Monitoring Studies of Shield Tunnels in Geotechnical Engineering: A Systematic Literature Review and Trend Analysis

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Abstract
In the field of shield tunnel engineering, with the acceleration of urbanization, the research on tunnel monitoring continues to expand. Therefore, this paper uses the systematic bibliometric analysis method to comprehensively sort out and visually reveal the evolution path and academic pattern of shield tunnel monitoring research. Compared with the early research based on single monitoring technology, the current research focuses more on the settlement prediction and the construction of intelligent monitoring system. Based on the bibliometrix package of R language, this paper carried out bibliometric research from multiple dimensions, including annual literature growth trend, identification of representative scholars, high-yield national statistics, analysis of highly cited literature, and distribution of core journals and research institutions. The results show that the research on shield tunnel monitoring has gradually developed since 2000, and entered a rapid growth stage after 2020. With the continuous evolution of technology and the expansion of data scale, this study provides a certain data support and analysis paradigm for the development of subsequent tunnel monitoring technology.
Keywords: Shield Tunnel, Monitoring, Bibliometric, Topic detection

Introduction
Under the background of the rapid development of urban underground space, shield tunnel as an important part of underground space engineering, its structural safety and construction safety are increasingly concerned. The construction process of shield tunnel is complex, involving a variety of geological conditions, environmental factors and construction disturbance. Its deformation control and structural stability are directly related to the overall safety performance of Tunnel Engineering (Zhang & Zhao, 2020). Especially in dense urban built-up areas and complex underground structure systems, shield construction is prone to cause risks such as ground settlement, response of surrounding structures and damage to existing facilities, so it is urgent to rely on high-precision monitoring methods for dynamic control of the whole process(Ran et al., 2023).

With the continuous development of intelligent sensors, Internet of things, big data and other technologies, shield tunnel monitoring has gradually moved from traditional manual measurement to automation, real-time and integration. A large number of studies have systematically explored different monitoring objects (such as settlement, convergence, internal force, vibration, air pressure, etc.), different sensing technologies (such as MEMS, FBG, DOF, laser point cloud, etc.), and multi-source data fusion and intelligent prediction methods (such as BP neural network, LSTM, atenet, etc.) (Tan et al., 2022). The continuous progress of monitoring technology not only improves the risk identification ability of shield construction, but also provides solid data support for structural health assessment and early warning in the long-term operation and maintenance stage of the tunnel.

With the continuous growth of the number of research tunnels, the field of shield tunnel monitoring presents the characteristics of diverse research objects, diverse technical methods, complex data forms, etc., which leads to difficulties in system integration and trend identification between different studies. Therefore, this paper will carry out a systematic review based on Bibliometrics and visual analysis to provide reference for promoting the collaborative innovation and development of tunnel engineering monitoring technology.

Literature Review

In recent years, the research heat of shield tunnel construction monitoring in the field of geotechnical engineering continues to rise. (Zhang & Zhao, 2020) and others proposed a low-cost and high-efficiency automatic monitoring system for circular deformation of shield tunnel, which uses MEMS inclinometer combined with ZigBee and GPRS wireless transmission technology to realize real-time monitoring of shield segment attitude. (Zhang et al., 2017) and others studied the influence of adjacent deep foundation pit on shield tunnel deformation, compared the deviation and applicability of manual and automatic monitoring methods, and emphasized the importance of multi-source data verification in improving monitoring accuracy. (Sun et al., 2020)and others have developed a mobile tunnel monitoring system based on laser scanning. Through point cloud data acquisition and cylindrical projection analysis, the fine visualization processing of shield tunnel section deformation is realized.

(Wang et al., 2021) Developed a new optical fiber monitoring system based on flexible long gauge FBG sensor for monitoring the convergence deformation of shield tunnel. (Yang et al., 2024)Studied the safety control technology and monitoring means in the process of shield tunnel passing through high-speed railway bridge, and the results verified the safety controllability during shield construction. (Ran et al., 2023)combined with the case of Hangzhou Metro, they built a settlement prediction model based on BP neural network, systematically analyzed the influence of adjacent shield construction on the deformation of existing tunnel structure and the effect of prediction structure setting, which provided technical support for the safety assessment and intelligent early warning of Metro structure.

