sustainability

MDPI

Review

Bibliometric and Knowledge Network of Global Research on Pile Foundations: A Review of Recent Developments

Aman Tiwari *, Nitin Dindorkar and Suneet Kaur

Maulana Azad National Institute of Technology, Bhopal 462003, India
* Correspondence: aman20tiwari@gmail.com; Tel.: +91-9926394648

Abstract: Foundation on soft soil has always been a challenge for civil engineers and pile foundation is by far the most suitable and comprehensive idea for construction on soft soil. In this study, we produced a comprehensive overview of pile foundation research from 1992 to 2021 by making use of bibliometric analysis. This study was conducted based on the Web of Science Core Collection Database. In this analysis, data were retrieved and then sieved for different parameters to organize the data into various categories by means of Excel and VOS viewer. The objective of the research was to make an explanatory data set in order to help researchers in the pile foundation area. A database of 4803 publications has been retrieved. The analysis results show that the People's Republic of China has yielded the greatest number of publications. Studies in this period are focusing on key factors associated with pile foundations such as soil structure interaction, pile group, settlement, liquefaction, bearing capacity etc. as suggested by the keywords analyzed in these publications. Analysis of the most cited articles in the field of Geotechnical and Geoenvironmental Engineering reveals that the research area has expanded from analyzing axial behavior and strength of pile foundations to analyzing seismic responses, further moving to sustainable structure and artificial intelligence applications in the concerned field in the last 30 years.

Keywords: bibliometric analysis; pile foundation; sustainable structure; VOS viewer; Web of Science

Citation: Tiwari, A.; Dindorkar, N.; Kaur, S. Bibliometric and Knowledge Network of Global Research on Pile Foundations: A Review of Recent Developments. *Sustainability* **2023**, *15*, 11108. https://doi.org/10.3390/su151411108

Academic Editors: Antonio Caggiano, Jian Zhou, Mahdi Hasanipanah and Danial Jahed Armaghani

Received: 16 June 2023
Revised: 6 July 2023
Accepted: 13 July 2023
Published: 17 July 2023

1. Introduction

1.1. General

Pile foundations are that part of the structure which transmits to, and into, the underlying soil or rock, the loads supported by the foundation and its self-weight. Pile foundations are the structural members used to transmit surface loads down to lower levels in the soil mass. This may be by vertical distribution of the load along the pile shaft or by direct application of the load to a lower stratum through the pile point. Piles are commonly employed in civil and marine engineering. Many studies on pile foundations have focused on the impact of vertical loads from above structures [1,2]. All piles have a combination of bearing and friction forces through which they transfer the load to the soil. It varies from one kind of soil to another. Rehabilitation and repairing of pile foundations is quite a difficult process. Therefore, strength, serviceability, economy, and constructability are all factors that must be taken into consideration while designing the structure [3]. With certain advantages of pile foundation, this field has evolved apparently in the construction area and some of its allied areas. In the early stages of its application, only static and vertical loading was considered. Later on, it has been examined and used for dynamic responses also [4,5]. Geotechnical parameters of soil, such as cohesion, internal friction angle, and many more, exhibit a high degree of variability and uncertainty and cannot be managed using typical deterministic design techniques [6]. Novak was the first to make an attempt to use continuum theory to understand the dynamic response of a single pile [7] and further proceeded with other theories [8]. Pile foundations without superstructures have been

increasingly popular in seismic research in recent years [9]. Various methods have been developed for soil structure interaction examinations, such as the Winkler model [10–12] and the plane strain model [13,14]. Furthermore, group of pile [15,16], combined pile [17,18], hybrid pile [19], pile subjected to lateral loads [20] owing to earthquakes, wind and water currents, traffic pressures, and soil conditions [21,22] and other advanced pile structures were developed after analysis by various researchers. Many of the recent studies on pile foundation are conducted by numerical modeling using various FEM software [23–25].

It is important to evaluate the growth trend in pile foundation research fully and quantitatively, as this can assist academic professionals in making educated decisions about their future studies. Additionally, it is difficult to organize, thoroughly summarize, and quantitatively assess the development trends and characteristics of a particular subject across a vast number of studies conducted over a lengthy period in typical review articles [26]. Pile foundation research, in particular, is an interdisciplinary field that encompasses environmental science [27], marine engineering [28], energy [29], economics, and other fields. Thus, bibliographic analysis is required to provide a full picture of pile foundation research.

In bibliometric analysis, statistical and mathematical methods are used to quantitatively evaluate various ways of distributing knowledge [30]. A research topic or field's intellectual structure and rising trends are presented by summarizing enormous amounts of data. Bibliometrics aims at a particular research area and scrutinizes the documentation produced, work conducted by each country, distribution of authors, changes in keywords, and spatiotemporal dynamics, which suggest the trends and reflect the direction of future research [31]. Thus, bibliometrics is widely used to analyze research publications [32], patents [33], international scientific and technological journals [34], institute and country collaborations [35], and other fields [36].

1.2. Research Focus

Bibliometric studies have the potential to facilitate the connection between scholarly research and the implementation of engineering practices, thereby addressing the gap in technology transfer and knowledge dissemination. Engineers can gain access to crucial knowledge for problem solving in the area of foundation and innovation by comprehending the papers that are most frequently cited and hold significant influence in their respective fields. The utilization of bibliometrics in engineering projects can facilitate the identification of pivotal technologies and methodologies that have exhibited significant influence within the field. This knowledge has the potential to inform and shape the process of pile foundation project planning and implementation, thereby increasing the likelihood of achieving successful outcomes.

2. Procedure of Analysis

The Web of Science Core Collection Database was used to conduct this investigation. Bibliometric analysis and science mapping are made possible with the use of tools such as MS Excel and VOS viewer. Using bibliometrics, the analysis was conducted on research on pile foundation from 1992 to 2021 based on various criteria such as number of publications, authors, collaboration, countries, and so on. The study included the geographical distribution of research areas and extensive analysis of authors, summarizing the trends of research globally in the last three decades. For the purpose of this study, the Science Citation Index (SCI) and the Science Citation Index Expanded (SCI-E) databases of the "Web of Science Core Collection" were used as object databases, and the search criterion is TS = ("PILE FOUNDATION" OR (("PILE *") AND ("FOUNDATION *"))). Records were extracted in a tab delimited file from the Web of Science. For each paper in the database, we scrutinized data based on the affiliations and initials of authors, language of publication, names of periodicals, year of publication, names of publishers, geographical locations, keywords, and the number of citations [37]. The citations and the number of publications may be slightly different because the data were collected at a specific time on 31 January 2022. New journals, issues, or articles may have been added to the index over the time period.

Furthermore, the retrieved database was refined to achieve the number of citations and the H-index of authors. The H-index indicates the authors' research quality and academic impact. A high H-index signifies high productivity and impact [38]. If two or more researchers, institutions, and/or countries are involved in a collaborative study, their present research patterns can be examined using cooperative network analysis [39]. Finally, research directions for the future are mentioned.

