mainly subway suicide and terrorist attacks (sarin gas). The earliest articles appeared in 1983, published by Gebbles: DR's Design for Safety Today - The Metro and Ward, D's Metro to Get Dunlop Safety Types. In 1984, an anonymous author published Fire Life Safety in the Subway in the journal Ashrae Journal-American Society of Heating Refrigerating and Air-Conditioning Engineers. It can be seen that the focus in the early stage was on safety design and fire safety.

Stable development stage (2003-2011): During the period from 2003 to 2011, the number of documents per year increased step-by-step. Compared with the previous stage, there was a quantitative leap, and the distribution of annual literatures was more regular. It can be considered that the URT safety research field was initially formed.

Rapid development stage (2012-2018): In 2012, the number of documents jumped to 69 and increased at an average rate of 20 per year. This shows that scholars paid more and more attention to the safety of URT, and relevant studies in this field were increasing and entering the stage of rapid development.

2) TEMPORAL DISTRIBUTION OF ACTIVE NATIONAL LITERATURE

By analyzing the time distribution of the literature from four countries, China, the United States, Canada and the United Kingdom, the respective development rules were compared (see Fig. 2). The United States started earliest, followed by

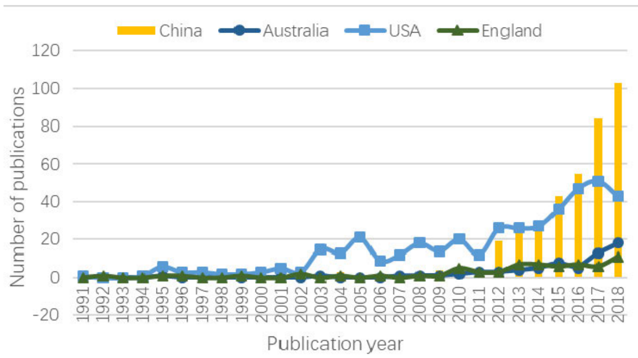

FIGURE 2. Publication growth trends of 4 countries (China, USA, England, and Australia.

Britain and Australia, and China started latest. A study by the American Johanning E [36] in 1991 showed that the back disease and hearing and gastrointestinal problems of subway train drivers are related to the environment of being exposed to whole-body vibrations and defective ergonomic conditions. In 1992, British scholars O'Donnell I. and Farmer RDT. studied the characteristics of subway suicide and proposed reducing the number of suicides in the subway [37]. The UK and Australia have similar development trends. Although the United States was the world leader from 1991 to 2013, China surpassed the United States in 2013 to become the most active country in the field.

TABLE 2. Top 10 most productive countries in URT safety studies, 1983-2018.

Rank	Country	Region	Quantity	Percentage	ACI	H-index	Total link strength
1	USA	North America	413	33.07%	16.01	44	168
2	China	East Asia	391	31.31%	6.90	28	174
3	Canada	North America	103	8.25%	13.67	21	42
4	Australia	Oceania	67	5.36%	7.15	15	59
5	England	Western Europe	62	4.96%	12.42	14	43
6	South Korea	East Asia	56	4.48%	8.32	13	11
7	Philippines	Southeast Asia	47	3.76%	11.79	12	36
8	France	Western Europe	39	3.12%	10.13	12	23
9	Germany	Central Europe	31	2.48%	11.10	11	19
10	Japan	East Asia	31	2.48%	11.16	10	19

*ACI: Average citations per item

B. SPATIAL DISTRIBUTION MAP OF THE LITERATURE

1) COUNTRY/REGION DISTRIBUTION

According to the analysis by VOSviewer, 61 countries (regions) have published papers related to the study of URT safety, from which the top 10 countries in terms of the total number of published papers were extracted. The details of each country are shown in Table 2, and the number of publications and H index are plotted in the world map (see Fig. 3). Quantity represents the quantity of publications of a country, percentage represents the proportion among the total literature, ACI represents the average publication quality of a country, the H-index represents the influence of the country's papers, and the total link strength represents the frequency of cooperation between the country and other countries. Most of the articles originated in developed countries, mainly North America, Oceania and Europe. China is the developing country with the highest number of publications, which shows that China attaches no less importance to URT safety than do developed countries. Among the top 10 countries in terms of publications, the top three countries in terms of the ACI are the United States, Canada and the United Kingdom, and the United States and Canada are also in the forefront of the field, indicating that the research results of these two countries are more mature. While China ranks high in the world in terms of the number of publications, the ACI is only 6.9, showing that the country has very big development potential. The H-index of each country is directly proportional to the number of publications, indicating that the disciplinary influence of each country has a certain relationship with the number of publications. From the perspective of the regional distribution, the overall level of articles in Europe and the United States is relatively high.

The analysis by VOSviewer shows that in total, 61 countries are studying the safety of URT, excluding the countries with less than 3 articles, and the cooperation network was drawn to include the remaining 40 countries' information (see Fig. 4). Each node in the figure represents a country, and the size of the node is proportional to the number of documents produced by the country, while the thickness of the connections between the nodes represents the strength of cooperation between the countries. As seen from Fig. 4, the United States is the most active in the research field of URT safety, followed by China, Canada, Australia and the United Kingdom. China (174) and the United States (168) have the highest total link strengths, as well as frequent cooperation with other countries.

2) DISCIPLINARY DISTRIBUTION OF LITERATURE

The disciplinary distribution of research literature helps in understanding the disciplinary structure of the research field. CiteSpace was used to count the literature in this field, distributed among 111 different disciplines. The statistics of the top 20 disciplines within the literature are shown in Table 3. Quantity shows the frequency of the occurrence of the discipline. Centrality is the betweenness centrality, and if the centrality of a node is not less than 0.1, the node is considered to be a key hub (turning point) in the network. Percent represents the proportion of the literature in the discipline. As shown in Table 3, Public, Environmental & Health (0.62), Engineering (0.56) and Environmental Science & Ecology (0.19) are the disciplines with the highest centralities, and they are the key hubs in the research field. In addition, the Engineering category ranked first,

