Analysis of Research Progress and Trends of Domestic Geotechnical Reinforcement Technology Based on Bibliometrics

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Abstract. An analysis of 516 core journal articles on rock and soil consolidation technology in China reveals that research in this field has grown since 2005. Research hotspots include consolidation of soil, excavation pits, loess, and shield tunnels, with numerical simulation being the frontier. Consolidation techniques and stability are also of interest, with a variety of consolidation techniques being widely applied. The study helps to understand the trends of progress and provide a basis for the safety of urban construction and infrastructure. Future research may place more emphasis on practicality, innovation, and environmental friendliness to meet the actual needs of rock and soil engineering and potentially have an impact on the sustainability and resilience of challenged urban infrastructure.

Keywords: Geotechnical reinforcement technology; Bibliometric analysis; Cooperation network; Numerical simulation; Research hotspots

1 Introduction

With the rapid development of China's social economy and the accelerated progress of urbanization, the importance of the geotechnical engineering field has become increasingly prominent. Geotechnical reinforcement technology, as a key foundation engineering method, plays an irreplaceable role in ensuring the safety of urban infrastructure[1], improving the seismic performance of buildings[2], and protecting the environment[3]. Facing the huge pressure of urban planning and construction, continuously improving the level and results of geotechnical reinforcement technology research has become an urgent need to ensure the sustainability of urban development and construction safety. With the rapid progress of science and technology and the advent of the big data era, the application of bibliometric analysis methods and tools has provided new possibilities for geotechnical reinforcement technology research[4]. With the help of bibliometric analysis, we can more comprehensively grasp the development trends in the field of domestic geotechnical reinforcement technology research and understand research trends and hotspots. In addition, the advocacy of multidisciplinary cross - cooperation has also promoted the vigorous development of

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geotechnical reinforcement technology research. The close cooperation among universities, research institutions, and engineering enterprises has made research results more in line with actual needs and provided more innovative solutions for urban infrastructure construction.

This study conducted a comprehensive analysis of the development of domestic geotechnical reinforcement technology, focusing on the paper literature data in key fields. It aims to deeply analyze the research progress and trends of domestic geotechnical reinforcement technology by studying the trends of paper publication, publishing journals, funds for funded papers, author institutions, author cooperation networks, and keyword co - occurrence networks, so as to provide a more scientific basis for decision-making in urban construction and infrastructure safety.

2 Data Processing and Research Methods

2.1 Data Acquisition and Processing

The paper data used for bibliometric analysis in this article was obtained from the CNKI database platform. The subject words were "geotechnical reinforcement + geotechnical anchoring + dangerous rock reinforcement + loess reinforcement + soil reinforcement", and the downloaded literature type was limited to core journals, resulting in a total of 516 papers. The specific data acquisition and processing procedures are as follows:

Firstly, the time trend of the number of published papers was analyzed. By counting the publication years of these 516 core journal papers, the trend of the number of papers published over time was obtained to reveal the development dynamics and evolution of research in this field.

Secondly, the journals in which the 516 papers were published were sorted and counted to understand which journals were more active in this field, to determine the academic mainstream journals and the direction of publication of high-quality papers in this field; at the same time, the funding information in the papers was collected and sorted. By analyzing the sources of funds for funded papers, the research project funding situation and support level in this field were understood.

Thirdly, the author and institution information of these papers was summarized and sorted to understand the more influential authors and research institutions in this field, and a network analysis of the cooperation among paper authors was conducted. By constructing an author cooperation network, the research teams or groups of scholars who cooperate frequently in this field and their cooperation patterns and influence in research could be revealed[5].

Finally, the keywords in the papers were sorted and counted. By constructing a keyword co - occurrence network, the relationships between keywords in this field could be revealed, helping to understand the research hotspots and frontier directions in this field[6].

Through the above data download, processing, and analysis processes, we can more comprehensively understand the current situation, progress, and trends of domestic geotechnical reinforcement technology research from aspects such as the time trend of

the number of published papers, publishing journals, funds for funded papers, author institutions, author cooperation networks, and keyword co - occurrence networks.