3. Results

3.1. Type of Document

By using the Web of Science database based on research on pile foundation, we have found that a total of 4803 documents are present in the last three decades, which includes articles, review, abstract etc depicted in Figure 1. To be precise, as shown in Table 1 there are 4494 articles, 102 article proceedings papers, 88 early access articles, 70 reviews, 29 editorial materials, and three meeting abstracts.

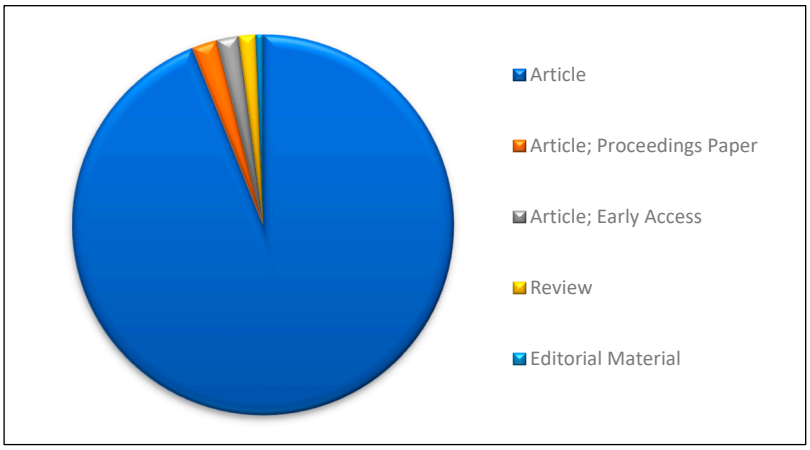

Figure 1. Pie chart representing the weightage of type of documents.

Table 1. Type of documents with number.

Document Type	N	%
Article	4494	93.5
Article, Proceedings Paper	102	2.1
Article, Early Access	88	1.8
Review	70	1.4
Editorial Material	29	0.6

N—number of documents, %—weightage with respect to total documents.

3.2. Features of Document Computed

With only 18 publications in 1991 to 644 publications in 2021, there has been a remarkable research increment (almost 35 times) in the field of pile foundation. Out of the total 4803 articles, there are 90 such articles that do not have any specified publication year. As shown in Figure 2, there is a marginal increase in the number of publications in the first two decades, i.e., 1992–2010, and then there is a thrust in the research area between 2010 and 2021. The length of a single publication in considered years ranges from 11 to 15 pages. As the research has gone wider in the area, so has the number of publications and, apparently the number of citations. The number of citations is one measure of a publication's scientific quality, since it signifies the publication's effect on the linked study area. In 2014, the total citation was 4991, which is the maximum and could be the reason for the rapid increment in the graph in the last decade. The low number of citations for the year 2021 signifies that the studies are new and will be cited in future studies to come. On the other hand, cited references have surged in every ten years, which shows the credibility, novelty,

and usefulness of the publications published in previous years. The Table 2 contains the document information.

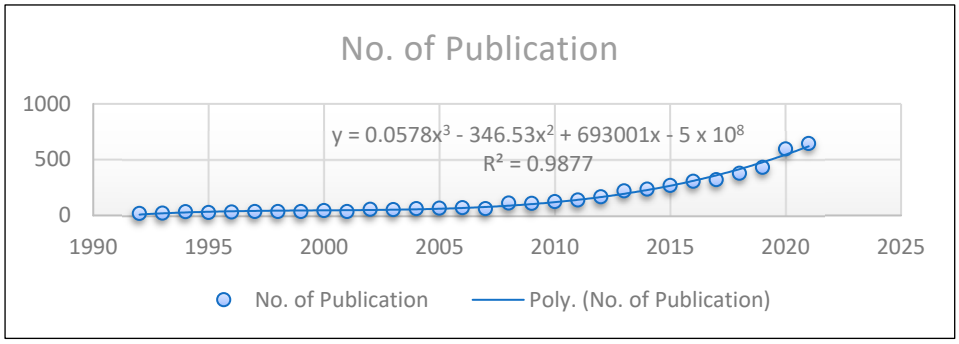

Figure 2. Graph with cumulative publications.

Table 2. Features of document year wise (1992–2021).

Years	P	PG	PG/P	CR	CR/P	TC	TC/P
1992	18	227	13	291	16	418	23
1993	21	267	13	350	17	371	18
1994	33	457	14	539	16	1124	34
1995	26	344	13	582	22	487	19
1996	31	362	12	1025	33	624	20
1997	34	434	13	622	18	1002	29
1998	35	373	11	603	17	916	26
1999	35	494	14	815	23	1184	34
2000	43	484	11	715	17	1529	36
2001	35	462	13	832	24	1674	48
2002	55	696	13	1136	21	1861	34
2003	52	674	13	1140	22	2066	40
2004	60	692	12	1230	21	1803	30
2005	65	932	14	1643	25	1922	30
2006	69	874	13	1431	21	3134	45
2007	61	697	11	1363	22	1728	28
2008	110	1322	12	2638	24	2482	23
2009	108	1380	13	2874	27	3495	32
2010	123	1398	11	3017	25	2846	23
2011	138	1698	12	3356	24	3081	22
2012	166	1964	12	4098	25	3182	19
2013	219	2632	12	5917	27	4362	20
2014	236	3002	13	7125	30	4991	21
2015	268	3334	12	8868	33	4797	18
2016	306	3901	13	9888	32	4388	14
2017	320	4296	13	11,616	36	4049	13
2018	377	5023	13	13,931	37	3759	10
2019	430	6044	14	16,314	38	2771	6
2020	595	8353	14	24,301	41	2444	4
2021	644	9393	15	26,053	40	636	1

P—number of publications, PG—pages, CR—cited references, TC—citations, PG/P—average number of pages, CR/P—average cited references, TC/P—average citations in a paper.

With the above tabled data, we have also performed a regression analysis (Figure 2) where it can be seen that the graph is accelerating in a fair manner, having R^2 value equal to 0.9877. Regression coefficients are estimations of unknown publication factors that characterize the relationship between a predictor and a response variable. R^2 coefficient of determination is a statistical measure of how well regression predictions approach the observed data points in regression. R^2 value of 1 shows that the regression predictions fit the data exactly.

3.3. Subject Category, Journals and Publishers

The data were also categorized and differentiated based on the subject category in which the documents fell. The number of subject categories in which documents were taken is 10, considering significant numbers had a percentage higher than five. Pile foundation research has been conducted extensively in various fields of science, such as geology, material science, civil engineering, oceanography, and many more. Out of the several fields, the 'Geological' engineering field has the maximum number of publications with 2264 publications, followed by 'Geosciences' with 1608, 'Civil' engineering with 1493, 'Construction and Building Technology' with 426 and so on. In Table 3, the 'Geological' engineering category has more than half the publications as compared to the core civil engineering category, which is at third position. The presence of 'Computer Science' in the list reveals the diffusion of software in the field of construction as well. Many of the current studies use various numerical modeling software to analyze and design the structures.

