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Review

High-Speed Railway Bridge and Pile Foundation: A Review

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Abstract: High-speed railway is trending in developing countries for economic reasons, mobility in the aftermath of COVID-19, and environmental concerns. The high-speed railway operators continuously improve the operational speed to transport more passengers in less time. However, increasing the train loads at high speed might increase the dynamic loads of bridges and affect their pile foundation. A stiffer railway bridge is mandatory for high-speed train safety and passenger riding comfort. However, a flexible bridge is ideal for responding to earthquakes. Thus, these two objectives are conflicting. This review paper provides a bibliometric review aiming to determine the published studies by year and by country, and to visualize different research trends in cluster maps using the VOSviewer software, summarizing the published research for high-speed railway bridges starting from 1964. The review also extracted information from the latest studies by summarizing some essential objectives, useful methodologies, and notable findings that might be applicable to future studies. In conclusion, there is a need for further research to fill the knowledge gap in the study related to the soil–structure interaction phenomenon considering the performance-based seismic design of a high-speed railway bridge on a monopile foundation in the event of lateral spreading due to soil liquefaction.

Keywords: high-speed railway; bridge; monopile foundation; systematic review; bibliometric

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1. Introduction

1.1. Overview

The rapid technological advancement of High-Speed Railway (HSR) networks is one of the 21st century's hallmarks. After Japan opened the world's first HSR in 1964, many countries started to invest in HSR construction, operation, and maintenance [1]. The exponential growth of the human population has necessitated the development of HSR [2]. Consequently, the success of HSR is conducive to the progress of major cities and promotes cooperation among cities by expanding the market [3]. Specifically, it provides convenient channels for inter-regional flows of people, drives product overflow, and improves the consumption level of neighboring cities [4]. Other important factors that promote the expansion of HSR are mobility in the aftermath of COVID-19, and environmental concerns [5]. One environmental benefit of having a network of HSR in a country is the shifting away from the intensive use of carbon fossil fuels for public transportation [6], which improves the air quality and significantly increases cities' good days in this regard [7].

Following the same path as Japan, Italy, France, Germany, and Spain, many more countries have now joined the HSR pioneers. As of 2022, thousands of kilometers of new lines are being studied or under construction in Turkey, Morocco, Europe, the United States of America, Iran, Russia, India, South-East Asia, and China. Over 4900 High-Speed Trains (HST) operate daily worldwide, transporting more than two billion passengers annually. China ranks no. 1 worldwide and in 10 years, expanded its HSR network to 40,474 km. Its HSTs run at an operational speed of 350 kph and transport 1.5568 billion passengers. Table 1 summarizes the data produced by the Geography and Railway Traffic Research

Group, Fundación de los Ferrocarriles Españoles, sent for publication to the International Union of Railways (UIC) on August 2022 [8].

Table 1. Global HSR data 2022. Adapted from [8].

Type of Collected Data	Ranking	Countries	Data
The longest length of the HSR network in commercial operation.	1	China	40,474 km
	2	Spain	3661 km
	3	Japan	3081 km
	4	France	2735 km
	5	Germany	1571 km
The maximum speeds of the HST in commercial operation.	1	China	350 kph
	2	Japan	320 kph
	3	France	320 kph
	4	Morocco	320 kph
	5	South Korea	305 kph
The number of passengers using the HSR network.	1	China	1.5568 billion
	2	Japan	154.10 million
	3	France	64.40 million
	4	Italy	59.70 million
	5	Germany	55.00 million

1.2. The Importance of Railway Bridges in the HSR Network

An essential structure in HSR networks is the railway bridge or viaduct. One of the reasons for constructing a viaduct in an HSR network is that this type of structure requires less area than constructing an earth embankment. Constructing a viaduct can avoid interrupting existing railways or highways [9], avoids occupying large land areas [10], and avoids disturbing arable lands [11]. A long-span HSR viaduct is essential for crossing rivers and seas [12]. China has been constructing its first HSR sea-crossing bridge. The railway is 277 km long, with an operating HST speed of 350 kph [13]. The complex conditions of the sea, such as the high risk of winds and waves [14], has made its design very challenging to maintain the rail track stability, and has required sophisticated aerodynamic analysis [15] and sea wave hydrodynamic analysis [16]. In mountainous areas, constructing tall pier HSR bridges is necessary to pass treacherous areas [17]. The most challenging tall pier HSR bridge project is the Sichuan-Tibet HSR, with an operating speed of 200 kph. The Sichuan–Tibet railway faced the greatest risk in railway construction in the world [18,19]. The HSR lines cross seven deep rivers and eight high mountains, which are potential sources of destructive earthquakes [20], large-scale landslides [21], massive floating ice impacts [22], wind-blown sand formations [23], and complex braking environments [24].

Table 2 summarizes the percentiles of the HSR bridge length in various countries in Asia and Europe. The highest percentile of HSR bridges is found in Asian countries: the Guangzhou–Zhuhai line in China has 94.2% of the bridge length; the Joetsu Shinkansen line in Japan has 61.5%; and the Seoul–Busan line in South Korea has 27.1%. Meanwhile, in the European countries, the top percentiles of the bridge lengths are 32.2% for the LGV Rhone–Alpes line in France, 19.1% for the Rome–Naples line in Italy, 12.5% for the Hanoverian–Wurzburg HSR line in Germany, and 12.2% for the Madrid–Barcelona line in Spain. The longest line of any HSR bridge is located in Beijing–Kowloon, China, with its total bridge length of 1384 km [25].

Table 2. HSR bridge length percentile in various countries. Adapted from [25].