(Schiessl & Raupach, 1992) developed the sensing system and software analysis system, which enables the structure to take protective measures before damage. (Fujii et al., 2004) developed the highway tunnel disease management and maintenance system based on GIS platform. (Lee et al., 2003) mainly studied the network communication of underground wireless sensor. (Metje et al., 2006) used fiber Bragg grating sensors to monitor the tunnel displacement and carried out the tunnel prototype test(Huang et al., 2023) proposed a high-

precision shield tail clearance measurement method based on line structured light. (Zeng et al., 2022) respectively established the real-time monitoring technology of shield tail gap by using image recognition method, filling the technical gap of shield tail gap measurement. 。 (Tan et al., 2020) built a structural health monitoring system (SHMS) for an underwater shield tunnel in the Yangtze River. Through monitoring, (You & Sun, 2022) found that with the advance of the shield, the embankment surface settlement gradually increased and tended to be stable, and its horizontal deformation groove shape was consistent with the numerical simulation results, which could provide a reference for the settlement control of large-diameter shield construction.

Research Methodology
We review the research status and related literature of shield tunnel monitoring in geotechnical engineering. We conducted a comprehensive search in the web of science database, and obtained all relevant articles related to the cross subject of shield tunnel monitoring in geotechnical engineering from 1991 to 2025.

We conducted a systematic literature search in the web of science database, which integrates academic journals, patents, research funding information, altimetric indicators, policy documents and clinical trial data, and is one of the most comprehensive research data resources in the world. In the retrieval process, we used "shield tunnel" and "monitoring" as the main search terms in all fields (including title, summary and keywords).

Bibliometrix software was used to perform bibliometric analysis in this study. The required data were retrieved from the web of science database and exported in BibTex format, followed by strict data screening (Bergeron et al., 2018). The functions of bibliometrix cover rich statistical output and graphical visualization, conform to the design concept of human-computer interaction, and support systematic scientific research evaluation. As described in (Yurui & Abdullah, 2024), it is currently the most comprehensive, highly integrated and easy-to-use class a open-source metrological analysis platform in the world.

Results and Discussions
Descriptive Analysis
The primary details of the chosen collection of articles obtained from the "Biblioshiny Tool for R-Package" are presented in Table 1.

Table 1
Demographic Profile of Respondents For Monitoring Studies of Shield Tunnels

Description	Results
Timespan	1991:2025
Sources (Journals, Books, etc)	151
Documents	500
Annual Growth Rate %	4.16
Document Average Age	6.12
Average citations per doc	29.24
References	12296
Keywords Plus (ID)	713
Author's Keywords (DE)	1737

Authors	1328
Authors of single-authored docs	6
Single-authored docs	6
Co-Authors per Doc	4.85
International co-authorships %	20.6
article	468
article; data paper	2
article; proceedings paper	6
proceedings paper	20

It can be seen from table 1 that the statistical data of this study covers the academic development in the field of shield tunnel monitoring from 1991 to 2025, and generally reflects the development trend of this field since the 1990s. Up to now, a total of 500 highly cited related literatures have been retrieved, which are distributed in 151 different publishing sources, showing the diversity and extensiveness of the sources of research results. This order of magnitude shows that shield tunnel monitoring, as the key technical direction of urban underground space engineering, has formed a relatively mature research system and attracted the continuous investment of many academic institutions and research teams. The average annual growth rate of literature is 4.16%. Although the growth rate is relatively moderate, it shows a long-term stable upward trend. In terms of citation performance, the average number of citations per article is 29.24, which is much higher than the conventional average level of geotechnical engineering literature. This shows that the achievements in this field have strong academic influence and reference value, and play an important role in guiding and guiding the follow-up research. At the same time, the average age of the literature is 6.12 years, which reflects the continuous updating and realistic attention of the research in this field, and does not rely on early results. The research covers 34 years, forming a relatively complete development chain, including not only the early basic technology exploration, but also the advanced directions of multi-sensor monitoring, data fusion, intelligent prediction and so on in recent years.
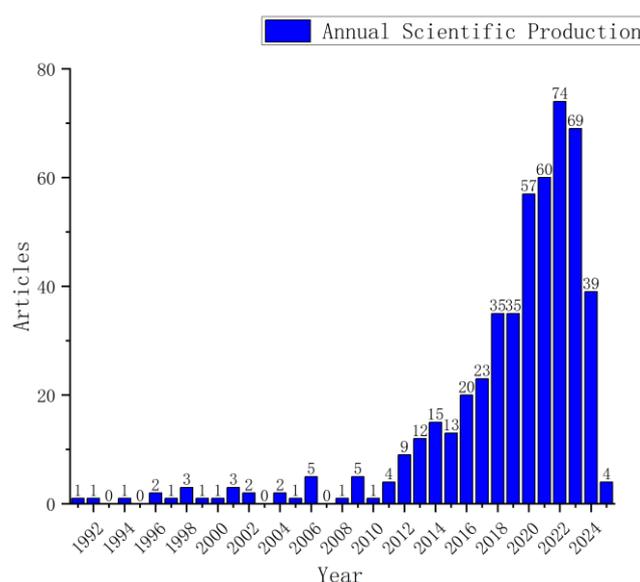