2.2 Research Methods

The bibliometric analysis method adopted in this study is a research method that uses mathematical and statistical methods to quantitatively analyze literature data[7]. Through bibliometric analysis, the relationships between literatures, research trends, research hotspots, and interdisciplinary aspects can be revealed, helping us to deeply understand the academic research status in a certain field.

The main tool used for bibliometric analysis in this article is "VOSviewer". This software is a free software tool specifically used for visualizing and analyzing bibliometric data, developed by Ludo Waltman and Nees Jan van Eck, bibliometricians from Leiden University in the Netherlands. It has been widely used in academic research, scientific evaluation, and science and technology policy formulation[8]. VOSviewer supports the processing of various literature data including papers, journals, and keywords, and can generate various types of visual charts such as word network charts, author cooperation network charts, and citation network charts. This study uses bibliometric analysis methods and the VOSviewer tool to conduct an in-depth analysis of the core journal literature in the field of domestic geotechnical reinforcement technology research. The relationships between literatures will be intuitively understood through visual charts, and important information such as research hotspots and disciplinary trends will be discovered, so as to provide valuable reference for academic research and scientific decision-making in this field.

3 Research Results Analysis

3.1 Analysis of Publication Trends and Literature Sources

From 1992 to 2023, the number of papers published in the field of domestic geotechnical reinforcement technology research showed an obvious growth trend, as illustrated in Fig 1. In the early 1990s, the number of papers published was small, but it gradually increased thereafter, growing rapidly around 2005, and then maintaining a relatively stable high publication level. The peak years of research in this field were 2010 and 2022, reaching 37 and 34 papers respectively, indicating the highest research activity in these years. Since 2010, the number of papers published has been relatively stable, with relatively small fluctuations, indicating that the field of geotechnical reinforcement technology research has entered a relatively mature and stable stage. Overall, the number of papers published in the field of domestic geotechnical reinforcement technology research has shown a significant growth trend over the past few decades and has maintained a relatively stable high publication level in recent years, indicating that this field has received extensive attention and importance, which is closely related to the needs of infrastructure construction and disaster prevention in China in recent years.

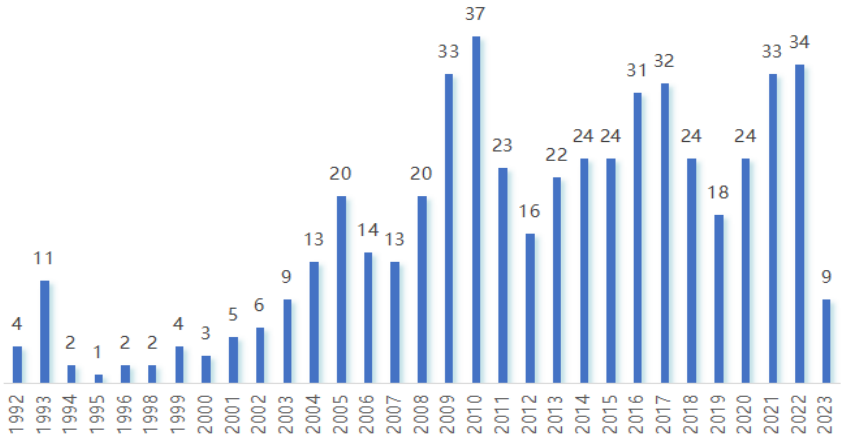

Fig. 1. Trend of Paper Publication[7]

The 516 journal papers obtained in the field of domestic geotechnical reinforcement technology research were published in 131 core journals. Among them, 14 journals published more than 10 papers. "Construction Technology", "Rock Mechanics and Engineering Journal", "Geotechnical Mechanics" and "Geotechnical Engineering Journal" are the mainstream journals that publish a large number of papers in the field of domestic geotechnical reinforcement technology research. In addition to journals focusing on the field of geotechnical reinforcement technology, some journals related to railway construction, urban rail transit, and underground space also published relevant papers, indicating that this research field has certain interdisciplinary characteristics. There were 249 papers from other journals. Although the number of papers published in these journals was small, they still accounted for a large proportion when combined. As shown in Fig 2.