Country	HSR Lines	Bridge Length (km)	Line Length (km)	Percentage of Bridge Length (%)
China	Guangzhou–Zhuhai	134.1	142.3	94.2
	Beijing–Shanghai	1060.9	1314	80.7
	Beijing–Kowloon	1384	2193	63.1
Japan	Joetsu Shinkansen	166	270	61.5
	Tohoku Shinkansen	344	493	58.1
South Korea	Seoul–Busan	111.8	412	27.1
France	LGV Rhone–Alpes	39	121	32.2
Italy	Rome-Naples	39	204	19.1
Germany	Hanoverian–Wurzburg	41	327	12.5
Spain	Madrid–Barcelona	75.8	621	12.2

1.3. Effect of Operational HST Speed Improvements on the Structural Design of HSR Bridges

To transport more people in less time, the HSR operators continuously improve their operations by increasing the train speed [26–28]. The necessity to upgrade the HSR tracks, including railway bridges, once the train speed increases is highlighted in [29]. Increasing the train speed increases the dynamic loads on the bridge structure [30], and this considerable amount of kinetic energy can cause the bridge to vibrate excessively [31]. If not adequately mitigated, the excess vibration may reach the area surrounding of the HSR bridge [32], and can resulted in inconvenience for homeowners and cause damage, such as malfunction of a nearby laboratory as reported in [33]. Thus, bridge design requirement for HSR is higher than for standard railway [10]. Structural stiffness must be adequate for serviceability requirements to guarantee the track's smoothness [12] for the riding comfort of passengers [34]. HSR bridge design is important not only for operational safety, but also for the vehicle–track contact performance [35], which might affect the interaction performance of the vehicle–overhead infrastructure [36].

As a rule, an HSR bridge is a high-performance structure for load-bearing and durability, with tight limits in vertical deflection and vibration control when the HST passes [17] because the safety of the passing HST depends on the bridge deformation [37]. Yet, in active-fault locations, bridges must be flexible structures to respond to earthquakes [38]; and when constructed in problematic geological settings such as soft soil, bridges typically rely on multiple piles for the foundation, as shown in Figure 1a. However, research has shown that lateral spreading due to liquefaction on soft soil during an earthquake imposes large forces on the bridge substructure, resulting in excessive movement, deformation, and significant bending moments in the pile foundation [39,40], as illustrated in Figure 1b. Past earthquake experience shows that bridges are vulnerable to damage because of defective seismic design [41]. Bridge collapse in a strong earthquake is due to underestimating the seismic demands and neglecting the effects of the Soil–Structure Interaction (SSI) [42].

The HST operational speed improvements may push the HSR bridge design to its limits and require complex upgrading. A stiffer structure for the HSR bridge is mandatory for HST safety and passenger riding comfort. However, a flexible structure for the HSR bridge is ideal for responding to strong earthquakes and considering the effect of lateral spreading due to soft soil liquefaction on the pile foundation. Thus, the objectives to achieve these two requirements are conflicting [43].

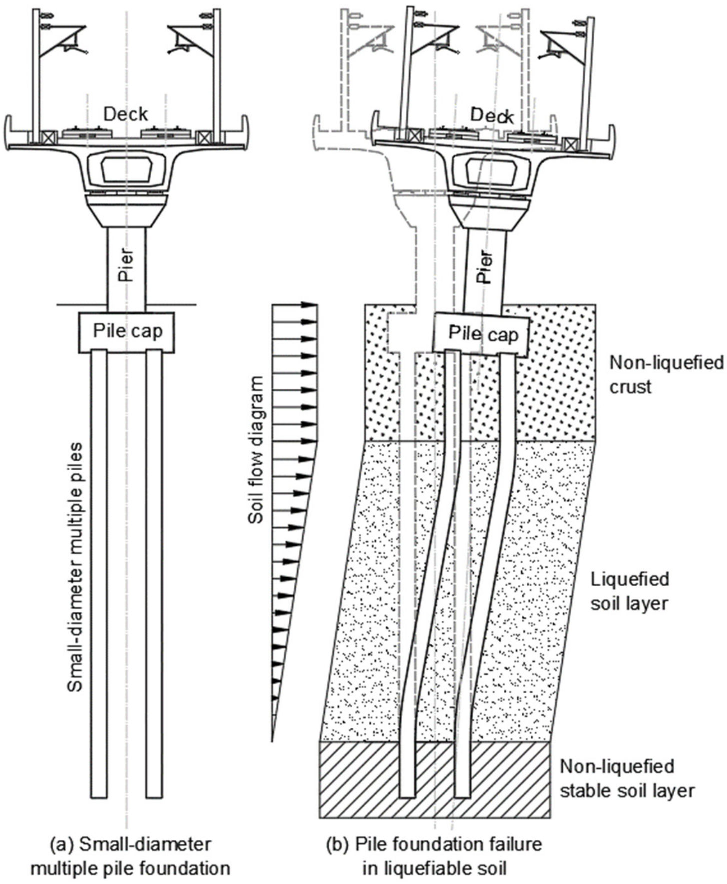

Figure 1. Lateral spreading due to liquefaction on pile foundation.

1.4. Review Papers and Published Studies for Railway Bridge Design

In 2012, Goicolea and Antolin [44] reviewed the issues in HSR bridge design focusing on the basic features related to the dynamic response of bridges under traffic loads, such as moving loads impact action, resonance, and bridge models for the dynamic analysis. Moreover, the study presented representative applications of vertical and lateral dynamics on viaducts by introducing coupled train–bridge full interaction models in three-dimensions (3D) for evaluating the safety of a HST passing over a viaduct. However, the HSR bridge design review is largely about serviceability and offers nothing on the ultimate requirements, such as the HSR bridge dynamic response to a strong earthquake, nor any bibliometric analysis for a systematic literature review.

For example, in 2019, Ji and Kim [45] reviewed the behavior of bridges under rail loading, focusing on train–structure interactions. They discussed the gravity loading effect, in situ responses of bridges, instrumentation techniques, impact or dynamic load allowance, centrifugal and longitudinal forces, rail break, load and resistance factors, and light rail transit features. The paper presented the development of the structural response of bridges in an analytical model and evaluated it using the finite element method. However, the train type under review was not a HST, and, typical of the issue previously highlighted, the railway bridge design review was on serviceability, not on requirements such as its dynamic response to an earthquake, nor was there a systematic literature review.

In 2019, Zhai et al. [35] comprehensively reviewed the evolution of understanding of the train–bridge dynamic interaction, from the simplest moving constant force model to the sophisticated train–track–bridge dynamic interaction model that causes the HSR bridge to vibrate. Moreoover, the review highlighted major components of the train–track–bridge modeling method, such as system excitation, train–track–bridge coupled system, and dynamic responses. The authors also present an experimental investigation and train–track–bridge dynamic interaction application through field testing, focusing on validation and assessment. This HSR bridge design review discussed both the serviceability and its ultimate requirements; however, there it offered no bibliometric analysis for a systematic literature review.