Figure 1. Annual Scientific Production For Monitoring Studies of Shield Tunnels

Figure 1 systematically reflects the annual distribution trend of shield tunnel monitoring research in the field of geotechnical engineering in recent years. In 2025, only four articles have been recorded so far. Since the statistical time has not ended, the data can not reflect the real output level of the whole year. In 2024, a total of 39 relevant papers were published, with a decrease compared with the previous year, which may be related to factors such as the segmentation of research topics or the extension of submission cycle. In 2023, a total of 69 articles were published throughout the year, showing the continuous attention of the academic community to the monitoring of shield tunnels. This year is also one of the periods in which research output has increased rapidly in recent years. 2022: the year with the most papers published in the past five years, 74 papers were published, marking that the research direction has entered an active development period, and the related monitoring technology and theoretical research have attracted extensive attention. 2021 and earlier years: the number of articles is relatively small, but it has laid the foundation for the current research.

Table 2

Most Productive Authors for Monitoring Studies of Shield Tunnels

Authors	Articles	Articles Fractionalized
ZHANG D	28	6.560714286
LI X	22	4.594444444
XIE X	18	4.189285714
HUANG H	17	4.233333333
LI P	17	3.345670996
LIU Y	16	3.578571429
ZHANG Z	16	3.329761905
LI J	15	2.821428571
LIU X	14	2.51468254
WANG Z	14	2.443650794

It can be seen from table 2 that in the field of shield tunnel monitoring research, Zhang D ranks first with 28 literatures, and its contribution under the "fractional counting method" is 6.56, showing its activity and dominance in this field. Secondly, Li X and Xie x published 22 and 18 articles respectively, with the corresponding fractional contributions of 4.59 and 4.19, which also reflected a high level of scientific research output.

Although both Huang h and Li P published 17 articles, the fractional contribution of the former (4.23) was slightly higher than that of the latter (3.35), indicating that they have certain advantages in the order of signature or the weight of cooperation. Other authors, such as Liu y, Zhang Z, Li J and Wang Z, also maintained the publication level of 14-16 articles, with fractional contributions ranging from 2.44 to 3.58, indicating that these researchers have certain representativeness and influence in shield monitoring related topics.

Table 3

Most Local Cited Sourcesfor Monitoring Studies of Shield Tunnels

Paper	Total Citations
TUNN UNDERGR SP TECH	3145
COMPUT GEOTECH	611
GEOTECHNIQUE	437
J GEOTECH GEOENVIRON	390
CAN GEOTECH J	374
AUTOMAT CONSTR	279
ENG GEOL	216
ROCK MECH ROCK ENG	178
INT J ROCK MECH MIN	177
INT J NUMER ANAL MET	168

From the data cited in Table 3, tunneling and underground space technology (tunn undergr SP Tech) has the most significant influence in the field of geotechnical engineering and sustainability research, with a total of 3145 citations, far ahead of other journals, reflecting its core position in the study of sustainable development of underground space. Computers and geotechnology (computer Geotech) and geotechnology also have a high number of citations, 611 and 437 respectively, indicating that these two journals have contributed a large number of influential achievements in numerical simulation, soil behavior modeling and foundation treatment.