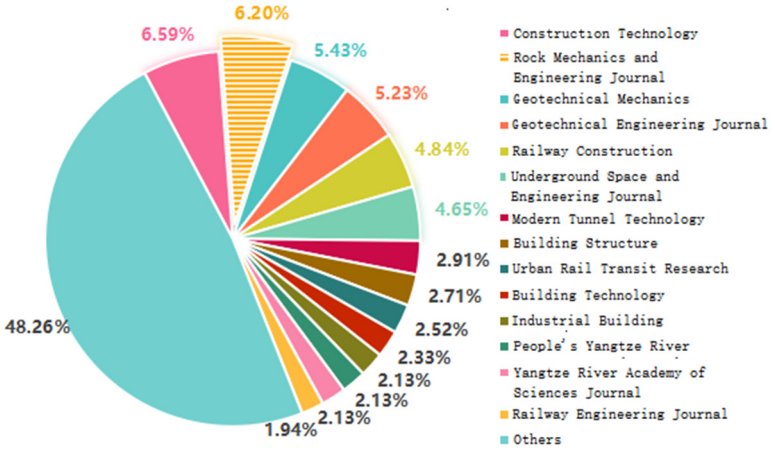

Fig. 2. Journal Distribution[6]

3.2 Analysis of Research Strength Funding Funds.

From the perspective of funds for funded research, the papers published in the field of domestic geotechnical reinforcement technology research have been funded by multiple different types of funds. A total of 268 papers have received funding, with a funding rate of 51.94%. Among them, the National Natural Science Fund is the largest source of funding, having funded 130 papers, and the National Key R & D Program has funded 26 papers. National-level projects usually fund high-quality basic research and frontier technology R & D, indicating that this field has received the attention and support of national-level scientific research projects. In addition, local-level funding has also made certain contributions in the field of geotechnical reinforcement technology research. For example, the Shaanxi Provincial Natural Science Fund, the Shandong Provincial Natural Science Fund, and the Shanghai Key Discipline Construction Project have all funded research in this field to a certain extent. The contributions of these funding projects have provided important financial support and scientific research guarantees for academic research in the field of domestic geotechnical reinforcement technology.

Research Institutions.

The institutions that have published a large number of papers in the field of domestic geotechnical reinforcement technology research mainly include Tongji University, Lanzhou University, Zhejiang University, Lanzhou Jiaotong University, Southwest Jiaotong University, Chang'an University, etc., with the number of papers published being more than 20. Meanwhile, universities such as Hohai University, Chongqing Jiaotong University, China University of Geosciences, Central South University, Nanjing Forestry University, and Dalian University of Technology have also published a relatively large number of papers, indicating that universities play an important role in research and academic exchanges in this field. In addition, some institutions in research institutes and enterprises have also published a relatively large number of papers, such as the Chinese Academy of Sciences (19 papers), the Yangtze River Academy of Sciences (12 papers), and China Railway Tunnel Stock Co., Ltd. (10 papers).

Author cooperation.

Table 1 lists 10 important authors with high paper output and influence in this field, and their research results have actively promoted the academic research and technological development in this field. From the perspective of the number of published papers, the number of papers published by important authors varies within a certain range. Cheng Liangkui, Yang Ping and Wang Xu ranked the top three with 9, 8 and 6 papers respectively. From the perspective of influence, Cheng Liangkui is the author with the highest citation frequency of papers in this field. A total of 9 papers have been cited 1444 times, with an average citation frequency of 160.4 times per paper, indicating that his research results have received extensive academic attention and citation. The author with the second highest citation frequency of papers is Zhang Peiwen. Four of his papers have been cited 404 times, with an average citation

frequency of 101.0 times per paper. Although the number of papers of authors such as Chen Wenwu, Han Jun and Han Wenfeng is not large, the citation frequency of each paper is relatively high, which also shows their high research quality and influence in this field. From the perspective of the author's unit, the units of important authors cover multiple different research institutions and universities, among which the institutions such as China Metallurgical Group Architectural Research Institute and Lanzhou Jiaotong University have the largest number of important authors.