In the 21st century, many published studies have discussed the structural performance of HSR bridges when a HST passes. Some studies have focused on developing an analytical method to carry out a rough assessment to estimate the bridge resonance [46] or calculate the bridge vibration [47], determine the effect of the bridge resonance and cancellation conditions [48], analyze the impact factor or dynamic load allowance [49], and develop a new HST load model [50]. A number of studies adopted the numerical simulation method to investigate the dynamic interaction response of a HSR bridge when a HST passes over it [51–57]. Far fewer studies adopted a semi-analytical method [58,59], but there were numerous experimental studies on an actual HSR bridge [60–67] to validate analytical or numerical simulation results. Meanwhile, other studies focused on the structural response of HSR bridges in an earthquake. For ultimate requirements, some studies aim to improve the safety of the HST passing over the bridge [68]. Yet others focused on the HSR bridge performance improvements [69–71], analyzing the HSR bridge vibration with a moving HST [72,73], and investigating the dynamic response of composite bridges [74]. However, these studies mainly outlined the problems and solutions without conducting a systematic literature review by bibliometrics.

Table 3 consolidates the information from the review papers and published studies for the railway bridge design in matrix format. It consists of the publication year, authors, type of paper, and five different topics. The "B-C" means Book Chapter, "C-P" means Conference Proceedings, "J-A" means Journal Article, and "R-P" means Review Paper. The "YES" mark means that the study included it, while the "NO" means not included. The percentile of the paper presenting a study for the serviceability requirements is 100%, studies discussing serviceability and ultimate requirements is 25.5%, analysis considering only the bridge deck dynamic response is 91.5%, and analysis considering the full-bridge structure including foundation response is 31.9%. However, the percentile of the studies that conducted a systematic literature review by bibliometric review is 0%.

Table 3. Summary of review papers and published studies for railway bridge design.

Date	Authors	Type of Paper	Discussed Serviceability Requirement	Discussed Ultimate Requirement	Analysis for Bridge Deck Response	Analysis for Full Bridge, Including Foundation	Conducted Bibliometric Review
2001	Fryba [46]	J-A	YES	NO	YES	NO	NO
2003	Ju and Lin [51]	J-A	YES	NO	YES	NO	NO
2005	Xia et al. [60]	J-A	YES	NO	YES	NO	NO
2007	Takemiya and Bian [32]	J-A	YES	NO	YES	YES	NO
2010	Lee and Kim [52]	J-A	YES	NO	YES	NO	NO
2010	Su et al. [31]	J-A	YES	NO	YES	NO	NO
2012	Cao and Li [58]	J-A	YES	NO	YES	YES	NO
2012	Goicolea and Antolin [44]	R-P	YES	NO	YES	YES	NO
2012	Salcher and Adam [47]	J-A	YES	NO	YES	NO	NO
2013	Ju [68]	J-A	YES	YES	YES	YES	NO
2013	Yoon et al. [62]	J-A	YES	NO	YES	NO	NO
2013	Youcef et al. [53]	J-A	YES	NO	YES	NO	NO
2013	Zhai et al. [54]	J-A	YES	NO	YES	NO	NO
2013	Zhai et al. [61]	J-A	YES	NO	YES	YES	NO
2014	Cheng et al. [38]	J-A	YES	YES	YES	YES	NO
2014	Kim et al. [63]	J-A	YES	NO	YES	NO	NO
2014	Norton et al. [55]	C-P	YES	NO	YES	NO	NO

Table 3. *Cont.*

Date	Authors	Type of Paper	Discussed Serviceability Requirement	Discussed Ultimate Requirement	Analysis for Bridge Deck Response	Analysis for Full Bridge, Including Foundation	Conducted Bibliometric Review
2015	Yan et al. [10]	J-A	YES	YES	NO	NO	NO
2015	Zeng et al. [72]	J-A	YES	YES	YES	YES	NO
2016	Cho et al. [48]	C-P	YES	NO	YES	NO	NO
2016	Kaloop et al. [64]	J-A	YES	NO	YES	NO	NO
2016	Pradelok et al. [56]	J-A	YES	NO	YES	NO	NO
2016	Sun et al. [33]	J-A	YES	NO	YES	YES	NO
2016	Yang et al. [74]	J-A	YES	YES	YES	YES	NO
2016	Youliang and Gaoxin [30]	J-A	YES	NO	YES	NO	NO
2017	Bebiano et al. [59]	J-A	YES	NO	YES	NO	NO
2017	He et al. [11]	J-A	YES	NO	YES	NO	NO
2017	Somaschini et al. [65]	J-A	YES	NO	YES	NO	NO
2018	Cao et al. [43]	J-A	YES	YES	YES	YES	NO
2018	Xia et al. [25]	B-C	YES	YES	YES	YES	NO
2019	Fang et al. [14]	J-A	YES	NO	YES	NO	NO
2019	Gou et al. [37]	J-A	YES	NO	YES	YES	NO
2019	Ji and Kim [45]	R-P	YES	NO	YES	NO	NO
2019	Lu [29]	J-A	YES	NO	NO	NO	NO
2019	Zhai et al. [35]	R-P	YES	YES	NO	NO	NO
2020	Li et al. [70]	J-A	YES	YES	YES	YES	NO
2020	Lui et al. [34]	C-P	YES	NO	NO	NO	NO
2020	Yang et al. [57]	J-A	YES	NO	YES	NO	NO
2021	Liu et al. [15]	J-A	YES	NO	YES	NO	NO
2021	Liu et al. [28]	J-A	YES	NO	YES	NO	NO
2021	Reiterer et al. [50]	C-P	YES	NO	YES	NO	NO
2021	Song [67]	C-P	YES	NO	YES	NO	NO
2022	Kim et al. [66]	J-A	YES	NO	YES	NO	NO
2022	Wang et al. [49]	J-A	YES	NO	YES	NO	NO
2022	Yu et al. [71]	J-A	YES	YES	YES	NO	NO
2022	Zhou et al. [73]	J-A	YES	YES	YES	YES	NO
2022	Zhu et al. [69]	J-A	YES	YES	YES	YES	NO
			100%	25.5%	91.5%	31.9%	0%