The Journal of geo technical and geo environmental engineering (390 times) and the Canadian geo Technical Journal (374 times) show the continued activity and academic influence of North America in this research field. Other journals such as Automation in Construction、 Engineering Geology、 Rock Mechanics and Rock Engineering Although the times of being cited are relatively low, they focus on the sub directions of construction automation and rock mechanics, showing the multivariate distribution of research hotspots.

Table 4

Most Cited Countries for Monitoring Studies of Shield Tunnels

Country	TC	Average Article Citations
CHINA	11697	28.1
USA	300	33.3
FRANCE	249	35.6
KOREA	242	48.4
NETHERLANDS	236	39.3
JAPAN	224	44.8
UNITED KINGDOM	219	24.3
SINGAPORE	183	61
INDIA	176	58.7
ITALY	174	43.5

According to the statistics of the quoted data in Table 4, in the field of shield tunnel monitoring research, China ranks first with the total number of citations of 11697, showing its high output and high attention in this research direction. However, the average number of citations per article is 28.1, which is slightly lower than that of some other countries, indicating that in addition to the number advantage, the influence of some literatures still has

room for improvement. The United States (tc=300, with an average of 33.3 citations), France (tc=249, with an average of 35.6 citations) and the United Kingdom (tc=219, with an average of 24.3 citations) also remain active in this field, with stable academic influence. Among them, Japan (44.8 citations on average), South Korea (48.4 citations) and Italy (43.5 citations) are outstanding in the average influence of the literature, indicating that although the total number of citations in these countries is slightly low, their research results are more far-reaching. Special attention should be paid to the performance of Singapore (tc=183, with an average of 61 citations) and India (tc=176, with an average of 58.7 citations). Although the number of literatures is relatively small, the average number of citations is in the forefront, indicating that the quality of research results in this region is high and has good recognition in the international academic community.

Table 5
Most Relevant Sources for Monitoring Studies of Shield Tunnels

Sources	Articles
TUNNELLING AND UNDERGROUND SPACE TECHNOLOGY	117
APPLIED SCIENCES-BASEL	23
UNDERGROUND SPACE	18
ADVANCES IN CIVIL ENGINEERING	15
JOURNAL OF PERFORMANCE OF CONSTRUCTED FACILITIES	13
COMPUTERS AND GEOTECHNICS	12
AUTOMATION IN CONSTRUCTION	11
TRANSPORTATION GEOTECHNICS	10
ROCK MECHANICS AND ROCK ENGINEERING	8
CANADIAN GEOTECHNICAL JOURNAL	7

According to the journal source statistics in Table 5, in the field of shield tunnel monitoring research, tunneling and underground space technology (tust) ranks first with 117 articles, which is the most representative core journal in this direction, covering a number of key research contents such as tunnel construction, monitoring, numerical simulation and risk control. At the same time, applied sciences Basel (23 articles) and underground space (18 articles) show that engineering comprehensive and underground space special journals pay high attention to this research topic. Advances in Civil Engineering (15 articles) and Journal of performance of constructed facilities (13 articles) mainly include articles on structural performance, construction monitoring and management. Computers and geotechnology (12 articles) and automation in construction (11 articles) reflect the rapid development trend of intelligent monitoring, automated construction and data-driven modeling in recent years.