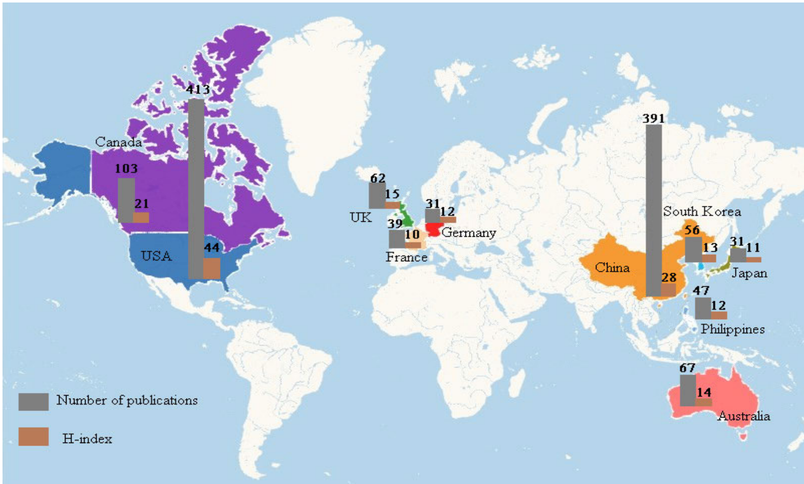

FIGURE 3. **Production and H-index of the top 10 countries.**

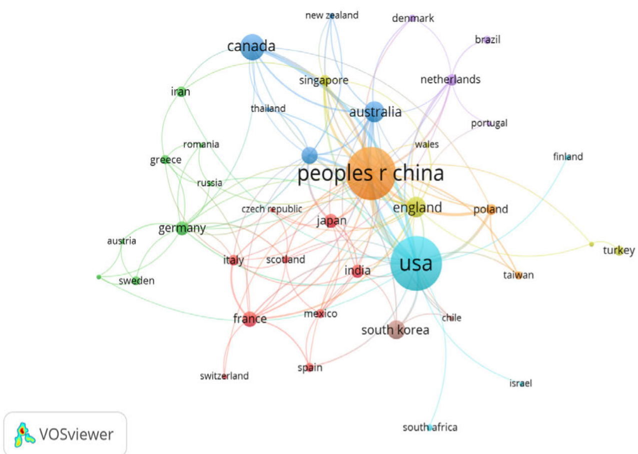

FIGURE 4. **Cooperation between countries in URT safety studies.**

with 452 and a high proportion of 36.19%. Engineering and Civil ranked next, totaling 235 (18.82%). Public, Environmental & Health (14.33%), Transportation (10.41%) and Construction & Building Technology (9.85%) followed. The distribution of the disciplines reflects ‘‘Engineering’’, ‘‘Civil Engineering’’, ‘‘Construction & Building Technology’’ and ‘‘Engineering, Industrial’’ as the basis of URT. ‘‘Public, Environmental & Occupational Health’’, ‘‘Environmental Sciences & Ecology’’ and ‘‘Environmental Sciences’’ embody the ecological environment and occupational health problems in the process of the construction and operation of URT. ‘‘Computer Science’’ has become an important tool in the construction and operation of URT. ‘‘Geosciences, Multidisciplinary’’, ‘‘Geology’’ and ‘‘Engineering, Geological’’ embody the close relationship between URT and geology. Based on the definition of the field, URT safety research is the application of safety engineering in URT safety. First, Safety Engineering is a new interdisciplinary subject. Second, URT involves geology, underground space, and construction engineering in the construction stage. In the operational stage, it also involves operations management, along with electrical and other aspects. In short, URT is a multidisciplinary and cross-disciplinary field.

TABLE 3. **The top 20 subject categories in URT safety studies, 1983-2018.**

Rank	Quantity	Centrality	WOS Categories	Percent
1	452	0.56	Engineering	36.19%
2	235	0.02	Engineering, Civil	18.82%
3	179	0.62	Public, Environmental & Occupational Health	14.33%
4	130	0.13	Transportation	10.41%
5	123	0	Construction & Building Technology	9.85%
6	122	0.19	Environmental Sciences & Ecology	9.77%
7	99	0.08	Environmental Sciences	7.93%
8	95	0.02	Transportation Science & Technology	7.61%
9	61	0.09	Computer Science	4.88%
10	58	0.01	Engineering, Industrial	4.64%
11	56	0.02	Geosciences, Multidisciplinary	4.48%
12	56	0.02	Geology	4.48%
13	54	0.07	Business & Economics	4.32%
14	45	0.02	Operations Research & Management Science	3.60%
15	40	0.07	Engineering, Geological	3.20%
16	39	0.07	Engineering, Mechanical	3.12%
17	39	0.07	General & Internal Medicine	3.12%
18	36	0.01	Science & Technology - Other Topics	2.88%
19	35	0.01	Water Resources	2.80%
20	34	0	Medicine, General & Internal	2.72%

TABLE 4. Top 20 institutions in URT safety studies, 1983-2018.

Rank	Institution	Country	Quantity	Total link strength	STC	ACI
1	Beijing Jiaotong Univ	China	60	11	199	3.32
2	Huazhong Univ Sci & Technol	China	55	52	576	10.47
3	Tongji Univ	China	48	18	447	9.31
4	Univ Maryland	USA	33	44	555	16.82
5	Shanghai Jiao Tong Univ	China	22	5	278	12.64
6	Southeast Univ	China	21	11	160	7.62
7	Simon Fraser Univ	Canada	17	22	122	7.18
8	Polish Acad Sci	Poland	15	33	272	18.13
9	Georgia Inst Technol	USA	15	17	207	13.80
10	Hong Kong Polytech Univ	Hong Kong (China)	14	14	269	19.21
11	Tsinghua Univ	China	13	6	50	3.85
12	Cent S Univ	China	13	4	24	1.85
13	Zhejiang Univ	China	12	6	88	7.33
14	Univ Michigan	USA	12	5	86	7.17
15	Univ Alberta	Canada	12	14	65	5.42
16	Delft Univ Technol	Netherlands	10	2	115	11.50
17	China Univ Min & Technol	China	10	4	43	4.30
18	Natl Univ Singapore	Singapore	9	10	141	15.67
19	Ohio State Univ	USA	9	5	106	11.78
20	Ateneo Manila Univ	Philippines	9	1	88	9.78

*STC: Sum of the Times Cited

3) INSTITUTE DISTRIBUTION OF LITERATURE

According to the data of the WOS core database, a total of 1363 organizations published literature, manually, after deleting some records that were not related to the topic, and the remaining 37 institutions had a cooperative relationship. Detailed information on the 20 institutions that published the most relevant papers is shown in Table 4. Among the top 20 research institutions, only the Polish Academy of Sciences is a national scientific research institution, indicating that universities are the main force of research in the field of URT safety. Nine of the institutions are from East Asia, nine are from North America, one is from Europe. China and the United States are the major contributors to the field. Among the 20 organizations, the highest-numbered organizations are Beijing Jiaotong University (60), Huazhong University of Science and Technology (55) and Tongji University (48). The institutions with the highest ACI were Hong Kong Polytechnic University (Hong Kong, China, 19.21), the Polish Academy of Sciences (Poland, 18.13) and the University of Maryland (USA, 16.82). Although Beijing Jiaotong University published the most papers, its ACI was only 3.32.

Beijing Jiaotong University has a wide range of research directions. Zhang *et al.* [38] proposed an accurate and efficient automatic crack detection and classification method for subway tunnel safety monitoring. Fang *et al.* [39] focused on studying subway construction, controlling the process of ground subsidence and existing building structures nearby and proposed risk management methods. Wei *et al.* [40] are committed to the study of track safety detection. Huazhong University of Science and Technology is mainly aimed at risk research during URT construction. Zhang *et al.* proposed the probability decision method for subway construction safety risk analysis in a complex project environment [2] and the system decision support method for safety risk analysis based on a fuzzy Bayesian network under the uncertainty of tunnel construction [41]. Zhou *et al.* [4] presented the use of four-dimensional visualization technology for the security management of subway construction. Ding and Zhou [42] presented a network-based URT construction safety risk early-warning system. Hong Kong Polytechnic University studied the safety in subway construction. For example, Ding *et al.* [5] proposed a real-time warning system based on the Internet of Things, and Chao *et al.* [43] developed a knowledge dynamics-integrated map as a blueprint for developing an effective safety knowledge management system. The Polish Academy of Sciences and the University of Maryland have cooperated with Huazhong University of Science and Technology to study the risks involved in URT construction using multidisciplinary principles and methods.

VOSviewer was used to filter institutions with a starting amount of not less than 7 to obtain 50 institutional records, manually delete unrelated institutional records, and generate a cooperative network map of the main research institutions (see Fig. 5). The sizes of the nodes in the figure represent the amount of literature published, and the widths of the connections between nodes represents the strength of the cooperation.

It is known that the University of Maryland has the most frequent cooperation with the Polish Academy of Sciences and Huazhong University of Science and Technology. VOSviewer's cluster analysis divides 28 institutions into 7 clusters. Red clusters (Beijing Jiaotong University, Shanghai Jiaotong University and Tongji University, etc.) occupy the dominant position, producing the largest number of papers and having extensive research directions. In inter-agency cooperation, purple clustering (Huazhong University of Science and Technology, University of Maryland and Polish Academy of Sciences, etc.) dominates this research field, and its research direction is risk analysis in the building construction stage. In this cluster, the total link strength of the nodes is the highest, followed by that of the yellow cluster headed by the University of British Columbia.