Table 3. Top 10 subject categories with respective number of publications.

Subject Category	TP	R	%
Geological	2264	1	47.14
Geosciences	1608	2	33.48
Civil	1493	3	31.08
Construction and Building Technology	426	4	8.87
Ocean	402	5	8.37
Materials Science	348	6	7.25
Oceanography	323	7	6.72
Mechanical	303	8	6.31
Computer Science	295	9	6.14
Mechanics	264	10	5.50

TP—Total number of publications, R—Ranking as per number of publications, %—Percentage of publication.

While analyzing the documents from 1992 to2021, out of the top 20 journals, "Soil Dynamics and Earthquake Engineering" is featured with a maximum of 294 publications, while "Journal of Geotechnical and Geoenvironmental Engineering" follows the table with 253 publications. Software evolution in the field of construction and allied areas insists researchers to publish articles in the concerned journals, which can be seen in the table having "Computers and Geotechnics" on the third position with more than 200 publications.

"Proceedings of The Institution of Civil Engineers-Geotechnical Engineering" and "Soils and Foundations" have the same rank as they both have the same number of publications, i.e., 133. "Geotechnique" has highest TC/TP ratio (52.6), on the other hand "Journal of Geotechnical and Geoenvironmental Engineering" being on the second rank has a maximum number of citations which is 7711. Table 4 shows the 20 most productive journals, with ranking corresponding to their number of publications. IF represents the impact factor of the respective journal taken from JCR. Impact factor is a measurement of the frequency with which the average article in a journal has been referenced in a specific duration, hence the higher the impact factor, the more the citation of a publication or journal, subsequently reaching a greater extent.

Out of a total of 4803 publications published in a specified duration of three decades, 3666 publications (more than 75%) are published by the top 20 publishers. Publication "Elsevier SCI LTD" is at the top with 763 publications (15.9% of total publications), followed by "ASCE-AMER SOC Civil Engineers" with 591 publications (12.3% of total publications). These two are the only publishers whose percentage of publications is greater than 10% in the pile foundation stream. The rest of the publishers have a lower percentage of publications, ranging from 7 to 1% only. On the contrary, "Elsevier Science BV", being on the 17th position, has the highest ratio (24.31) of citations. Details in Table 5 is showing twenty most active publishers in the field.

Table 4. Top twenty journals that publish pile foundation related studies.

Journal Name	TP (R)	TC	TC/TP	IF
Soil Dynamics and Earthquake Engineering	294 (1)	5573	19.0	3.718
Journal of Geotechnical and Geoenvironmental Engineering	253 (2)	7711	30.5	4.012
Computers and Geotechnics	205 (3)	4124	20.1	4.956
Canadian Geotechnical Journal	169 (4)	3759	22.2	3.725
Ocean Engineering	135 (5)	1433	10.6	3.795
Proceedings of The Institution of Civil Engineers-Geotechnical Engineering	133 (6)	1278	9.6	1.341
Soils and Foundations	133 (6)	2372	17.8	2.436
International Journal of Geomechanics	120 (7)	1396	11.6	3.819
Géotechnique	105 (8)	5518	52.6	4.592
Advances in Civil Engineering	98 (9)	193	2.0	1.924
Marine Georesources and Geotechnology	91 (10)	450	4.9	2.673
Engineering Structures	84 (11)	1180	14.0	4.471
International Journal for Numerical and Analytical Methods in Geomechanics	72 (12)	2279	31.7	4.264
Geomechanics and Engineering	71 (13)	440	6.2	3.223
Soil Mechanics and Foundation Engineering	69 (14)	141	2.0	0.806
Geotechnical Testing Journal	62 (15)	575	9.3	1.469
Acta Geotechnica	60 (16)	774	12.9	5.856
KSCE Journal of Civil Engineering	59 (17)	381	6.5	1.805
Journal of Bridge Engineering	57 (18)	785	13.8	3.066
Bautechnik	52 (19)	135	2.6	0.408

TC—citations, TC/TP—average citations, IF—Impact factor.

Table 5. Twenty most active publishers in the pile foundation field.

Publisher	TP	(%)	TC	TC/TP
Elsevier Sci Ltd.	763	15.9	14,360	18.82
ASCE	591	12.3	12,757	21.59
Pergamon-Elsevier Science Ltd.	335	7.0	7019	20.95
Ice Publishing	265	5.5	4704	17.75
Springer	206	4.3	2131	10.34
Hindawi Ltd.	179	3.7	426	2.38
MDPI	165	3.4	638	3.87
Springer Heidelberg	147	3.1	1018	6.93
Japanese Geotechnical Soc	133	2.8	2372	17.83
Techno-Press	113	2.4	723	6.40
Taylor & Francis Ltd.	102	2.1	688	6.75
Taylor & Francis Inc.	101	2.1	534	5.29
Wiley	96	2.0	1354	14.10
Amer Soc Testing Materials	80	1.7	608	7.60
Elsevier	76	1.6	871	11.46
Canadian Science Publishing, NRC Research Press	72	1.5	1588	22.06
Elsevier Science BV	65	1.4	1580	24.31
Ernst & Sohn	62	1.3	117	1.89
Korean Society of Civil Engineers-KSCE	58	1.2	372	6.41
Canadian Science Publishing	57	1.2	875	15.35

3.4. Author and Language

While examining the author yield in this particular area of research, it has been seen that the author "El Naggar MH" has topped the list with 59 publications, followed by him "Liu HL" has a total of 39 publications. Ratio CP/TP indicates the relation between collaborative and total publication. Table 6 shows that 19 out of 20 top authors have published their articles collaboratively. Surprisingly, there is only a single author (Liang, FY) who has published an individual publication. Many of the authors have published the same number of articles, hence it is not easy and righteous to rank them. Sometimes

the H-index is the proper criterion to identify authors' yield and valuable contribution in a particular field. Based on this criterion, the author "Randolph, MF" has contributed pre-eminently in the field of pile foundation with an H-index of 68. Apart from him, "Ng, CWW", "Gazetas, G", and "Zhang, LM" are some other authors having an H-index of more than or equal to 50. Figure 3 depicts the total publications of each author in the form of the intensity of color in the picture; the dark yellow color indicates a high number of publications. The present picture is obtained with the help of the VOS viewer application.

Table 6. Ten most productive authors of pile foundation related research.