Table 1. Statistics of the number of published papers and citation frequency of important authors[5]

Number	Author	Unit	Number of papers	Citation frequency	Average citation frequency per paper
1	Cheng Liangkui	Architectural Research Institute of MCC Group	9	1444	160.4
2	Yang Ping	School of Civil Engineering, Nanjing Forestry University	8	255	31.9
3	Wang Xu	School of Civil Engineering, Lanzhou Jiaotong University; National - Local Joint Engineering Laboratory for Disaster Prevention and Control of Bridge and Tunnel Engineering	6	49	8.2
4	Chen Wenwu	School of Civil Engineering and Mechanics, Lanzhou University	5	364	72.8
5	Wang Xudong	Conservation Research Institute, Dunhuang Academy	5	49	9.8
6	Zhang Dexuan	Department of Civil Engineering, Shanghai Normal University	5	51	10.2
7	Zhang Peiwen	Architectural Research Institute of MCC Group	4	404	101.0
8	Yang Youhai	School of Civil Engineering, Lanzhou Jiaotong University	4	142	35.5
9	Han Jun	Rock Foundation Research Institute, Yangtze River Scientific Research Institute	4	274	68.5
10	Han Wenfeng	Tianjin Institute of Urban Construction	4	352	88.0

The cooperation frequency among authors in the field of domestic geotechnical reinforcement technology research is not high, and the range of cooperation times varies from 1 to 6 times. The five authors who have the most cooperation times with other authors are Wang Xu, Zhang Yanjie, Li Jiandong, Li Shucai and Jiang Daijun, etc., all with more than 4 times. The cooperation times of other authors are less, only 1 or 2 times. From the perspective of cooperation relationships, the research teams where Li Shucai, Zhang Qingsong and Tian Zhaobin, as well as Li Jiandong, Zhang Yanjie and Jiang Daijun are located cooperate more frequently, and members have cooperated in many papers. Although there is cooperation among other authors, no large-scale cooperation group has been formed. From the perspective of cooperation years, the average cooperation year of most authors is relatively new, concentrated after 2020, indicating that the cooperation and communication in this research field have increased in recent years, and the research cooperation has become more active.

3.3 Research Status Analysis

According to statistics, the keywords with higher frequencies in the papers of the domestic geotechnical reinforcement technology research field cover different aspects such as soil reinforcement, numerical simulation to construction technology, and shield tunneling, reflecting the diversity and extensiveness of the research in this field. Keywords such as soil reinforcement, numerical simulation, deep foundation pit, collapsible loess, and geotechnical anchorage have higher frequencies and are the research hotspots in this field; the appearance frequencies of keywords such as experimental research, model test, on-site monitoring, and on-site test are also relatively high, indicating that the research on experimental and on-site construction technologies has also received extensive attention in this field; high-frequency keywords such as shield tunneling construction, geotechnical anchorage technology, prestressed anchor cable, high-pressure jet grouting pile, and support structure reflect the technical and engineering application directions in this field; keywords such as collapsible loess foundation and loess tunnel appear as high-frequency words, indicating that the research on reinforcement technologies under special geological conditions has also been emphasized; from keywords such as "stability", "shear strength", "displacement", and "settlement", it can be inferred that the concerns in this field include the stability of soil and structures, shear strength, and deformation control; keywords such as numerical simulation, numerical analysis, finite element analysis, and finite element reflect the research methods of numerical calculation and simulation applied in this field. From the high-frequency keywords in the domestic geotechnical reinforcement technology research field, it can be seen that the research in this field focuses on multiple aspects such as from experimental research to technical application and from soil reinforcement to structural stability, reflecting the diversity and complexity of this field. These research hotspots provide important references and directions for academic research and engineering applications in this field.

The relevant literature in the field of domestic geotechnical reinforcement technology research is concentrated in the following five research themes:

(1) Research on geotechnical reinforcement technology for foundation pit and tunnel engineering. This theme mainly focuses on the application and research of reinforcement technology for geotechnical foundation pits and subway tunnels. The research content covers keywords such as deep foundation pit, geotechnical anchorage, numerical analysis, foundation pit excavation, and shield tunneling. These keywords reflect the concern of this research field for the reinforcement and stability problems in foundation pit and tunnel engineering. Keywords such as construction technology, prestressed anchor cable, anchor rod, and end anchorage indicate that the main content of the research is the research and application of reinforcement technology. Keywords such as displacement, deformation control, and monitoring reflect the evaluation and control of the reinforcement effect of foundation pits and tunnels in engineering practice. In addition, keywords such as optimization, freezing method, double-row piles, and underground diaphragm wall show the exploration of optimizing and improving the reinforcement technology in this research field.