Transportation geotechnology, rock mechanics and rock engineering, and Canadian geotechnical journal published 10, 8, and 7 related literatures respectively, focusing on geological response, geotechnical mechanical properties, and engineering case analysis during shield construction.
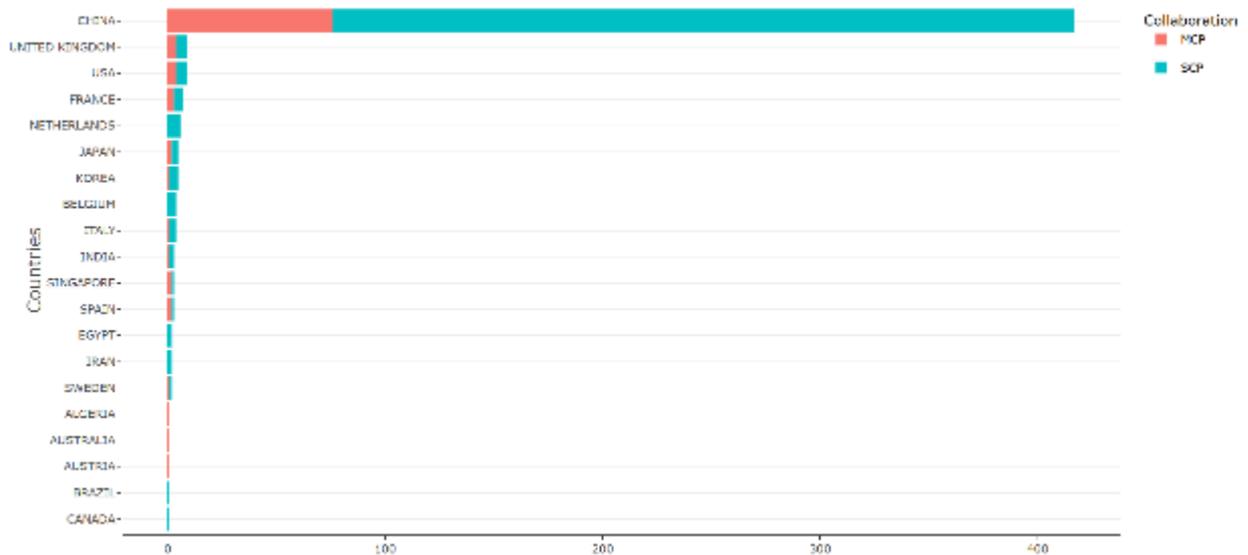
Figure 2. Corresponding Author's Countries for Monitoring Studies of Shield Tunnels

From the perspective of the distribution of corresponding authors' countries, 417 articles (accounting for 83.4%) occupy the absolute dominant position in the field of shield tunnel monitoring in China, of which the proportion of multinational cooperation (MCP) is 18.23%, which shows that the Chinese scientific research team is dominated by domestic research, and international cooperation is relatively limited. In contrast, although the United Kingdom and the United States have published only 9 articles respectively, the proportion of their multinational cooperation is as high as 44.4%, showing their activeness in international cooperation. France (42.9%), Italy (25%), Singapore (66.7%) and other countries also showed a high tendency of cooperation. Some countries with a small amount of research, such as Austria, Algeria, Denmark, the United Arab Emirates, etc., 100% of the literature are the results of multinational cooperation, indicating that these countries rely more on international cooperation to carry out research.
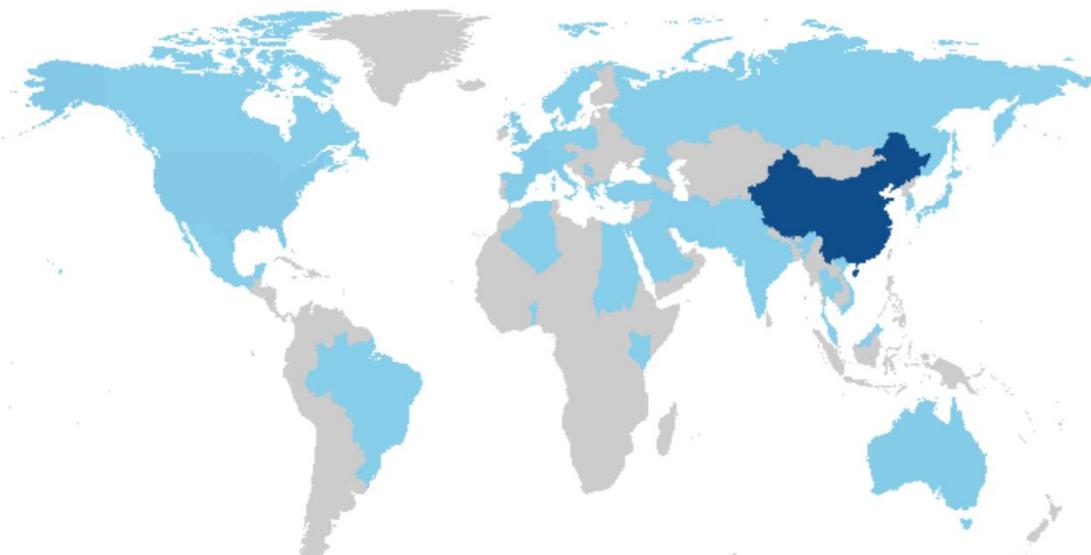