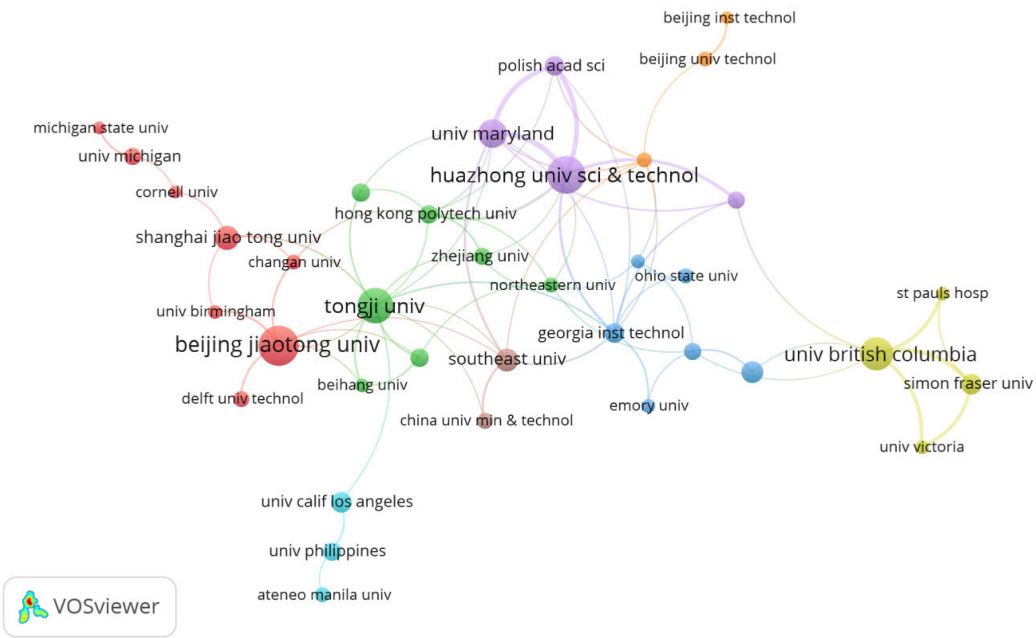

FIGURE 5. Cooperation among institutions in URT safety studies.

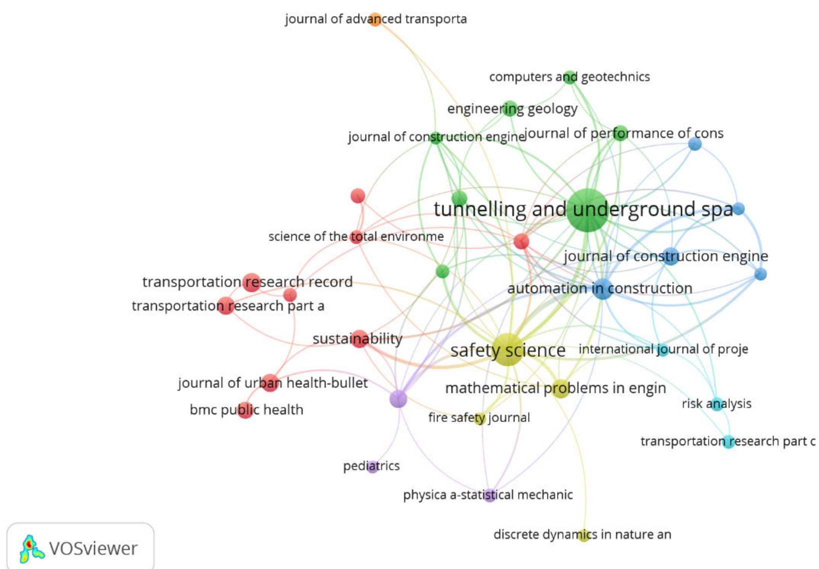

FIGURE 6. Cooperation among main research journals in URT safety studies.

4) JOURNAL DISTRIBUTION

Academic journals are important information carriers for the exchange, dissemination and inheritance of scientific results [25]. Through the analysis of the distribution of major source journals in the research field by VOSviewer, 33 records were obtained of journals with no less than 6 publications. The main journal network map was exported (see Fig. 6). In the network diagram, each node represents a journal, and the size of the node is proportional to its published volume. The numbers of publications available for Tunneling and Underground Space Technology, Safety Science and Automation in Construction rank in the top three. Among the seven clusters, green and red are dominant, while the largest nodes in the green cluster are Tunnel and Underground Space Technologies, and the node sizes in the red clustering are relatively average. Green clustering is mainly based on Geological Engineering and Geotechnical Engineering and on using other disciplines to study a certain field, such as Tunnelling and Underground Space Technology, Engineering Geology, and Computers and Geotechnics.

TABLE 5. Top 15 journals in URT safety studies, 1983-2018.

Rank	Journal Title	Quan-tity	ACI	Citation Index	Impact Factor
1	Tunnelling and Underground Space Technology	58	10.53	SCIE	2.418
2	Safety Science	33	14.61	SCIE	2.835
3	Automation in Construction	15	13.67	SCIE	4.032
4	Transportation Research Record	12	6.00	SCIE	0.695
5	Mathematical Problems in Engineering	12	1.42	SCIE	1.145
6	Sustainability	11	3.91	SCIE	2.075
7	Journal of Construction Engineering and Management	11	2.82	SCIE	2.201
8	Journal of Urban Health-bulletin of the New York Academy of Medicine	10	22.50	SCIE	1.738
9	Transportation Research Part a-policy and Practice	10	17.70	SCIE	3.026
10	Accident Analysis and Prevention	10	11.60	SSCI	2.584
11	BMC Public Health	9	10.22	SCIE	2.42
12	Engineering Geology	8	18.75	SCIE	3.1
13	Building and Environment	8	10.88	SCIE	4.539
14	Journal of Performance of Constructed Facilities	8	7.63	SCIE	1.197
15	International Journal of Environmental Research and Public Health	8	1.4	SCIE	2.145

*ACI: Average Citations per Item

Red clustering is complemented by journals in transportation and public health research, while yellow clustering is mainly composed of journals for safety engineering research.

Table 5 lists the 15 journals with the highest numbers of publications and their corresponding quantity, ACI, and impact factor. In Table 5, the Journal of Urban Health-bulletin of the New York Academy of Medicine, Engineering Geology, and Transportation Research Part a-policy ranked in the top three in terms of the ACI, with impact factors of 1.738, 3.1, and 3.026, respectively, indicating that the ACI and the academic level of related articles in journals are not directly related to the journal's impact factor. At the same time, only Accident Analysis and Prevention is included in SSCI, and most URT safety research belongs to the areas of natural science and engineering technology. Throughout the themes of the 15 journals, the URT safety field is not only inseparable from tunnels and underground spaces but is also closely related to construction, automation, the environment and health.

C. HIGHLY CITED LITERATURE ANALYSIS

To understand the most influential literature in the field of URT safety, the first 15 most cited documents were selected, as shown in Table 6. Table 6. lists the title, author, journal, year, average citations per year (ACY), institute number (IN), and country number (CN) of the literature. If co-authored literature exceeds three authors, only the first author is displayed.