(2) Research on dynamic compaction and stability in geotechnical reinforcement technology. This theme mainly focuses on the reinforcement technology and stability problems in complex geological conditions, such as dangerous rock areas and high slope areas. The research content includes reinforcement technologies such as dynamic compaction, foundation treatment, ps material application, and vacuum preloading, as well as research on rock mass, soil mechanics, rock mechanics, collapsibility, dry density, and microorganisms. Stability is the focus of this category of research. Keywords such as slope stability, collapsibility coefficient, and strength have a relatively high frequency in the research, indicating that parameters such as the dry density, collapsibility, collapsibility coefficient, and heat conduction rate of the soil are also key considerations in the research. In addition, reinforcement measures for dangerous rock areas such as dangerous rock reinforcement and patterned anchors are also one of the research directions of this category.

(3) Research on geotechnical reinforcement technology for foundation pit reinforcement and foundation engineering. This theme mainly focuses on the research on taking reinforcement measures and controlling foundation deformation in foundation pit engineering. The main research content includes the research on the reinforcement methods and techniques of foundation pit engineering, the bearing capacity of the foundation and the research on the effective reinforcement depth, as well as the reinforcement and deformation control measures in collapsible loess foundation and soft soil layer conditions. At the same time, foundation pit support and road engineering are also keywords with a relatively high frequency in this category. The research on reinforcement means such as high-energy dynamic compaction is also concerned in this category. The research on uneven settlement, surface settlement, and cantilever support structure is to control the ground settlement and deformation during the foundation pit construction process and ensure the engineering stability and long-term performance.

(4) Reinforcement of collapsible loess foundation and its application in tunnel engineering. This theme mainly focuses on the reinforcement technology of collapsible loess foundation and its application in underground engineering. The research content includes underground engineering construction and reinforcement technologies such as

soil reinforcement, shield tunnel, tunnel engineering, loess tunnel, and subway station. Among them, collapsible loess as a key research object under special geological conditions is widely discussed. Model tests, on-site monitoring, and on-site tests are important verification means in the research. In addition, the exploration of reinforcement mechanism, reinforcement range, influencing factors, and reinforcement effect is also the main research content of this category. Support structures, high-pressure jet grouting piles, and grouting are commonly used means in the reinforcement of collapsible loess foundation.

(5) Research on geotechnical loess reinforcement and stability. This theme mainly focuses on the application and stability problems of geotechnical reinforcement technology in loess geological conditions. The research content includes numerical simulation, experimental research, shear strength, finite element analysis, etc., as well as in-depth discussions on loess microscopic structure, microorganism-induced calcium carbonate deposition, and solidification mechanism. In addition, reinforcement technologies such as grouting reinforcement, underground pipelines, and loess slopes are also keywords with a relatively high frequency in this research field. Stability analysis and effect evaluation are important assessment and verification means in the research to ensure the effectiveness of reinforcement measures.

3.4 Research Hotspots and Frontier Analysis

According to the number of papers published in the field of domestic geotechnical reinforcement technology research over the years, this research field is divided into four different periods. Analyzing the high-frequency keywords in each stage can reveal the evolution process of research hotspots and frontiers in this field.

Fig 3 further shows the occurrence and frequency of the main high-frequency keywords in different periods. In 2005 and before, the main research hotspots in this field included soil reinforcement, foundation pits, shields, loess, and other aspects. The research in the fields of soil reinforcement and shields was relatively prominent. The keywords "soil reinforcement" and "shield" appeared 7 times and 12 times respectively, indicating that the research hotspots at this stage were mainly focused on soil reinforcement technology and shield tunnel engineering.

From 2006 to 2010, the research hotspots continued the directions before 2005 and began to pay attention to some new keywords, such as collapsible loess, numerical analysis, and model tests. The research on loess, shield tunnels, and deep foundation pits continued to increase, and numerical simulation and model tests became new research hotspots, reflecting the application of numerical analysis technology in research.