1.5. Factors Affecting the HSR Bridge Design and Pile Foundation Subject to Bibliometric Review

Identifying the multiple factors affecting the future of bridge design is essential [75]. This review paper focuses on the interaction between the HSR bridge performance, pile foundation behavior, and base soil movement [43,73]. Most HSR bridges are multiple spans or a viaduct with many supports or piers. Over long distances, they frequently cross irregular topographic soil profiles. Moreover, a HSR viaduct is a massive structure that is more susceptible to a Multiple Support Excitation (MSE) phenomenon than a building because the arrival time of the seismic waves at each pier is different [76]. During a strong earthquake, the bridge movement affects the soil, while the soil movement affects the whole bridge, including the pile foundation, a phenomenon called Soil–Structure Interaction (SSI) [77]. For a bridge to respond effectively to a strong earthquake, the structural design should consider a method that reflects the structure's seismic performance. This makes the structural design of a bridge both economical and logical: thus the Displacement-Based Design (DBD) method [78] is used instead of the traditional Force-Based Design (FBD) method [79]. The DBD method is one of the Performance-Based Seismic Design (PBSD) methods [80], and some international standards-setting bodies started implementing the PBSD concept, such as the American Association of State Highway and Transportation Officials (AASHTO) [81], Japan Road Association (JRA) [82], Canadian Standards Association (CSA S6) [83], and the New Zealand Transport Agency (NZTA) [84]. Thus, the MSE, SSI, DBD, and PBSD are subject to bibliometric review.

Another factor affecting the HSR bridge design is the innovation of pile foundations. Instead of designing multiple piles of small diameter, see Figure 2a, the HSR bridge pier is on the top of a monopile foundation, see Figure 2c. Lessons learned from bridge projects highlighted that a monopile foundation is preferable when working in limited spaces and congested areas such as busy streets [85]. It could reduce conflicts with existing utilities [86] and minimizes the risk of foundation damage caused by an active fault line passing directly underneath the pier [87]. Moreover, a large-diameter monopile foundation can be a practical choice of HSR bridge foundation for areas subjected to a lateral spreading caused by liquefaction, as illustrated in Figure 2b, because the monopile has greater stiffness and relative strength than multiple small-diameter piles [88]. Thus, the monopile foundation is also a subject for bibliometric review.

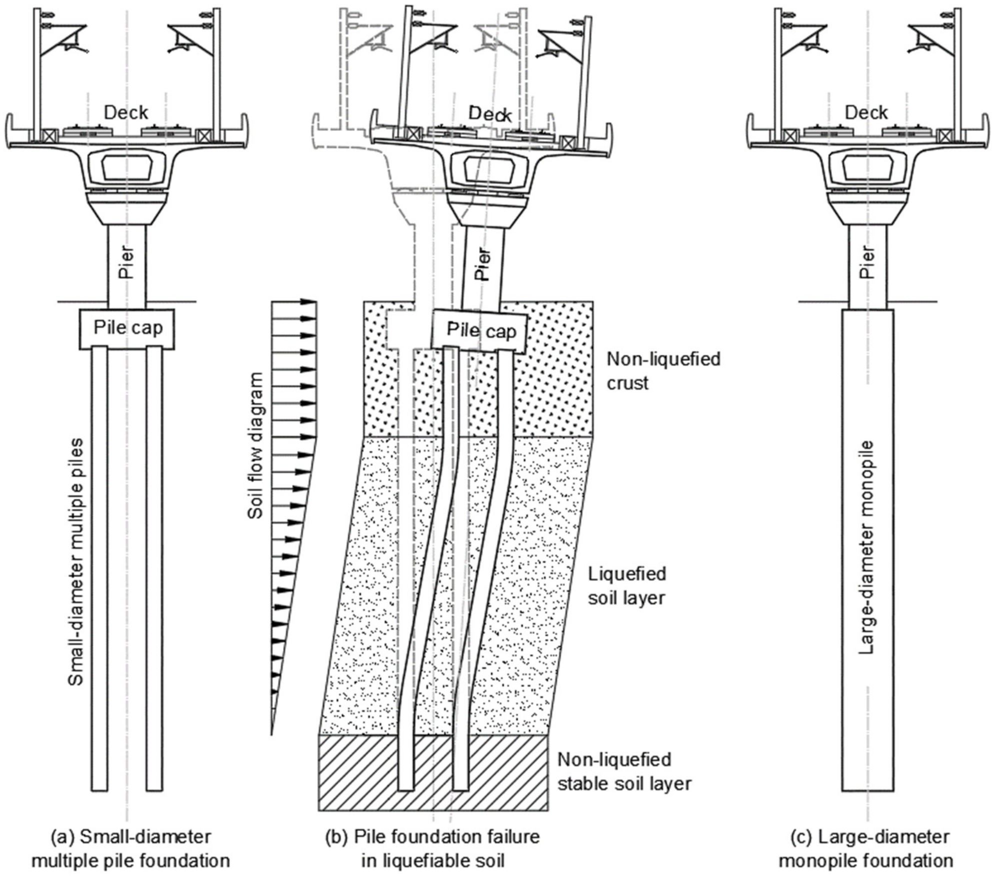

Figure 2. Innovation of HSR bridge foundation.

1.6. Features, Objectives, and Outline of the Review Paper

This current review paper features the importance of the HSR in an overpopulated country, as providing faster channels for inter-regional flows of people, improving cities, and expanding the market. The HSR is the practical choice for a public transportation system because it is environmentally friendly. In the HSR network, bridges are essential structures that need design upgrading due to the continuous improvement of train speed to mobilize more people in less time. The HSR bridge has a strict serviceability requirement for passenger riding comfort and safety of the running HST. However, a flexible bridge is ideal in areas with strong earthquakes and considering the effect of liquefaction on the pile foundation. Many published studies explained the importance of the HSR bridge serviceability and ultimate requirements, presenting different analytical studies and numerical simulations. Some researchers performed experimental studies on the bridge to validate the results. However, the percentile of the published studies that have conducted a bibliometric review is 0%.

This paper also features the interaction between the HSR bridge performance, pile foundation behavior, and base soil movement. The factors that could affect the HSR bridge design upgrading are the MSE, SSI, DBD, and PBSD. Another factor is the HSR bridge foundation innovation, such as adopting the monopile foundation instead of using multiple piles of small diameter. The published research on MSE, SSI, DBD, PBSD, and monopile foundation should undergo a systematic review of literature by bibliometric review [89] to ensure better quality within the study's reference list [90].