Papers by Seaton et al. are the most cited, with an ACI of 9.13, and include detecting the dust concentrations in different subway stations and carriages to assess the risk of dust in the London subway air to human health [44]. Papers by Ripanucci et al. ranked second, assessing the hazards of exposure to dust in tunnels and platforms on the Rome metro lines A and B and finding that the dust concentrations in tunnels and platforms were three times higher than that at the entrance to the subway station [45]. Ranked third are papers by Choi *et al.* [46], which introduce the risk assessment method for underground construction projects and develop formal procedures and related tools for use in assessing and managing the risks of underground construction projects. Ranked next, Huabei Liu and Erxiang Song used the fully coupled dynamics finite element program DYNA Swandyne-II to study the dynamic behavior of metro stations in saturated sandy deposits and found that the increase of the burial depth improved the safety of underground structures against seismic damage [47]. Papers written by Shi *et al.* [48] were ranked fifth in terms of citations, using computer simulations to study the evacuation behaviors, time flows and safety strategies of different types of fires affecting passengers.

According to the publication times of the references with high citation frequencies, there were 2 papers published during the initial stage, 8 papers during the stable development stage and 5 papers during the rapid development stage. Seven of the papers were completed through international cooperation. International exchanges and cooperation between scholars need to be strengthened, as inter-agency cooperation is more common. Among the top 15 most-cited articles, there are four research directions: health risk assessment, risk assessment during construction, safety study of underground structures and emergency evacuation simulation.

D. CO-AUTHORSHIP ANALYSIS

VOSviewer was used to analyze the data derived from the WOS. After removing the authors with fewer than 2 posts, the remaining 52 authors had cooperative relationships and formed 8 clusters automatically to generate a cooperative network of highly productive authors (see Fig. 7). The nodes represent the authors, and the node size represents the number of documents published. The connections between the nodes represent cooperation between the authors, and the widths of the connections represent the strengths the cooperation. It can be seen that Zhang, Limao (26), Wu, Xianguo (25) and Skibniewski, Miroslaw J (20) have the highest numbers of authors. The cooperation between authors is relatively

TABLE 6. The top 15 papers with the most citations., 1983-2018.

Rank	STC	ACY	Title	Authors	Journal	Year	IN	CN
1	137	9.13	The London Underground: dust and hazards to health	Seaton et al	Occupational and Environmental Medicine	2005	3	1
2	69	4.93	Dust in the underground railway tunnels of an Italian town	Ripanucci et al	Journal of Occupational and Environmental Hygiene	2006	1	1
3	66	4.13	Risk assessment methodology for underground construction projects	Choi et al	Journal of Construction Engineering and Management	2004	2	1
4	60	4	Seismic response of large underground structures in liquefiable soils subjected to horizontal and vertical earthquake excitations	Liu et al	Computers and Geotechnics	2005	1	1
5	55	6.88	Modeling and safety strategy of passenger evacuation in a metro station in China	Shi et al	Safety Science	2012	3	1
6	55	1.9	Back Disorders and Health-Problems Among Subway Train Operators Exposed to Whole-Body Vibration	Johanning et al	Scandinavian Journal of Work Environment & Health	1991	1	1
7	54	6.75	Risk analysis during tunnel construction using Bayesian Networks: Porto Metro case study	Sousa et al	Tunnelling and Underground Space Technology	2012	1	1
8	54	3.6	Steel dust in the New York City subway system as a source of manganese, chromium, and iron exposures for transit workers	Chillrud et al	Journal of Urban Health-Bulletin of The New York Academy Of Medicine	2005	3	1
9	47	7.83	Bayesian-network-based safety risk analysis in construction projects	Zhang et al	Reliability Engineering & System Safety	2014	4	4
10	45	4.09	CFD simulation and assessment of life safety in a subway train fire	Roh et al	Tunnelling And Underground Space Technology	2009	2	1
11	45	4.09	Airborne fungi in four stations of the St. Petersburg Underground railway system	Bogomolova et al	International Biodeterioration & Biodegradation	2009	1	1
12	45	2.5	Prediction and analysis of subsidence induced by shield tunnelling in the Madrid Metro extension	Melis et al	Canadian Geotechnical Journal	2002	1	1
13	43	6.14	Development of web-based system for safety risk early warning in urban metro construction	Ding et al	Automation in Construction	2013	2	1
14	42	6	Prediction of tunnel displacement induced by adjacent excavation in soft soil	Zhang et al	Tunnelling and Underground Space Technology	2013	1	1
15	41	2.73	Monitoring ground deformation in tunnelling: Current practice in transportation tunnels	Kavvadas et al	Engineering Geology	2005	1	1

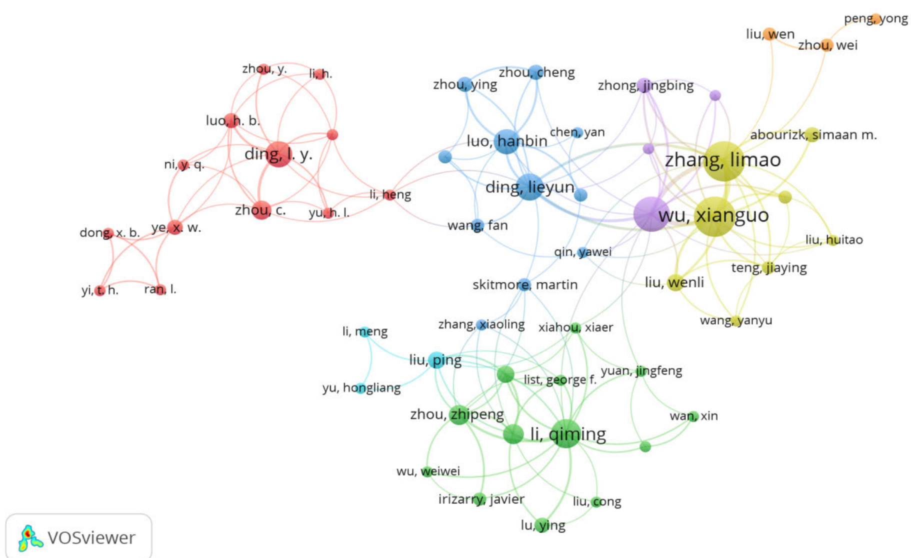

FIGURE 7. Cooperation among authors in URT safety studies.

average, and there are few particularly frequent cooperative relationships, forming a perfect cooperation system.

The top 15 authors who published the most articles were extracted, see Table 7 Among them, 13 authors are

TABLE 7. Top 15 authors in URT safety studies, 1983-2018.

Rank	Author	Organization	Country	Links	Quantities	ACI
1	Zhang, et al	Huazhong Univ Sci & Technol	China	15	26	12.54
2	Wu, et al	Huazhong Univ Sci & Technol	China	13	25	13
3	Skibniewski, Miroslaw J.	Univ Maryland	USA	16	20	16.15
4	Li, Qiming	Southeast Univ	China	16	14	9.29
5	Ding, Lieyun	Huazhong Univ Sci & Technol,	China	11	12	10.33
6	Luo, Hanbin	Huazhong Univ Sci & Technol	China	10	10	1.8
7	Deng, Yongliang	China Univ Min & Technol,	China	9	7	7.14
8	Zhou, Zhipeng	Southeast Univ	China	9	7	8.71
9	Zhou, C.	Huazhong Univ Sci & Technol	China	7	6	24.5
10	Liu, Ping	Southeast Univ	China	8	5	1.2
11	Liu, Wenli	Huazhong Univ Sci & Technol	China	6	5	3.6
12	Song, Liangliang	Hohai Univ,	China	6	5	2.4
13	Abourizk, Simaan M.	Univ Alberta	Canada	2	4	7
14	Lu, Ying	Southeast Univ	China	3	4	15.25
15	Ye, X. W.	Hong Kong Polytech Univ	China	7	4	15

ACI: Average Citations per Item

from China, indicating that China is the main force in the field of URT safety research. Zhang et al. has the highest number of publications, with an ACI of 12.54, as well as cooperation with many well-known institutions, such as Huazhong University of Science and Technology, Nanyang Technological University, Georgia Institute of Technology, University of Alberta, etc. The other two authors are Skibniewski and Abourizk, both of whom are from North America. The links represent cooperation with other authors. According to this indicator, scholars have a strong sense of cooperation.