From 2011 to 2017, the research hotspots showed obvious expansion and deepening. The keywords "soil reinforcement" and "numerical simulation" became the main research frontiers, with frequencies reaching 26 times and 23 times respectively, indicating significant progress in soil reinforcement technology and numerical simulation. In addition, shield tunnels, loess, collapsible loess, etc. still maintained a high research heat, reflecting that these fields still received much attention during this period.

Fig. 3. Changes in high-frequency keywords in different periods[6]

From 2018 to the present, the research hotspots in the field of geotechnical reinforcement technology research continue to focus on the key points of previous periods. The keyword "numerical simulation" is still the main research frontier, with a frequency of 5 times. In addition, the frequencies of keywords such as "soil reinforcement" and "loess" also remain high, indicating that the research on soil reinforcement technology and loess geology still continues. During this period, "deep foundation pit" and "foundation reinforcement" also became new research hotspots, both with a frequency of 6 times, reflecting the attention to deep foundation pit and foundation reinforcement technology.

In general, the research hotspots and frontiers in the field of domestic geotechnical reinforcement technology research have evolved from early soil reinforcement and shields to later numerical simulation, deep foundation pits, and foundation

reinforcement technologies. These research hotspots reflect the diversity and development trend of research content in this field. The application of numerical simulation technology has received more attention in recent years, indicating that this technology plays an important role in the research of geotechnical reinforcement. At the same time, research on specific geological conditions, such as loess and collapsible loess, has also received continuous attention in various periods.

4 Research Conclusions

This paper studies the progress and trends of domestic geotechnical reinforcement technology research by using bibliometric analysis methods and vosviewer tools, combined with data analysis and visualization display methods. The research shows that the number of research documents in this field is increasing year by year, the academic community's attention to this field continues to increase, and the research institutions involve multiple universities, scientific research institutes and engineering enterprises. The cooperation network is also gradually expanding, showing the trend of multidisciplinary cooperation in this field.

From the perspective of research topics, domestic geotechnical reinforcement technology research topics cover multiple aspects such as soil reinforcement, foundation pit and subway tunnel reinforcement, loess geology, and shield tunnel engineering. The research content includes reinforcement technology and stability, numerical simulation and numerical analysis, experimental research, construction technology, etc. For reinforcement technologies under special geological conditions, such as collapsible loess foundations, special research has also been conducted. The breadth and diversity of research content indicate that domestic geotechnical reinforcement technology research has formed a comprehensive disciplinary system.

From the perspective of technology application and engineering practice, domestic geotechnical reinforcement technology research is not only limited to academic research, but also pays more attention to technology application and engineering practice. Means such as experimental research, field monitoring and effect evaluation provide important support for the application of reinforcement technology. Various reinforcement technologies, such as grouting reinforcement, prestressed anchor cables, and bolts, have been widely used in practical engineering.

From the perspective of research hotspots and frontiers, the hotspots and frontiers of domestic geotechnical reinforcement technology research are constantly evolving. In the early stage, it mainly focused on aspects such as soil reinforcement, shields, and foundation pits. Later, it gradually expanded to fields such as collapsible loess, numerical simulation, deep foundation pits, and foundation reinforcement. The application of numerical simulation technology has become the main research frontier in recent years, reflecting the important role of computational mechanics in geotechnical reinforcement research. Reinforcement technologies for specific geological conditions, such as loess and collapsible loess, continue to receive attention. Geotechnical anchoring, anchor cable technology and tunnel engineering are all hot research fields in multiple periods.

In general, while the field of domestic geotechnical reinforcement technology research is continuously making progress, the trend is gradually developing towards multidisciplinary intersection and comprehensiveness, especially the application of numerical simulation technology. In addition, reinforcement technologies for special geological conditions, such as loess and collapsible loess, also continue to receive attention in different periods. The practical application and engineering practice of reinforcement technologies have also become an important development direction in this field. Therefore, the future research trend may pay more attention to practicability, innovation and environmental friendliness to meet the actual needs of the geotechnical engineering field.

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