The research contribution of this paper is the bibliometric review of the HSR research using the VOSviewer [91]. It intends to attain the following objectives:

- current and future trends in HSR bridge design,
- current and future trends in the monopile foundation design,
- extraction of information from current studies for HSR bridge design, and
- extraction of information from current studies for monopile foundation design.

Extracting the information from the latest studies captures the essential objectives, methodologies used, and notable findings that might apply to future studies.

The outline of this review is as follows:

Section 1 introduces the overview of the study in a broader context by presenting the HSR global data. This section highlights the importance of upgrading the design of HSR bridges and of innovation for their pile foundations. Reflecting the current state of the research, it cites the key publications related to the serviceability and ultimate requirements for designing a HSR bridge. In addition, our present review highlights controversial conflicts between serviceability and ultimate requirements, including liquefaction. Finally, we define the main purpose and significance of conducting a systematic review by bibliometric analysis.

Section 2 describes the collection of materials and the methods for reviewing these materials. The collection of a significant amount of literature uses multiple search systems that are open-access. The search for documents had a timeline start date of 1964, the birth of the HSR, to statistically evaluate the research development and contributions for almost six decades. The subsequent bibliometric review determines the published studies by year and country for bridge superstructure and substructure. The bibliometric map is then generated using VOSviewer software to visualize the latest trends in the studies related to HSR bridge design, MSE, SSI, DBD, PBSD, and monopile foundation.

Section 3 discusses the results from Section 2. It is evident from the results that more researchers dedicated their time to conducting and publishing studies for SSI, HSR bridge, PBSD, DBD, and monopile foundation from 2020 to 2021 than previously, due to COVID-19 restrictions. However, the bibliometric map shows that there is a wide gap in numbers of studies on PBSD and SSI relative to HSR bridge studies. Moreover, studies on the application of the monopile foundations more often relate to offshore structures rather than to bridges.

Section 4 presents the concluding statement. There is a need for further research to fill the gaps in the studies on soil–structure interaction that consider the performance-based seismic design of a railway bridge with its pile foundations in the event of lateral spreading due to soil liquefaction.

2. Materials and Methods

2.1. Sequence of Bibliometric Review

The review maps out and categorizes existing literature on HSR bridges, monopile foundations, and some factors that could affect HSR bridge design. Performing a systematic literature review [90] by conducting a bibliometric analysis [89] is the most appropriate way to ensure best quality in the reference lists. A bibliometric review statistically evaluates the latest research outcomes of published articles, book chapters, and conference proceedings related to the topic of HSR bridges.

Figure 3 illustrates the sequence of the bibliometric review.

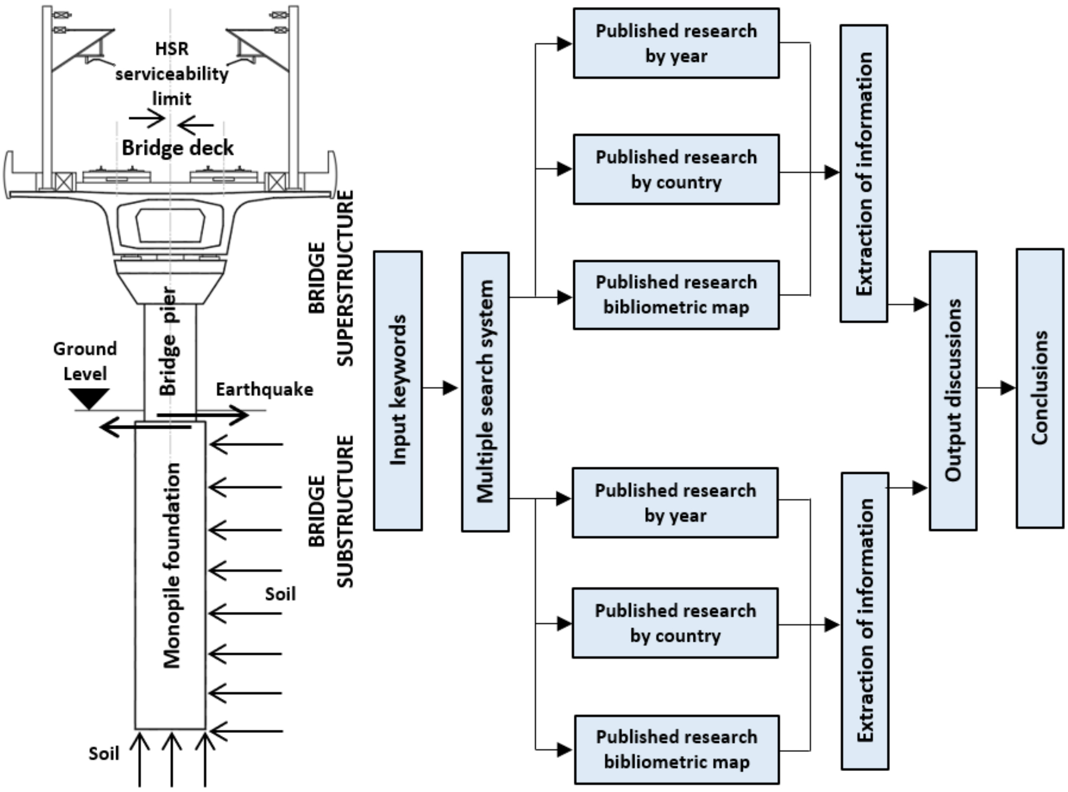

Figure 3. Sequence of the bibliometric review.

Step 1: Keywords input using two groups. Refer to Table 4 for the groupings.
Step 2: Collection of electronic materials from multiple search systems. Refer to Table 5 for the three search systems used.
Step 3: The bibliometric review determines the published studies by year and country for the bridge superstructure. Then, create the bibliometric map using VOSviewer to visualize the latest trends related to HSR bridge, MSE, SSI, DBD, and PBSD studies.
Step 4: Extraction of information from step 3, which captures the research objectives, methods used, and findings that might be applicable for future studies.
Step 5: The bibliometric review determines the published studies by year and country for the bridge substructure. Then, create the bibliometric map using VOSviewer to visualize the latest trends related to monopile foundation studies.
Step 6: Extraction of information from step 5, which captures the research objectives, methods used, and findings that might be applicable for future studies.
Step 7: Output discussions for bibliometric review.
Step 8: Concluding statement of this study.

Table 4. Developed keywords for the current review.