Zhang *et al.* mainly analyzes and makes decisions on the risk of urban rail transit construction. Not only two different risk analysis methods for construction safety were proposed [41], but also the risk of adjacent buildings in the tunnel environment was further analyzed [49], [50]. Wu *et al.* is more inclined to propose a decision support approach: A Pdynamic Bayesian network based approach in tunnel construction and a dynamic decision method for complex project risk analysis [51]. Skibniewski often cooperates with Zhang and Wu, the research direction is similar, but more attention was paid to the application of information technology in construction assurance [52]. Li *et al.* is aimed at the safety of subway operations [7], [53]. He came up with a Case-based reasoning risk analysis method for automated safety and A MOHN approach to understand metro operation safety. The main research direction of Ding *et al.* is the tunnel construction safety management, and also through the complex network perspective to characterizing time series of near-miss accidents [54], [55].

E. RESEARCH KNOWLEDGE BASE

The concept of co-citation analysis was developed by American intelligence scientist Henry Small. The concept refers two references appearing together in the bibliography of a third citation, thus forming a co-citation relationship [56]. Co-cited literatures constitute the knowledge foundation of the research field. Co-cited journals carry co-cited literatures, which are the carriers of the knowledge foundation. Meanwhile, highly co-cited journals also represent core journals in the research frontier of the field. VOSviewer was used to analyze co-cited literatures and their sources to identify the knowledge basis and core journals in the research field of URT safety.

1) THE REFERENCE CO-CITATION ANALYSIS

The co-citation relationship of literatures reflects the correlations between literatures. The higher the co-citation frequency of two literatures, the stronger is the correlation between their academic research directions [57]. Using VOSviewer, a network picture of cited references with 36 nodes (see Fig. 8) was obtained after filtering. The sizes of the nodes indicate the citation frequency of the co-cited literatures. The distance between the nodes represents the strength of the relationship between the studies—the closer is the distance, the stronger is the co-cited relationship. According to Fig. 8, the literature citation knowledge base in the field of URT safety from 1983 to 2018 mainly includes four categories:

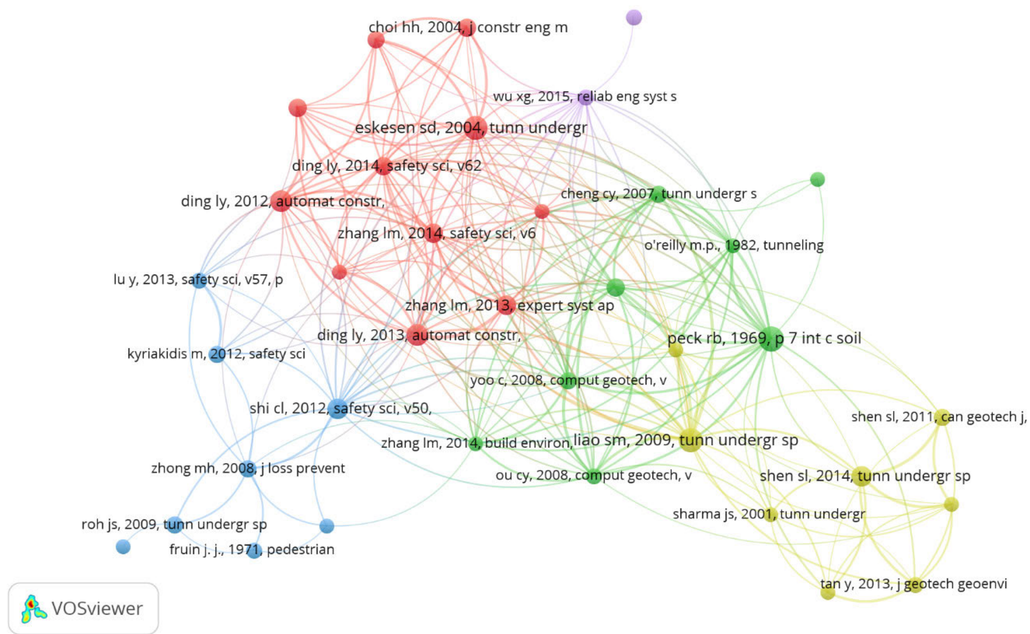

FIGURE 8. The reference co-authorship network of URT safety publications.

Risk analysis in the construction stage (red clustering): Eskesen Sd (cited 25 times) provided guidance for personnel in developing overall risk identification and management schemes for tunnels and underground projects [58]. Ding *et al.* summarized the safety risks and risk factors in the process of subway construction, interpreted the acquisition process of risk identification rules, and developed the overall risk identification process and the group-retrieval matching algorithm based on meta-rules and certainty factors [59] (cited 20 times), as well as presented the development and application of a web-based system for safety-risk early warning in urban metro construction [42] (cited 20 times). Zhang *et al.* respectively proposed the probabilistic decision-making method for subway construction safety risk analysis [2] (cited 16 times) and a new systemic decision support model based on a Bayesian network for safety control in dynamic complex project environments [60] (cited for 17 times).

Method for predicting ground movements (green clustering): Loganathan and Poulos [61] proposed a method for predicting the ground displacement caused by tunnels (cited 15 times). Yoo and Lee [62] described the deep excavation-induced ground surface movements based on the results of a numerical investigation (cited for 13 times). Cheng *et al.* [63] depicted the displacement control model (DCM) used to predict the influence of tunnel excavation on adjacent pile foundations to accurately predict the size and shape of ground displacement (cited 12 times).

Risk analysis in the operational phase (blue clustering): This type of analysis includes two topics, fire emergency evacuation and accident causal analysis in the operational phase.

Fire emergency evacuation: Zhong *et al.* [64] used CFD to simulate the evacuation process of passengers in deep subway stations under fire conditions (cited 12 times). Roh *et al.* [65] used a CFD simulation to evaluate the impact of PSD and ventilation on passenger safety in subway train fires (cited 12 times). Shi *et al.* [48] proposed a calculation method for the evacuation time of subway stations, simulated the evacuation process of subway stations, and studied the characteristics of evacuation behaviors of occupants, evacuation times, traffic flows and the strategies for using escalators as escape routes (cited 18 times).

Analysis of the causes of accidents in the operational phase: Kyriakidis *et al.* [66] proposed a new safety maturity model (SMM) designed to address not only the behavioral and attitudinal culture but also the technical, operational and methodological elements and actual achievements in terms of safety outcomes (cited 12 times). Ying *et al.* proposed a risk analysis method based on the use of case-based reasoning (CBR) (cited 11 times) [7].

Reason analysis of tunnel deformation and settlement (Yellow Clustering): Sharma *et al.* [67] monitored the deformation of tunnels during excavation and found that the stiffness of the tunnel lining has a significant impact on the tunnel displacement and deformation caused by adjacent excavation (cited 10 times). Shen *et al.* analyzed the phenomenon and causes of settlement in the Shanghai Metro [68] (cited 19 times).