Figure 3. Country Scientific Production for Monitoring Studies of Shield Tunnels

From the statistical chart in Figure 3, it can be seen that China is far ahead in the research of shield tunnel monitoring with 1652 documents, showing its leading position and high scientific research output ability in this field. This is followed by the United States (47), Britain (32), Australia (27), France (23) and other traditional engineering powers, reflecting their sustained scientific research investment and international influence. Although some countries, such as the Netherlands, Japan, South Korea and Singapore, have less papers than the top ones, they are active in regional innovation and cross cooperation.
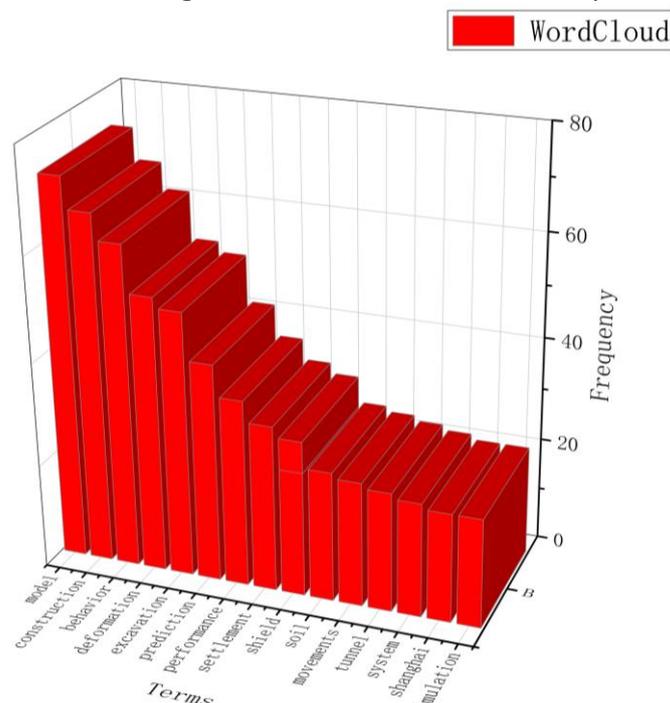

Figure 4. WordCloud for Monitoring Studies of Shield Tunnels

According to the keyword frequency analysis in Figure 4, the current research on shield tunnel monitoring is highly focused on core issues such as model, construction process and structural behavior response (behavior, deformation), indicating that numerical modeling and mechanical mechanism analysis are the main research line in this field; At the same time, the high frequency of prediction and simulation reflects the wide application trend of intelligent prediction and simulation technology.

Conclusions

In recent years, shield tunnel monitoring research has shown a good trend of continuous growth, showing its important position in geotechnical engineering and underground space development. While the number of publications has steadily increased, the degree of international cooperation has also gradually increased. Keyword analysis shows that the terms "model", "deformation", "prediction" and "excavation" appear frequently, indicating that the current research mainly focuses on the core technology path of numerical modeling, risk assessment and performance analysis. At the same time, many scientific research institutions from Asia, Europe and North America actively participate in the research in this field, highlighting the globalization and interdisciplinary nature of shield tunnel monitoring, covering civil engineering, sensing technology, data science and other research directions.

Discussion

In the past decades, shield tunnel monitoring, as an important branch of geotechnical engineering, has shown a continuous growth trend. With the increasing demand for underground space development, research activities in this field are increasingly frequent, and international cooperation is gradually strengthened. Intelligent monitoring has become a hot research direction. However, with the changing social environment, the field of shield tunnel monitoring will also face new challenges and transformation opportunities.

Possible future research trends include the following aspects:
Intelligent Infrastructure: research will be more artificial intelligence, automation, self-learning intelligent monitoring system.

Full life cycle monitoring and maintenance management: the research will expand from monitoring during construction to health diagnosis and maintenance optimization during operation, so as to improve the safety and management efficiency of the whole life cycle of the tunnel.

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