Author	TP	(%)	IP	CP	CP/TP	H-Index
El Naggar, MH	59	1.23	0	59	1	19
Liu, HL	39	0.81	0	39	1	39
Bhattacharya, S	28	0.58	0	28	1	29
Aznarez, JJ	27	0.56	0	27	1	16
Randolph, MF	26	0.54	0	26	1	68
Ling, XZ	26	0.54	0	26	1	19
Ding, XM	26	0.54	0	26	1	20
Maeso, O	25	0.52	0	25	1	17
Wang, KH	24	0.50	0	24	1	16
Huang, MS	24	0.50	0	24	1	30
Jeng, DS	22	0.46	0	22	1	43
Kong, GQ	20	0.42	0	20	1	24
Laloui, L	20	0.42	0	20	1	45
Ng, CWW	19	0.40	0	19	1	50
Ibsen, LB	19	0.40	0	19	1	18
Gazetas, G	19	0.40	0	19	1	50
Liang, FY	18	0.37	1	17	0.95	15
Zhang, LM	18	0.37	0	18	1	51
Zhang, F	18	0.37	0	18	1	26
Sritharan, S	18	0.37	0	18	1	23

TP—Total number of publications, IP—Individual-author publications, CP—Collaboration publications.

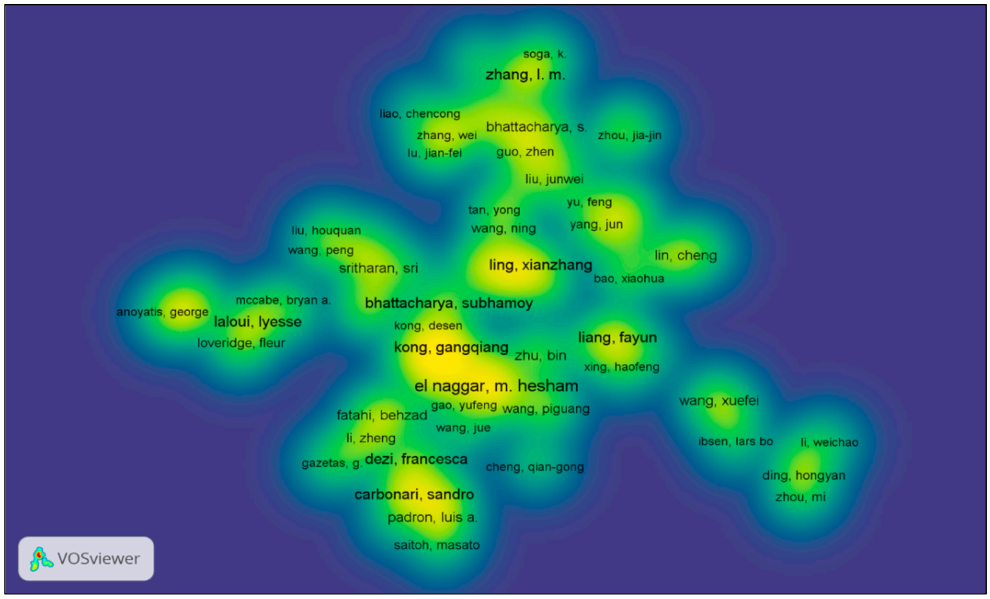

Figure 3. Intensity of authors according to number of publications.

As it is known that English is the most acceptable language across the globe, the maximum number of documents published are in English. Out of 4803 documents, 4683 are in English (approx. 97%), followed by German with 87 documents, 11 in Spanish, six in Turkish and four in Japanese, and a few documents in Portuguese, Croatian, French, Czech,

Polish, Finnish, Chinese, and Russian languages. Top five languages with corresponding number of documents are shown in Table 7 and with a share depiction in Figure 4.

Table 7. Top five languages used in published articles.

Language	N
English	4683
German	87
Spanish	11
Turkish	6
Japanese	4

N—Number of Documents.

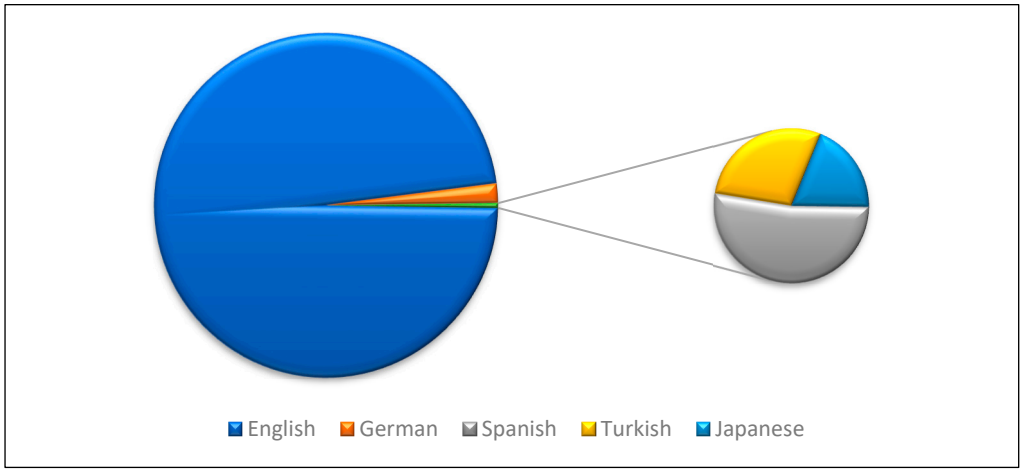

Figure 4. Weightage of languages in overall publications.

3.5. Author Keyword

Author keywords were extracted and segmented for every decade separately to understand the usage and coverage of each keyword in different times, i.e., 1992–2001, 2002–2011, and 2012–2021. In total, we found 2142 keywords from 1992 to 2021, which was for the last three decades considered in this study. 'Pile', being the most widely used word is on the top position all through three decades as certain as it is, while 'pile foundation' improved its position in the second decade, keeping it for the next decade, while also positioning itself as second in the overall analysis. It can be clearly seen that as research on pile foundation increased in the last decade of consideration, similarly, the occurrence of keywords increased exponentially in this period. Word 'Monopile' is practiced interestingly, with 0 in first to 103 in last decade. In Figure 5, each term is represented by a circle on the map. The figure depicts the co-occurrence of a keyword in extracted publications at a minimum of five times. The diameter of the circle shows the number of links between the two keywords. As a result, a wider circle indicates more connections with other keywords. Between two circles, the thickness of the line represents the frequency with which the words are used together. Table 8 shows the usage of each keyword with respect to the different decades, and Figure 6 presents the temporal analysis of these keywords for three decades.