2) THE JOURNAL CO-CITATION ANALYSIS

The co-citation analysis of journals is widely used in research fields of multiple disciplines. Through the co-citation

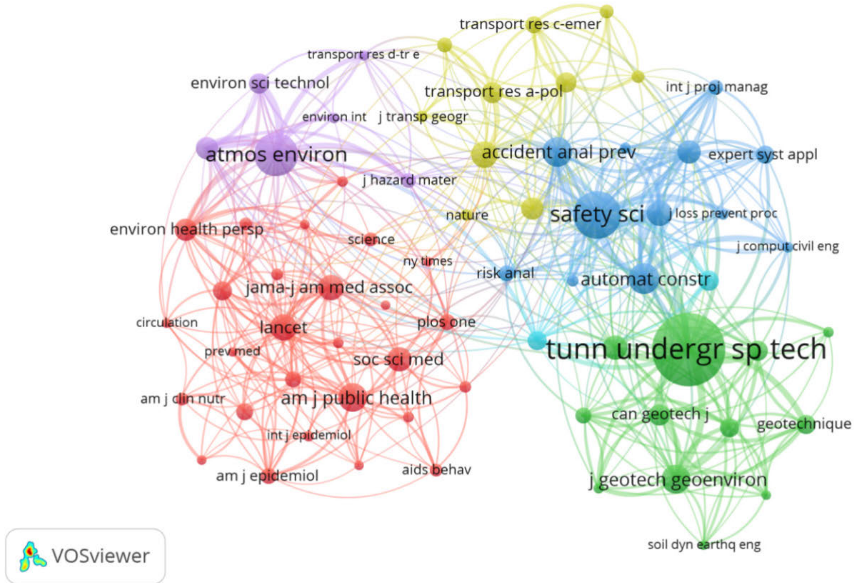

FIGURE 9. The journal co-citation network of URT safety publications.

analysis of journals, journals can be positioned and classified, and their core or edge positions can be determined for the evaluation of academic journals. VOSviewer was used to draw a journal co-citation network map, with ''Co-citation'' selected in the analysis category and ''Cited sources'' selected as the node type, resulting in a 69-node journal co-citation network map after screening (see Fig. 9). The sizes of the nodes indicate the reference quantities of the co-cited journals. The distances between the nodes represent the strengths of the relationships between the journals. The shorter is the distance, the stronger is the co-cited relationship of the journal. The 69 journals are divided into six clusters, with green, blue and red clusters as the main body. There are four main research directions: geotechnical engineering, safety, public health and transportation. The green cluster is a cluster of journals covering geotechnical engineering and construction, mainly composed of Tunnelling and Underground Space Technology (cited 968 times) and the Journal of Geotechnical and Geoenvironmental Engineering (cited 257 times). The blue cluster is an interdisciplinary and social science journals cluster, represented by Safety Science (cited 538 times), Accident Analysis and Prevention (cited 274 times) and Automation in Construction (cited 283 times). The red cluster is the environmental and public health journals cluster, which is mainly composed of the American Journal of Public Health (cited 257 times), Lancet (cited 232 times) and the Jama-Journal of the American Medical Association (cited 217 times). The yellow clustering is a journal cluster covering transportation, mainly composed of the Transportation Research Record (cited 232 times) and Transportation Research Part A-Policy and Practice (cited 170 times). The most-cited journals were extracted from four research categories: Tunnelling and Underground Space Technology, Safety Science, Atmospheric Environment, Lancet and Transportation Research Record, which are the core journals of different research directions.

F. RESEARCH HOTSPOTS AND FRONTIER ANALYSIS

1) RESEARCH HOTSPOT ANALYSIS

Keywords reflect the core content of articles, so keyword analysis can be used to identify evolving research fronts related to the knowledge domain [69]. Through analysis using VOSviewer, a total of 6398 keywords, including keywords that appeared more than 8 times, was selected, and the keywords were checked one-by-one. The top 20 keywords in terms of frequency were extracted to generate Table 8 Among them, ''risk'' is in absolute position, and it is the product of the probability of an accident and the consequences of an accident, indicating the degree of danger; ''system'' proves that the research target is the system and that URT is a dynamic and organic system as a whole; ''management'' is an important means by which to achieve safety; ''model'' is a way to calculate and evaluate the safety risks of URT; and ''construction'' is the most accident-prone stage.

In the keyword co-occurrence network (see Fig. 10), the thicker is the connection between nodes, the more times the two keywords appear together. The total link strength in Fig. 10 is 3199, and the total links are 1852. Seven clusters were formed, with risk assessment (red) and model-based research (green) predominating. In order to understand the main research directions of different clusters, read the high-cited documents in the target database which corresponding to the main keywords in the cluster. The main research directions of clusters are described as follows.

TABLE 8. **The top 20 keywords of the URT safety studies, 1983-2018.**

Rank	Keywords	Occurrences	Total link strength	Rank	Keywords	Occurrences	Total link strength
1	risk	118	456	11	simulation	50	106
2	system	101	474	12	tunnel	48	120
3	management	98	462	13	design	44	98
4	model	93	385	14	environment	40	152
5	construction	87	451	15	excavation	34	106
6	health	73	318	16	impact	33	107
7	subway	73	292	17	performance	31	89
8	behavior	70	308	18	exposure	31	73
9	safety	61	269	19	risk assessment	30	94
10	subway station	60	259	20	children	28	75

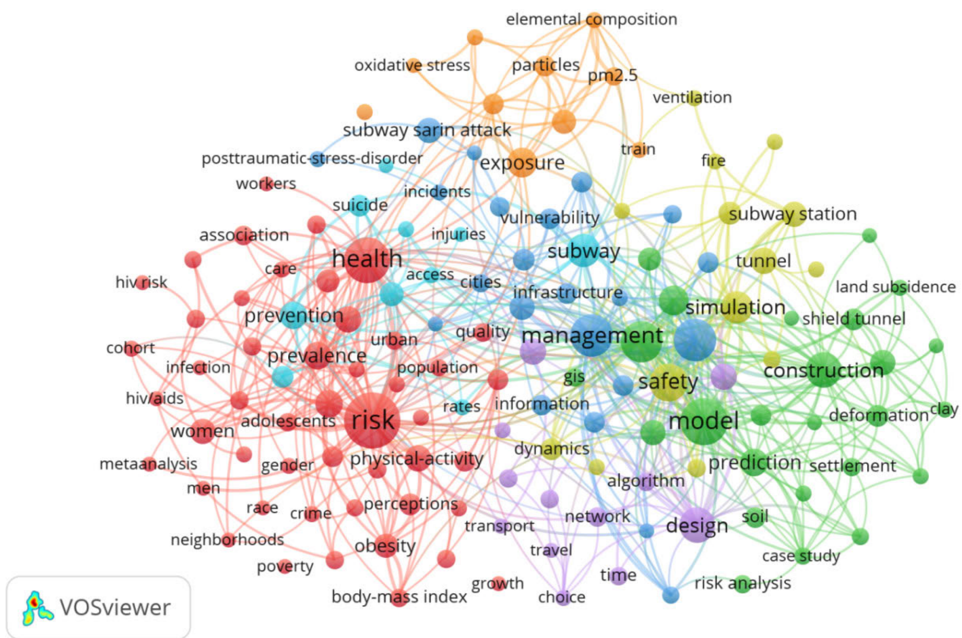

FIGURE 10. **Keyword co-occurrence network of URT safety studies.**

a: RISK ASSESSMENT (RED)

''Risk'' and ''health'' are given priority, it mainly explores the safety risks/occupational health risks in urban rail transit. For example, South Korea's scholars have developed procedures and tools for assessing and managing the risks of underground construction projects [46] and have proposed a risk-based approach to the safety impact assessment model framework for construction projects [70]. Johanning explored the relationship between the overall vibration of subway train operators and back diseases [36]. Gershon *et al.* conducted an environmental survey of the noise level of the New York City transportation system with noise levels as an entry point. The survey indicated that the noise level in the subway and bus station environment have the potential to exceed recommended exposure guidelines from WHO and EPA, given sufficient exposure duration [71].

b: MODEL-BASED RESEARCH (GREEN)