Keywords	
1st Group	**2nd Group**
"high-speed railway bridge" "multiple support excitation" and "bridge" "soil–structure interaction" and "bridge" "displacement-based design" and "bridge" "performance-based seismic design" and "bridge"	"monopile foundation" "pile shaft" and "bridge"

Table 5. Suitable search systems [92].

Search Systems		
Name	**Subjects**	**No. of Documents**
Science Direct [93]	Multi-discipline	Over 18 million
BASE [94]	Multi-discipline	Over 280 million
World Wide Science [95]	Multi-discipline	Over 100 million

2.2. Keywords Input and Collection of Documents from Multiple Search Systems

Before initiating the systematic review, an important step is collecting the relevant documents from multiple sources. This section collects a significant amount of literature by developing keywords using three suitable search systems. It ensures the systematic filtration and structured search for documents that provide a body of raw materials that line up with the issues raised in Section 1. Table 4 shows the two groups of developed keywords. The 1st Group focused on research related to a "high-speed railway bridge", "multiple support excitation", "soil–structure interaction", "displacement-based design", and "performance-based seismic design", all related to "bridges"; while the 2nd Group of keywords focused on "monopile foundation" and the combined keywords of "pile shaft" and "bridge". Identifying the significant aspects of the review is the initial intention of the study, with a view to revealing the current developments in theory and research contributions related to HSR bridges and monopile foundations.

Selecting an appropriate search system is a key factor for the results of this review. The performance requirements for choosing the search systems should enable queries to be carried out, filters to be applied, or citation searching to be managed with high standards and accessibility of data resources. Searching using multiple search systems is more suitable than one. Table 5 summarizes the three suitable search systems [92] used in this review: Science Direct, Bielefeld Academic Search Engine (BASE), and World Wide Science. The main reason for choosing these search systems is that they are open-access search engines.

The search for relevant documents had a timeline start of 1964, the birth of the HSR [96]. The primary search was to quantify the published research from 1964 to 2022. The search also included quantifying the published research from the beginning of the 21st century to 2022, and the last five years of records from 2018 to 2022. The criteria for the search included review articles, research articles, conference proceedings, books, and chapters of a book, written and published in the English language. The collected electronic materials are in Research Information System (RIS) file format, enabling citation programs to exchange data. The Mendeley Reference Manager software [97] organized all the collected RIS files without any duplications for easy referencing.

Table 6 summarizes all the collected electronic data from multiple search systems. The electronic data collection date is 30 September 2022 in Science Direct, BASE, and World Wide Science. Most of the data for the keywords "high-speed railway bridge", "multiple support excitation", and "bridge", "displacement-based design" and "bridge", the "performance-based seismic design", and "bridge", "monopile foundation", "pile shaft" and "bridge" were collected from the World Wide Science. However, for the keywords "soil-structure interaction" and "bridge", more data came from Science Direct. The total collected RIS files for the 1st Group were 12,018; however, after organizing using Mendeley Reference Manager and removing duplications, the number of reduced files was 6004. Similarly, the 2nd Group was initially composed of 3824 total RIS files, which were then reduced to 1239.

Table 6. Collected electronic data from multiple search systems.

Keywords	No. of Documents in Several Timelines								
	Science Direct			BASE			World Wide Science		
	1964 to 2022	2000 to 2022	2018 to 2022	1964 to 2022	2000 to 2022	2018 to 2022	1964 to 2022	2000 to 2022	2018 to 2022
1st Group									
"high-speed railway bridge"	252	249	141	194	186	92	1553	1220	739
"multiple support excitation" and "bridge"	85	47	21	82	56	18	1456	1116	527
"soil-structure interaction" and "bridge"	2321	1629	820	906	807	283	1598	1154	612
"displacement-based design" and "bridge"	198	176	100	107	100	19	1515	1124	635
"performance-based seismic design" and "bridge"	307	307	169	79	77	30	1365	984	574
2nd Group									
"monopile foundation"	515	513	356	421	393	207	1183	871	516
"pile shaft" and "bridge"	442	337	191	47	42	16	1201	835	302

2.3. Published Research for Bridge Design by Year

The bibliometric review resulted in the graphical presentation in Figure 4, to visualize the 6004 searched documents from the full 1964–2022 collection using Science Direct, BASE, and the World Wide Science. The oldest published article for the keywords "high-speed railway bridge" was in 1987 [98]. In 2006, the number of publications started to increase, with the highest of 51 documents recorded in 2014. The oldest papers for the keywords "multiple support excitation" and "bridge" were published in 1976 [99,100]. In 2009, publications increased, reaching 7 documents in 2018. For the keywords "soil–structure interaction" and "bridge", the oldest articles were published in 1972 [101,102]. The publication rate started to increase in 1984, but dropped in 1991, only to increase again in 1994, with the highest number of annual publications recorded of 194 documents for 2021. The oldest published document for the keywords "displacement-based design" and "bridge" was a book in 1990 [103]. In 2009, these publications increased, reaching 27 documents in 2021. For the keywords "performance-based seismic design" and "bridge", the oldest published document was in 1994 [104]. In 2001, the rate of publication started to increase, with 39 as the highest recorded number, in 2021.

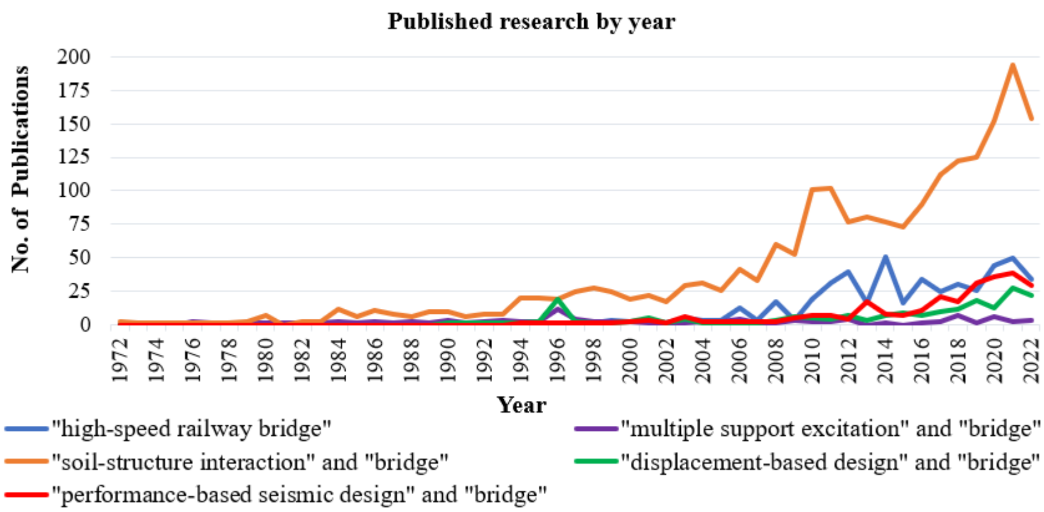

Figure 4. Graphical presentation of published research by year for bridge design.