3.6. Ten Most Cited Articles in Pile Foundation Research

Table 9 shows the articles that are most cited in the pile foundation field for the selected duration of this study. The "Energy foundations and other thermo-active ground structures" [40] article is the most cited with a total citation of 684. The article was published in the year 2006 and is still quite useful and relevant for current studies as it is citated 258 times in the last ten years. "Seismic soil-pile-structure interaction experiments and analyses" [41] is the second oldest article in the list and has the second most citations with 441 times, whereas "Axisymmetrical time-domain transmitting boundaries" is the oldest article [42] and "Response of stiff piles in sand to long-term cyclic lateral loading" [43] is

the newest article with 331 and 275 citations, respectively. An analysis of the tabled data reflects that energy related work and dynamics in pile foundations are dominant in these years. Total citation data were collected with respect to all of the databases retrieved from the Web of Science [44–49].

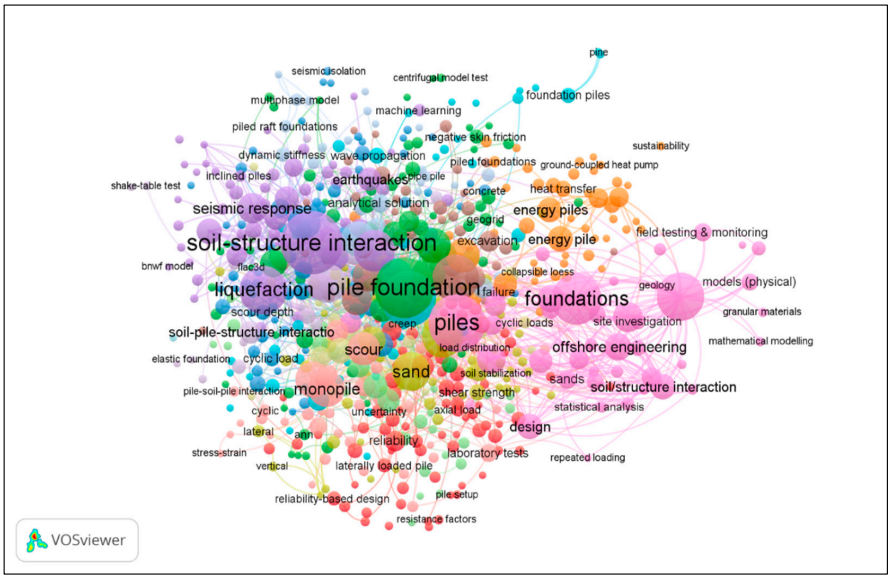

Figure 5. Keyword analysis map.

Table 8. Top ten keywords with temporal differentiation for each decade.

Keywords	1992–2021	1992–2001	2002–2011	2012–2021
Pile	431	48	114	269
Pile foundation	360	16	87	257
Soil structure interaction	292	19	67	206
Foundation	248	17	76	155
Pile group	159	5	46	108
Settlement	153	16	28	109
Liquefaction	152	5	39	108
Sand	125	6	22	97
Bearing capacity	115	9	17	89
Monopile	107	0	4	103

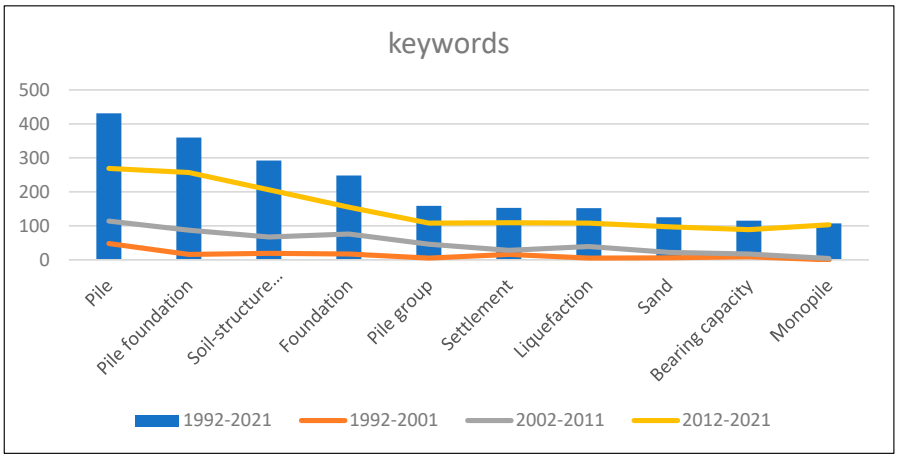

Figure 6. Temporal analysis of keywords.

Table 9. Ten most productive articles.

Article	TC	Citation in Last 10 Years	PY
Energy foundations and other thermo-active ground structures	684	258	2006
Seismic soil-pile-structure interaction experiments and analyses	441	127	1999
Experimental and numerical investigations of the behavior of a heat exchanger pile	413	109	2006
Science and empiricism in pile foundation design	410	176	2003
Energy pile test at Lambeth College, London: Geotechnical and thermodynamic aspects of pile response to heat cycles	385	141	2009
Axisymmetrical time-domain transmitting boundaries	331	34	1994
Piled raft foundations: Design and applications	282	49	2001
Response of stiff piles in sand to long-term cyclic lateral loading	275	138	2010
Behavior of monopile foundations under cyclic lateral load	244	152	2009
A new model and analytical solutions for borehole and pile ground heat exchangers	213	61	2010

TC—Total Citation, PY—Publication Year.

3.7. Countries Involved

The People's Republic of China is leading the way as far as the number of publications is considered, with 1672 total publications in the last three decades, followed by the USA with 739 publications, which is less than half of the earlier one. Though total citation is highest for the country having the highest number of publications, the ratio of citation to publication is led by Australia (TC/TP = 24.30), even if its ranking is fourth out of the top 10 nations worldwide as reflects in Table 10. The data show that analysis on pile foundation is conducted in abundance by Asian countries, since the top 10 countries consist of five Asian countries, and two countries from the European and American continents. If the top two countries are excluded then the rest of the countries have less than 10 percent of publications individually, considering the total publication. Ironically, South Korea spends 4.53% of its GDP on research and development, just managing to be in the table of the top ten productive countries in our concerned area. India, being a developing nation is spending only 0.65% of its GDP on R&D [50,51]. Here, one matter of fact should be brought to attention, which is that 113 countries' data are missing, or can be said that it is not declared in the given data.

While creating a graphical representation on VOS viewer software (version 1.6.17), the minimum number of documents for considering any country is taken as three and the minimum number of citations for a country is taken as five, where out of 91 countries, 68 meet the thresholds. A VOS viewer created network diagram is shown in Figure 7, which designates different countries and collaboration. The size or intensity of the circle represents the quantity of publications of a respective country, and the intensity of the link represents collaboration between the countries.