''Model'' appears the most frequently, supplemented by ''construction'', ''deformation'', ''settlement'', ''risk analysis'' and ''case study''. Explain that the clustering reflects the risk analysis and the ground/underground structure motion analysis supported by the ''model'' method. Yang *et al.* [72] used mathematical statistical models to quantitatively analyze the topological properties of URT; Lyu *et al.* [73] used a GIS-based modeling method for the flood risk assessment of metro systems in megacities; Zhang *et al.* [74] used the VEP model to study the characteristics of tunnel excavation and predicted the tunnel displacement caused by excavation near soft-soil foundations; and Lai *et al.* [75] explored the vibration response characteristics of cross-tunnel structures through a (3D) dynamic finite element model.

c: EMERGENCY EVACUATION SIMULATION (YELLOW)

Yellow cluster is mainly composed of ''simulation'', ''tunnel'', ''subway station'' and ''dynamics''. It reflects the dynamic characteristics of the smoke in the tunnel/subway station, which is related to the impact of platform screen doors and ventilation on smoke flow [65], [76], simulations of the spread of smoke and the proposal of measures by which to control smoke transmission [77], [78]. Based on the former, the emergency evacuation simulation study of passengers in subway stations was developed [48], [79].

d: AIR QUALITY (ORANGE)

This cluster focuses on the exposure to inhalable particulate matter in URT, the representative keywords are ''exposure'', ''particles'' and ''pm2.5''. For example, Chillrud *et al.* [80] studied the health effect to transit workers exposed to steel dust in New York City subway system. Jung *et al.* [81] studied the genotoxic effects and oxidative stress caused by PM10 in Seoul Metro tunnel, Korea. Kam *et al.* [82] have assessed PM2.5 exposure values and lung cancer risk in Los Angeles light rail, metro, highway and ground street environments.

e: SYSTEM-BASED RISK ANALYSIS (BLUE)

Blue clustering mainly includes ''management'', ''system'', and ''vulnerability''. ''Management'' indicates the way to achieve a safe state, ''system'' represents a research object, and ''vulnerability'' is the entry point for research. This cluster represents the research direction of assisting safety management by analyzing the vulnerability of the system. Song *et al.*, based on an AHP and ISM integrated method, the literature analysis method and the Delphi method, identified 21 vulnerability factors and their relationships and weights [83]. Sun *et al.* analyzed the network and site vulnerability of URT systems [84]. Deng *et al.* put forward a new framework based on the network theory and FMECA method and studied the vulnerability of subway systems through risk matrix analysis of the network efficiency using the network theory and FMECA method [10].

f: THE DESIGN OF THE RELEVANT SYSTEM/METHOD (PURPLE)

It is mainly composed of ''design'', ''network'' and ''algorithm''. The main content of the cluster includes equipment system and method/solution design in the field of urban rail transit safety: the design of the lighting system [85], the integrated design of the ventilation, air conditioning and emergency equipment systems [86], the design of the passenger flow status identification method [87], the design of the emergency evacuation capacity estimation of the subway station [88], and the design of the solution for improving the resilience of the subway vehicle in the explosion event [89].

In summary, the red and green clusters laterally support the research hotspots in the URT safety field, while the blue, orange, yellow, and purple clusters constitute the longitudinal extension of the hotspot. It is not difficult to find that red and green are not specific research directions, representing a certain type of research hotspot; while the directions of blue, orange, yellow and purple are relatively clear. In addition, Fig. 10 illustrates the three main phases of the construction project (design, construction and operation). Although there is no ''operation'', emergency evacuation simulation (yellow) and air quality (orange) are included in the operational stages.

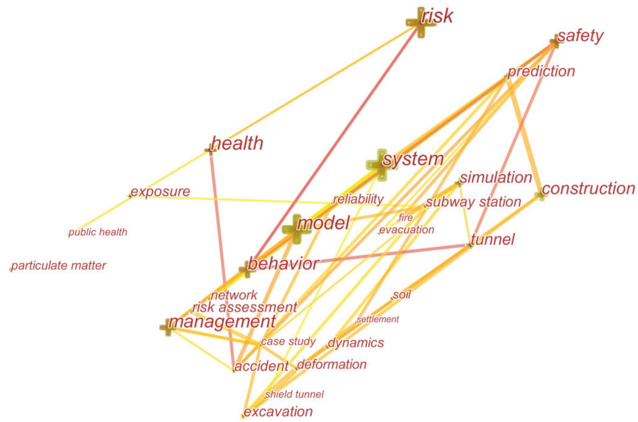

FIGURE 11. The research theme evolution path of URT safety studies.

2) COMBING EVOLUTION PATH

The keyword co-occurrence knowledge map was generated using CiteSpace, and three main evolutionary paths of research themes in the field of URT safety from 1983 to 2018 were identified (see Fig. 11.)

The ''health risk'' research path was the earliest research path, and the research of this direction was mainly performed from the micro perspective. In the early stage, studies focused on the occupational health of subway train drivers [36], particulate matter [44] and public health [13] were taken as the main research objects. While in the later stage, the research object was transformed to subway construction workers and passengers, the exposure value was quantitatively studied [82]. The research direction of public health in URT has been developed through continuous digging and expansion of the path of health risk.

The ''risk analysis-safety management'' research path describes the changes that the scholars taking risk assessment as a means by which to achieve the state of safety. Early, safety management was conducted after accident, and later developed to establish model to control risk and prevent accidents [7]. The network and system were taken as the objects for risk management, successively, and then the risk prediction was achieved by means of case analysis, accidents and reliability assessments and models. At the same time, the research path of ''fire, emergency evacuation'' was refined,

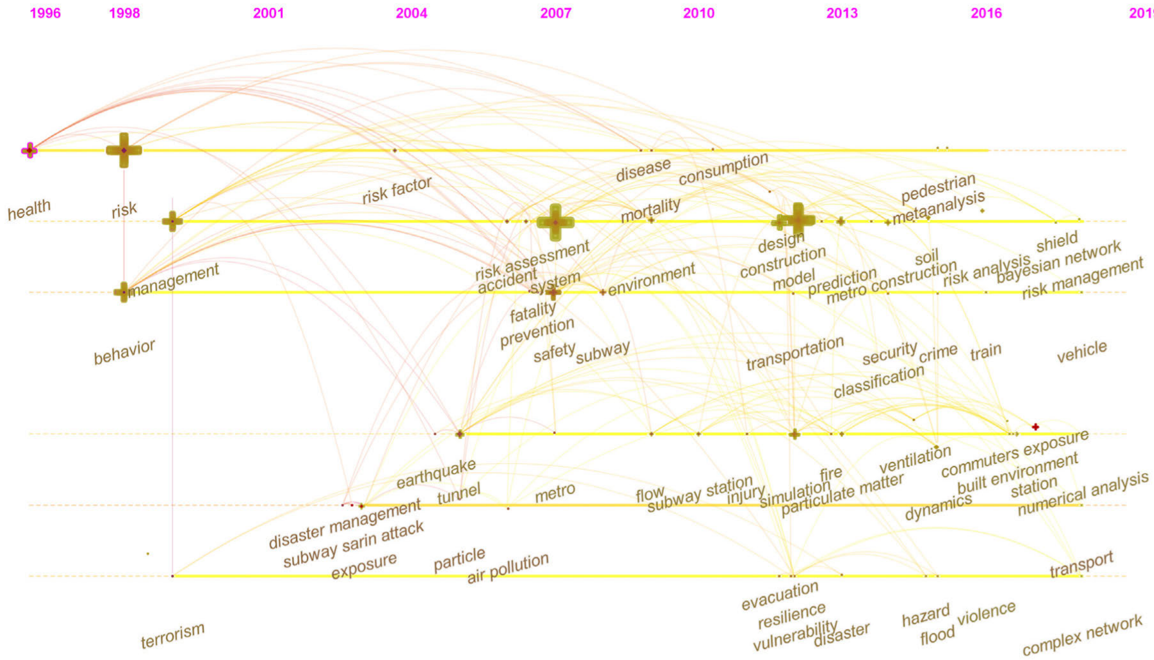

FIGURE 12. The keyword timeline view of URT safety studies.

and subway stations were used as research sites to simulate the emergency evacuation of personnel [48] and smoke numerical simulation in the case of a fire [79].