The graphical presentation in Figure 4 statistically reveals that SSI research for bridges has the highest publication rate, shown in the orange line, followed by the HSR bridge research with a blue line. The red line represents the PBSD research which has a lower publication rate than for SSI and HSR bridge research. Lastly, DBD and MSE research for bridges have lower publication rates than for PBSD research; see green and magenta lines, respectively. It is evident from the graphical presentation that more researchers dedicated their time to conducting studies for SSI, HSR bridge, PBSD, and DBD from 2020 to 2021 than before, due to COVID-19 restrictions. By contrast, the rate of publication for MSE drops from 2020 to 2022.

2.4. Published Research for Bridge Design by Country

The bibliometric review is presented in a bar chart format in Figure 5, which displays the top 10 countries of origin for the searched documents from the 1964–2022 collection based on World Wide Science only because Science Direct and the BASE did not provide any data. The leading countries publishing research on HSR bridges, MSE, SSI, DBD, and PBSD are the United States of America with 308 publications, Japan with 159, Russia with 110, Ireland with 101, India with 100, Korea with 60, Canada with 52, Germany with 50, Spain with 50, and the United Kingdom with 24 publications. However, most of the authors of the HSR bridge research are Chinese.

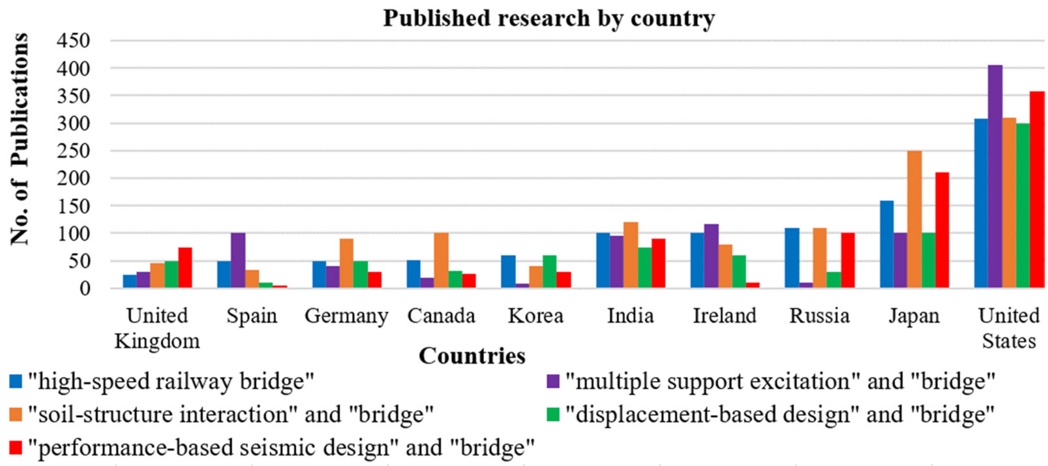

Figure 5. Bar chart presentation of published research by country for bridge design.

2.5. Published Research for Bridge Design Bibliometric Map

VOSviewer software is a good tool for creating a bibliometric map. It has a powerful mapping technique and advanced viewer in a single user-friendly computer program [91]. The VOSviewer uses the binary option to delete duplicated documents. It identifies the number of keywords in the title and abstract fields of the uploaded electronic files based on bibliographic data. The type of analysis is that of co-occurrence considering a full keyword counting method. This analysis determines the relatedness of items based on the number of documents in which they occur together. Limiting the results to a minimum number of occurrences significantly reduces the number of keywords that meet the threshold; for example, a typical range from 10 to 30 would establish these minimum and maximum figures as limits. Next, the co-occurrence is linked to total strength with the other keywords and the most significant total link strength is selected.

The bibliometric map generated from VOSviewer, shown in Figure 6, represents the latest trend in the HSR bridge, MSE, SSI, DBD, and PBSD published research using the 6004 searched documents from the 1964–2022 collection. The limitation of the analysis is that 30 was set as the minimum number of occurrences of the 18,679 captured keywords, and so only 254 documents met the threshold. Subsequently, after verifying and excluding generic words unrelated to the topic, the generated bibliometric map has 4 clusters, with 19,695 links and a total link strength of 121,554.

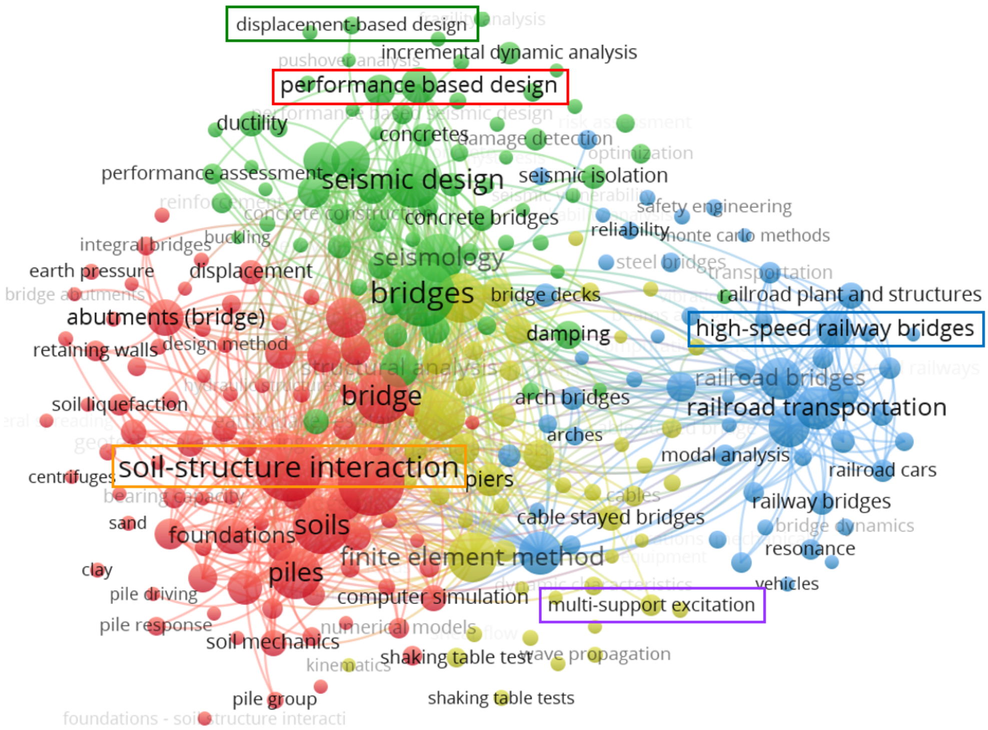

Figure 6. Bibliometric map of published research for bridge design.