3.8. Sustainablity in Focus

Recently, sustainability has become an increasingly important factor in all aspects of infrastructure development, but especially in the installation of pile foundations. Eco-friendly procedures that lessen the infrastructure's negative effects on the environment and boost its long-term viability are becoming increasingly important as the need for such projects rises. Significant developments have been made to improve the sustainability of pile foundations. The carbon footprint of building has decreased because to engineers' increased emphasis on eco-friendly materials like recycled steel and concrete [52,53]. Precast piles, another cutting-edge building method, are rising in popularity due to their efficiency

and lower waste output. Environmental issues are taken into account in sustainable pile foundation designs to provide maximum energy efficiency and little impact to local ecosystems. Sustainable approaches included into pile foundation construction not only increase the infrastructure's durability, but also pave the way for a more environmentally friendly and long-lasting future. The most influential journals and publishers that have covered sustainable development in infrastructure projects in the recent past are shown in Table 11. Table 11 shows the journals, their publishers, year of publication and citations of respective papers. It can be seen that after the year 2010 there has been substantial progress in the area of suitable development and its research, which can be inferred by the increasing number of citations also, rising from 21 citations of a paper from "Water Resource Management" journal in 2011 to 68 citations of a paper from "Processes" in 2020.

3.9. Significance of the Analysis

Bibliometric research possesses inherent scientific significance and engineering application value, owing to its distinctive contributions to the realms of academia and practical industries. The evaluation of research impact can be achieved through bibliometric research, which provides a quantitative assessment of the influence of research papers, journals, or individual researchers. Through the examination of citation patterns and other bibliometric indicators, scholars are able to assess the impact and significance of scientific publications, thereby offering valuable insights into the caliber and importance of research output. The assessment of research productivity is facilitated by bibliometrics, which enables the evaluation of researchers, institutions, or countries based on their scientific output. Comparisons and benchmarking are facilitated by this process, thereby assisting funding agencies and policymakers in making well-informed decisions regarding the allocation of research funding.

Bibliometric analyses have the capacity to unveil collaborative networks among researchers and institutions through the process of mapping. The comprehension of how knowledge dissemination and interdisciplinary collaborations contribute to scientific advancements is of utmost importance. Resource allocation is a crucial aspect in engineering disciplines, and bibliometrics plays a significant role in facilitating the efficient distribution of resources. Through the process of identifying areas of active research and prominent researchers, institutions and companies are able to strategically allocate their efforts and investments towards projects that are both relevant and impactful.

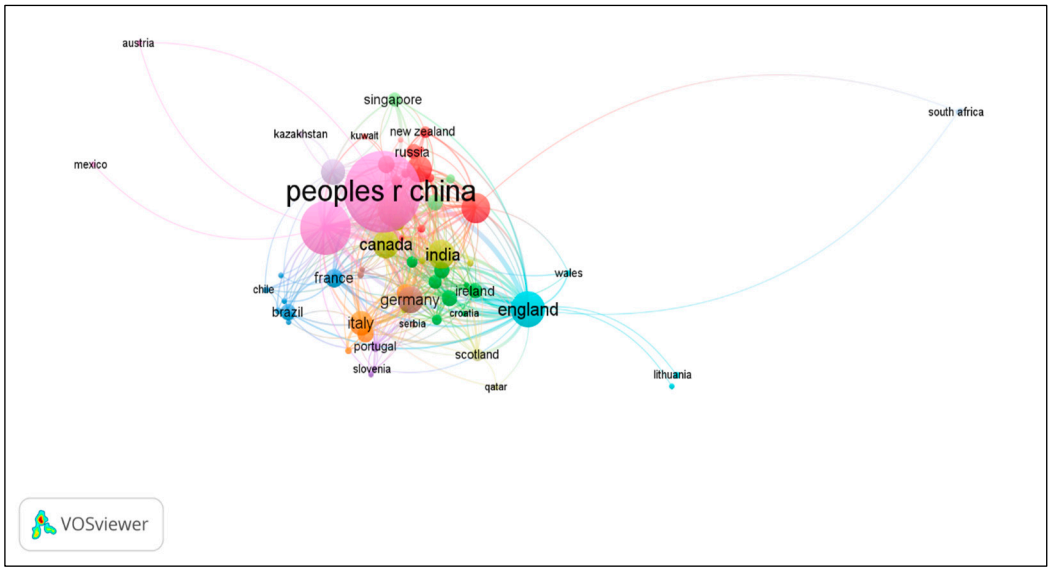

Figure 7. Intensity and collaboration of countries.

Table 10. Ten most productive countries/territories conducting pile foundation related research.

Countries/Regions	TP	TC	TC/TP	%	GDP (in Trillion $)	% of GDP on R&D
People's Republic of China	1672	16,279	9.74	34.81	13.4	2.14
USA	739	12,305	16.65	15.39	20.49	2.83
England	344	6427	18.68	7.16	2.83	1.70
Australia	303	7363	24.30	6.31	1.33	1.87
Japan	247	4685	18.97	5.14	4.97	3.28
India	237	2965	12.51	4.93	2.72	0.65
Canada	212	3510	16.56	4.41	1.71	1.54
Germany	203	2373	11.69	4.23	4.00	3.13
Iran	191	2678	14.02	3.98	0.61	0.83
South Korea	180	2094	11.63	3.75	1.58	4.53

TP—Total number of publications, TC—Total number of citations, TC/TP—Average number of citations in a publication, GDP—Gross domestic production of country.

Table 11. Most promising journals and publishers conducting sustainable pile foundation related research.

S.No.	Source Title	Publisher	Publication Year	Cited Reference Count
1	Applied Acoustics	Elsevier Sci Ltd.	2003	19
2	Water Science and Technology	IWA Publishing	2006	5
3	Water Resources Management	Springer	2011	21
4	Journal Of Water Supply Research and Technology-Aqua	IWA Publishing	2013	24
5	Water Science and Technology	IWA Publishing	2014	25
6	Clean-Soil Air Water	Wiley	2014	25
7	Expert Systems with Applications	Pergamon-Elsevier Science Ltd.	2014	52
8	Materiales De Construccion	Consejo Superior Investigaciones Cientificas-Csic	2015	41
9	Construction And Building Materials	Elsevier Sci Ltd.	2016	10
10	Advances In Applied Ceramics	Taylor & Francis Ltd.	2017	11
11	Journal of Cleaner Production	Elsevier Sci Ltd.	2018	54
12	Proceedings of the Institution of Civil Engineers-Water Management	ICE Publishing	2018	34
13	Processes	MDPI	2020	68
14	Sustainability	MDPI	2021	19
15	Building And Environment	Pergamon-Elsevier Science Ltd.	2021	41

4. Discussion and Conclusions

In the present article, bibliometric analysis has been applied to the pile foundation literature, allowing for a more accurate classification of prior studies, and facilitating the projection of future work in the field. Using bibliometric analysis, one can look at a wide range of patterns in the existing research, including those between authors, collaboration

networks, countries, journals, and keywords. In this article, we present an up-to-date assessment of the research trends in pile foundation based on a bibliometric study of publications published between 1992 and 2021, from a global perspective to a detailed profile.