The ''displacement/deformation of the tunnel'' research path is a characteristic path branched from ''risk analysis-safety management''. As the URT is dominated by tunnels, its deformation and displacement have a great impact on the safety of the entire URT system. From the analysis of excavation and shield tunneling in the initial stage to the analysis of deformation and settlement in the later stage and, further, to the identification of tunnel cracks, the research objects have gradually turned from macro to micro. Therefore, the study of the deformation [67] or settlement [68] of the ground or tunnel caused by construction are always going on.

3) RESEARCH FRONTIER IDENTIFICATION

This article is a continuous knowledge management convergence process expanding learning frontiers, identifying the frontiers [90]. The keyword co-occurrence distribution was analyzed using CiteSpace, and the keyword timeline view was generated after the keywords were properly edited (see Fig. 12). In the keyword timeline view, the horizontal axis represents time, the nodes represent keywords, and the connecting lines between nodes represent the co-occurrence relationships between keywords. The ''cross'' nodes represent high-frequency keywords, and the bigger is the ''cross'', the higher is the frequency of this keyword. The red nodes represent keywords with a burst of frequency on behalf of a new research trend. Nodes with purple outer rings indicate that the keyword centrality is not less than 0.1, so this keyword is a hub connecting other keywords. The three keywords with the highest centrality are ''health'' (0.24), ''risk'' (0.18) and ''safety'' (0.17). In the initial stage of development (1983-2002), there were few research directions, focusing on ''health'', ''risk'', ''management'' and ''behavior''. After entering the stable development stage (2003-2011), the research direction was expanded, and the research focus turned to ''system'', ''safety'' and ''subway'', completing the transition from studying ''people'' to studying the ''system''. During the rapid development stage (2012-2018), research hotspots included ''model'', ''construction'', ''design'' and ''simulation'', which reflect that scholars conducted research on URT safety by means of computer science, natural science and engineering principles.

The burst detection function was used to identify the burst keywords, as shown in Table 9. ''Health'' (10.8181) had the strongest burst strength, followed by ''risk'' (7.6056), ''subway sarin attack'' (6.0508), and ''exposure'' (4.9184). The reason why the health burst started earliest and lasted for the longest period may be that the technology of early URT was not mature enough, resulting in a harsh environment, which affected the health of passengers and staff. The ''disaster management'' and ''subway sarin attack'' bursts happened at the same time. The reason for this finding may be that subway terrorist attacks such as the Tokyo Metro gas incident caused widespread concern among scholars. ''Station'', ''particulate matter'' and ''optimization'' are in a state of burst change and are at the forefront of URT safety research.

In fact, the URT safety is closely related to the development of the city. Although we can find out the evolution

TABLE 9. Top 15 Keywords with the strongest citation bursts.

Keywords	Year	Strength	Begin	End	1983 - 2018
health	1983	10.8181	1996	2011	
disaster management	1983	3.3961	2003	2010	
subway sarin attack	1983	6.0508	2003	2010	
victim	1983	3.5914	2003	2008	
exposure	1983	4.9184	2003	2009	
risk	1983	7.6056	2004	2011	
fatality	1983	2.9683	2007	2008	
epidemiology	1983	3.843	2008	2014	
disease	1983	4.0219	2009	2012	
safety	1983	4.2423	2010	2013	
settlement	1983	3.0547	2013	2015	
case study	1983	3.1613	2014	2016	
station	1983	3.1259	2017	2018	
particulate matter	1983	3.1259	2017	2018	
optimization	1983	4.6543	2017	2018	

path of URT safety studies through keyword timeline view, keywords such as smart cities and smart transportation that have recently been debated have not appeared. The cause of this phenomenon may be related to the threshold setting of Citespace software. For example, in recent years, some researchers are studying the smart city services and thinking traffic safety related to smart city [91]–[93], but the keywords have not been in the timeline view because of the small number of literature.

IV. CONCLUSION

In this paper, the information visualization software CiteSpace and VOSviewer were used to conduct bibliometric analysis of relevant literature on URT safety studies in SCIE and SSCI from 1983 to 2018. The main content includes the spatial and temporal distribution, core literature, author contribution, research knowledge basis, research hotspots and research frontier analysis. By mapping the co-citation network of research literature on URT safety, we identified the four knowledge bases in this field. Through the co-occurrence analysis of keywords, the research hotspots of each period were identified, and the core evolution paths of the themes were combed. Then, the current research frontiers of URT safety were identified. The main conclusions are as follows:

(1) The development process of URT safety can be roughly divided into three stages: the initial stage (1983-2002), the stable development stage (2003-2011) and the rapid development stage (2012-present). The United States had the highest number of publications in the field of URT safety research and was the world leader from 1991 to 2013. China followed it closely and surpassed it in 2013. However, the research results of the United States were more mature. The discipline distribution reflects that URT safety is a multidisciplinary supported research field, in which Civil Engineering, Construction & Building Technology, Geology and Industrial Engineering are the bases and Public, Environmental & Occupational Health and Computer Sciences are the tools. A relatively complete cooperation system has been formed among institutions and authors in various countries. Chinese institutions and authors are the main force of the research, but the ACI values are uneven. Tunneling and Underground Space Technology, Safety Science and Computers and Geotechnics are the main vehicles for literature in this field.

(2) Risk analysis at the construction/operation stage, methods for predicting ground movements and causal analysis of tunnel deformation and settlement are the knowledge bases of the research field of URT safety. In the construction/operation stage, most scholars used natural science as a means of risk analysis, while computer science and engineering principles were often used in the prediction of ground movements and the analysis of tunnel deformation and settlement. The carriers of co-cited literatures can be roughly divided into four categories: geotechnical engineering, safety, public health and transportation. The journals with the highest amounts of co-citations were extracted from each category as the core journals in this field, namely, Tunnelling and Underground Space Technology, Safety Science, Atmospheric Environment, Lancet and the Transportation Research Record.

(3) There are four hotspots in URT safety research: risk assessment, model-based research, emergency evacuation simulation and assessment of the impact of particulate matter in the environment on human health. The basic theory and research system of this field have been basically constructed, but the research directions are too concentrated, and the frontier branches are too few. The evolution process of URT safety research themes can be roughly divided into three core paths: the ''health risk'' path, the ''risk analysis - safety management'' path and the ''underground structure - dynamic behavior'' path. In the process of evolution, the research paths were

refined step-by-step, gradually trending toward risk analysis in the operational stage, and the research directions also transformed to micro analysis stage-by-stage. The research of emergency evacuations of subway personnel, the effects of particulate matter in subway air on human health and the application of computer technology to engineering optimization are the research frontiers of URT safety at present.

In this research, we focus on the knowledge structure and research evolution of urban rail transit safety studies where we put forward a systematic analysis based on mapping knowledge domains to identify the knowledge bases, evolution path and research frontier. Although we have identified some interesting results, there have some shortcomings in the research. Some emerging frontier research is difficult to display in mapping knowledge domains due to the small number of literature. For future work, emerging frontier topics and hotpots in the research field of URT safety will be further studied.

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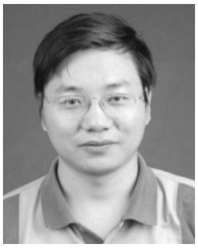

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