According to the statistical findings,

1. There has been a huge increase in pile foundation research over the past three decades, with China accounting for nearly 35% of all publications.
2. Research on pile foundations developed rapidly after 2008 and is accelerating exponentially, which shows the severity and importance of pile foundations in modern infrastructure taking place around the globe.
3. As the research on pile foundation has increased in the last decade, every individual area, i.e., soil structure interaction, pile group, settlement, liquefaction, monopile, etc., has been touched extensively by researchers.
4. The People's Republic of China allocates around 2.14% of its GDP for R&D has nearly 35% of total publications, whereas South Korea allocates the highest 4.53% for R&D, out of the top productive countries considered in the study.
5. Based on current trends, it is evident that future research on pile foundation will prioritize sustainable development.
6. It can be mentioned that future studies will be focused on the dynamics of pile foundations and software involvement with artificial intelligence.

The reliance of bibliometric analysis on pile foundation research is predominantly centered on quantitative data. This type of analysis primarily emphasizes citation counts and other quantitative metrics as indicators of the impact of research in this field. Retrospective studies inherently possess a retrospective nature, as they heavily rely on historical data. The present bibliometric analysis can play a crucial role in the identification of emerging research trends and areas of interest within a pile foundation discipline. Through the examination of publication patterns and the identification of co-occurring keywords, scholars can accurately identify domains experiencing rapid expansion or diminishing interest. This analytical approach facilitates a more comprehensive understanding of the present status and prospective trajectories of a particular field.

Author Contributions: Conceptualization, A.T.; methodology, A.T.; software, A.T.; resources, N.D.; data curation, A.T.; writing—original draft preparation, A.T.; writing—review and editing, A.T.; supervision, N.D. and S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study is retrieved from the Web of Science database.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bea, R.G.; Jin, Z.; Valle, C.; Ramos, R. Evaluation of reliability of platform pile foundations. *J. Geotech. Geoenviron. Eng.* **1999**, *125*, 696–704. [CrossRef]
2. Tang, W.H.; Kulhawy, F.H. Uncertainties in Offshore Axial Pile Capacity. In *Foundation Engineering*; ASCE: Reston, VA, USA, 1989; pp. 833–847.
3. Magade, S.B.; Ingle, R.K. Analysis methods for pile foundation: A critical review of the literature and recommended suggestions. *Innov. Infrastruct. Solut.* **2021**, *6*, 1–11. [CrossRef]
4. Pender, M.J. Aseismic pile foundation design analysis. *Bull. New Zealand Soc. Earthq. Eng.* **1993**, *26*, 49–160. [CrossRef]
5. Vugts, J.H.; Dob, S.L.; Harland, L.A. The extreme dynamic response of bottom supported structures using an equivalent quasi-static design wave procedure. *Appl. Ocean. Res.* **1998**, *20*, 37–53. [CrossRef]
6. Liang, R.Y.; Nusier, B.O.; Malkawi, A.H. A reliability based approach for evaluating the slope stability of embankment dams. *Eng. Geol.* **1999**, *54*, 271–285. [CrossRef]
7. Novak, M. Dynamic stiffness and damping of piles. *Can. Geotech. J.* **1974**, *11*, 574–598. [CrossRef]
8. Zheng, C.; Ding, X.; Sun, Y. Vertical vibration of a pipe pile in viscoelastic soil considering the three-dimensional wave effect of soil. *Int. J. Geomech.* **2016**, *16*, 04015037. [CrossRef]

9. Zhao, M.; Huang, Y.; Wang, P.; Cao, Y.; Du, X. An analytical solution for the dynamic response of an end-bearing pile subjected to vertical P-waves considering water-pile-soil interactions. *Soil Dyn. Earthq. Eng.* **2022**, *153*, 107126. [CrossRef]
10. Di Laora, R.; Mandolini, A.; Mylonakis, G. Insight on kinematic bending of flexible piles in layered soil. *Soil Dyn. Earthq. Eng.* **2012**, *43*, 309–322. [CrossRef]
11. Anoyatis, G.; Di Laora, R.; Mandolini, A.; Mylonakis, G. Kinematic response of single piles for different boundary conditions: Analytical solutions and normalization schemes. *Soil Dyn. Earthq. Eng.* **2013**, *44*, 183–195. [CrossRef]
12. Anoyatis, G.; Lemnitzer, A. Kinematic Winkler modulus for laterally-loaded piles. *Soils Found.* **2017**, *57*, 453–471. [CrossRef]
13. Ke, W.; Zhang, C. A closed-form solution for kinematic bending of end-bearing piles. *Soil Dyn. Earthq. Eng.* **2017**, *103*, 15–20. [CrossRef]
14. Zhang, C.; Deng, P.; Ke, W. Assessing physical mechanisms related to kinematic soil-pile interaction. *Soil Dyn. Earthq. Eng.* **2018**, *114*, 22–26. [CrossRef]
15. Xu, Q.; Zhu, H.; Ma, X.; Ma, Z.; Li, X.; Tang, Z.; Zhuo, K. A case history of shield tunnel crossing through group pile foundation of a road bridge with pile underpinning technologies in Shanghai. *Tunn. Undergr. Space Technol.* **2015**, *45*, 20–33. [CrossRef]
16. Yan, K.; He, J.; Cheng, Q.; Fan, G.; Wang, Z.; Zhang, J. A centrifugal experimental investigation on the seismic response of group-pile foundation in a slope with an inclined weak intercalated layer. *Soil Dyn. Earthq. Eng.* **2020**, *130*, 105961. [CrossRef]
17. Bhaduri, A.; Choudhury, D. Steady-state response of flexible combined pile-raft foundation under dynamic loading. *Soil Dyn. Earthq. Eng.* **2021**, *145*, 106664. [CrossRef]
18. Chanda, D.; Saha, R.; Haldar, S. Behaviour of piled raft foundation in sand subjected to combined VMH loading. *Ocean Engineering.* **2020**, *216*, 107596. [CrossRef]
19. Li, L.; Liu, H.; Wu, W.; Wen, M.; El Naggar, M.H.; Yang, Y. Investigation on the behavior of hybrid pile foundation and its surrounding soil during cyclic lateral loading. *Ocean. Eng.* **2021**, *240*, 110006. [CrossRef]
20. Matlock, H.; Reese, L.C. Generalized solutions for laterally loaded piles. *Trans. Am. Soc. Civ. Eng.* **1962**, *127*, 1220–1248. [CrossRef]
21. Randolph, M.F. The response of flexible piles to lateral loading. *Geotechnique* **1981**, *31*, 247–259. [CrossRef]
22. Rollins, K.M.; Peterson, K.T.; Weaver, T.J. Lateral load behavior of full-scale pile group in clay. *J. Geotech. Geoenviron. Eng.* **1998**, *124*, 468–478. [CrossRef]
23. Khari, M.; Dehghanbandaki, A.; Armaghani, D.J. Physical modelling of bending moments in single piles under combined loads in layered soil. *Geomech. Eng.* **2021**, *25*, 373. [CrossRef]
24. Lv, Y.; Liu, H.; Ng, C.W.; Ding, X.; Gunawan, A. Three-dimensional numerical analysis of the stress transfer mechanism of XCC piled raft foundation. *Comput. Geotech.* **2014**, *55*, 365–377. [CrossRef]
25. Mendonca, A.V.; Paiva, J.B. An elastostatic FEM/BEM analysis of vertically loaded raft and piled raft foundation. *Eng. Anal. Bound. Elem.* **2003**, *27*, 919–933. [CrossRef]
26. Zeng, J.; Qu, J.; Ma, H.; Gou, X. Characteristics and Trends of household carbon emissions research from 1993 to 2019: A bibliometric analysis and its implications. *J. Clean. Prod.* **2021**, *295*, 126468. [CrossRef]
27. Björdal, C.G.; Elam, J. Bacterial degradation of nine wooden foundation piles from Gothenburg historic city center and correlation to wood quality, environment, and time in service. *Int. Biodeterior. Biodegrad.* **2021**, *164*, 105288. [CrossRef]
28. Li, L.; Gong, W.; Li, J. Service life of prestressed high-strength concrete pile in marine environment considering effects of concrete stratification and temperature. *Constr. Build. Mater.* **2020**, *253*, 119233. [CrossRef]
29. Yu, Q.; Yu, H.; Zhou, L.; Meng, A.; Hu, X.; Hou, X. Structural energy transfer to the elevated pile-cap foundation of an offshore wind turbine based on extracted transfer path analysis. *J. Sound Vib.* **2021**, *512*, 116388. [CrossRef]
30. Rahman, M.; Haque, T.L.; Fukui, T. Research Articles Published in Clinical Radiology Journals: Trend of Contribution from Different Countries1. *Acad. Radiol.* **2005**, *12*, 825–829. [CrossRef]
31. Wang, Z.; Zhao, Y.; Wang, B. A bibliometric analysis of climate change adaptation based on massive research literature data. *J. Clean. Prod.* **2018**, *199*, 1072–1082. [CrossRef]
32. Peng, Y.; Lin, A.; Wang, K.; Liu, F.; Zeng, F.; Yang, L. Global trends in DEM-related research from 1994 to 2013: A bibliometric analysis. *Scientometrics* **2015**, *105*, 347–366. [CrossRef]
33. Narin, F. Patent bibliometrics. *Scientometrics* **1994**, *30*, 147–155. [CrossRef]
34. Dastidar, P.G.; Kumar, J.D. Content analysis of documents using neural networks: A study of antarctic science research articles published in international journals. *Adv. Polar Sci.* **2012**, *23*, 41–46. [CrossRef]
35. Mindeli, L.E.; Markusova, V.A. Bibliometric studies of scientific collaboration: International trends. *Autom. Doc. Math. Linguist.* **2015**, *49*, 59–64. [CrossRef]
36. Rajendram, R.; Lewison, G.; Preedy, V.R. Worldwide alcohol-related research and the disease burden. *Alcohol Alcohol.* **2006**, *41*, 99–106. [CrossRef]
37. Zhao, Y.; Jiang, Y.; Zhou, Z.; Yang, Z. Global trends in karst-related studies from 1990 to 2016: A bibliometric analysis. *Alex. Eng. J.* **2021**, *60*, 2551–2562. [CrossRef]
38. Zhai, L.; Yan, X.; Zhu, B. The h l-index: Improvement of h-index based on quality of citing papers. *Scientometrics* **2014**, *98*, 1021–1031. [CrossRef]
39. Powell, W.W.; Koput, K.W.; Smith-Doerr, L. Interorganizational collaboration and the locus of innovation: Networks of learning in biotechnology. *Adm. Sci. Q.* **1996**, *1*, 16–45. [CrossRef]
40. Brandl, H. Energy foundations and other thermo-active ground structures. *Géotechnique* **2006**, *56*, 81–122. [CrossRef]

41. Boulanger, R.W.; Curras, C.J.; Kutter, B.L.; Wilson, D.W.; Abghari, A. Seismic soil-pile-structure interaction experiments and analyses. *J. Geotech. Geoenviron. Eng.* **1999**, *125*, 750–759. [CrossRef]
42. Deeks, A.J.; Randolph, M.F. Axisymmetric time-domain transmitting boundaries. *J. Eng. Mech.* **1994**, *120*, 25–42. [CrossRef]
43. LeBlanc, C.; Houlsby, G.T.; Byrne, B.W. Response of stiff piles in sand to long-term cyclic lateral loading. *Géotechnique* **2010**, *60*, 79–90. [CrossRef]
44. Laloui, L.; Nuth, M.; Vulliet, L. Experimental and numerical investigations of the behaviour of a heat exchanger pile. *Int. J. Numer. Anal. Methods Geomech.* **2006**, *30*, 763–781. [CrossRef]
45. Randolph, M.F. Science and empiricism in pile foundation design. *Géotechnique* **2003**, *53*, 847–875. [CrossRef]
46. Bourne-Webb, P.J.; Amatya, B.; Soga, K.; Amis, T.; Davidson, C.; Payne, P. Energy pile test at Lambeth College, London: Geotechnical and thermodynamic aspects of pile response to heat cycles. *Géotechnique* **2009**, *59*, 237–248. [CrossRef]
47. Poulos, H.G. Piled raft foundations: Design and applications. *Géotechnique* **2001**, *51*, 95–113. [CrossRef]
48. Achmus, M.; Kuo, Y.S.; Abdel-Rahman, K. Behavior of monopile foundations under cyclic lateral load. *Comput. Geotech.* **2009**, *36*, 725–735. [CrossRef]
49. Man, Y.; Yang, H.; Diao, N.; Liu, J.; Fang, Z. A new model and analytical solutions for borehole and pile ground heat exchangers. *Int. J. Heat Mass Transf.* **2010**, *53*, 2593–2601. [CrossRef]
50. The World Bank, Research and Development Expenditure (%GDP). Available online: https://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS (accessed on 20 April 2022).
51. World GDP Ranking 2020, Data and Charts. Available online: https://knoema.com/nwnfkne/world-gdp-ranking-2020-gdp-by-country-data-and-charts (accessed on 20 April 2022).
52. Wang, C.; Xiao, J.; Liu, W.; Ma, Z. Unloading and reloading stress-strain relationship of recycled aggregate concrete reinforced with steel/polypropylene fibers under uniaxial low-cycle loadings. *Cem. Concr. Compos.* **2022**, *131*, 104597. [CrossRef]
53. Wang, C.; Wu, H.; Li, C. Hysteresis and damping properties of steel and polypropylene fiber reinforced recycled aggregate concrete under uniaxial low-cycle loadings. *Constr. Build. Mater.* **2022**, *319*, 126191. [CrossRef]