Cluster no. 1, in red color, is the largest of all the clusters. It highlights the keyword linkages to "soil–structure interaction". This cluster interconnects the foundation, pile response, soil liquefaction, and displacement. Moreover, the cluster links to the topic from other clusters such as high-speed railway bridges, performance-based design, displacement-based design, and multi-support excitation.

Cluster no. 2, in green color, represents the linkages between the performance-based design, displacement-based design, performance assessment, seismic design, damping, buckling, seismic isolation, incremental dynamic analysis, concrete bridges, and ductility. However, it is evident in this cluster that the research topic displacement-based design is a portion of performance-based design.

Cluster no. 3, in blue color, focused on the interconnections of the high-speed railway bridges to railroad transportation, railroad plant and structures, railroad bridges, bridge dynamics, resonance, modal analysis, and reliability. However, there is a big gap between this cluster and other clusters. Moreover, more studies related to serviceability were published than to the ultimate requirements because of fewer linkages to seismic design.

Cluster no. 4, in yellow color, highlights the suitability of the finite element method in the analysis related to high-speed railway bridge dynamics, soil–structure interaction, performance-based design, and multi-support excitation. This cluster interconnects the kinematics, wave propagation, and shaking table test. However, there are no linkages between multi-support excitation and the high-speed railway bridges.

Moreover, this bibliometric map shows that the published studies on performance-based design and soil–structure interaction are closely linked, but there is a wide gap between these two areas of study and that of high-speed railway bridges. Thus, there is a need for further research to fill this wide gap in the studies relating to the soil–structure interaction phenomenon in connection with performance-based seismic design of high-speed railway bridges.

2.6. Extraction of Information from Published Research into Bridge Design

The extraction of information from the latest studies is carried out by summarizing the essential objectives, useful methodologies, and notable findings that might apply to future studies related to the high-speed railway bridge design. Table 7 summarizes some of the latest studies from 2021 to 2022, searched for using the keywords "high-speed railway bridge", "soil–structure interaction", and "performance-based seismic design" using multiple systems.

Table 7. Extraction of information from latest studies on bridge design.

Year	Research Description	Keywords
2022	The study demonstrated a logical model for the HSR bridge under earthquake loading. The goal was to improve the capability of numerical calculations using ANSYS software and reduce the usage of high-memory in computers during simulations. The research outcome requires further study by eliminating the drawbacks, such as insufficient spatial variation of ground motion in the simulation [105]. Moreover, the bridge model used in the analysis considers no pile foundation.	"high-speed railway bridge"
2022	The study introduced a step-by-step probabilistic SSI using SASSI software incorporating the ground motion incoherency on a bridge supported by pile foundations, and then compared the results with a deterministic SSI approach. The study concluded that the probabilistic SSI methodology could not capture the actual dynamic behavior of the structure, and missed some earthquake certainties [106]. In this case, the bridge foundation analysis considered multiple piles.	"soil-structure interaction" and "bridge"
2022	This review summarizes the PBSD knowledge for bridge piers. It scrutinized the PBSD methods used in buildings and then applied them to bridges. The review concluded that creating the bridge design code requires an operational level risk identification [107]. Moreover, various barriers, such as financial, scientific, and societal, must first be overcome before a bridge design code can fully implement the PBSD.	"performance-based seismic design" and "bridge"
2021	The study illustrated an analytical model of HST safety in running performance over a HSR bridge in an earthquake. The simulation used the finite element method for a multi-span, simply-supported bridge. The results generated the seismic response limit value of the bridge considering different speeds of HST and the structure's oscillation period [108]. Here, the bridge model used in the analysis considers no pile foundation.	"high-speed railway bridge"
2021	The study presented a simplified analytical model of the soil-pile structure interaction for the seismic response of a single-pier bridge using multiple earthquake records. The results captured the deck's maximum acceleration response and the computed structure's natural period, which is 10% to 40% nearer to the instrumentation data [109]. This bridge foundation analysis considered multiple piles.	"soil–structure interaction" and "bridge"
2021	The study summarizes the successful seismic performance on bridges in Turkey after the Sivrice Earthquake. The researchers conducted post-inspection on several bridges and performed a case study using modern structural analysis. One of the results highlighted that both heavier structures with rigid substructures and lighter structures with flexible substructures had a successful seismic performance [110]. However, the studied bridges are not HSR bridges and require different performance parameters to the latter, due to serviceability and ultimate operational requirements.	"performance-based seismic design" and "bridge"

2.7. Published Research for Monopile Foundation by Year

The bibliometric review used the graphical presentation in Figure 7 to visualize the 1522 collected documents from the 1964–2022 search using Science Direct, BASE, and the World Wide Science. The oldest published document for the keywords "monopile foundation" was in 1986 [111]. The publication rate of the monopile foundation studies, shown in the blue line, increased in 2007 but dropped in 2011. It then increased again in 2012 but dropped in 2014. From 2016 to 2022, there is a steady increase, with the highest number of documents of 100 recorded in 2022. For the keywords "pile shaft" and "bridge", the oldest publication is a book chapter on drilled pier foundations in 1975 [112]. The publications on pile shafts for bridges, shown in the magenta line, began to increase in 2009, and continued to do so up to 2022, with the highest number of documents of 50 recorded in 2022. It is evident from the graphical presentation that more researchers dedicated their time to conducting studies on monopile foundations from 2020 to 2021 due to COVID-19 restrictions.

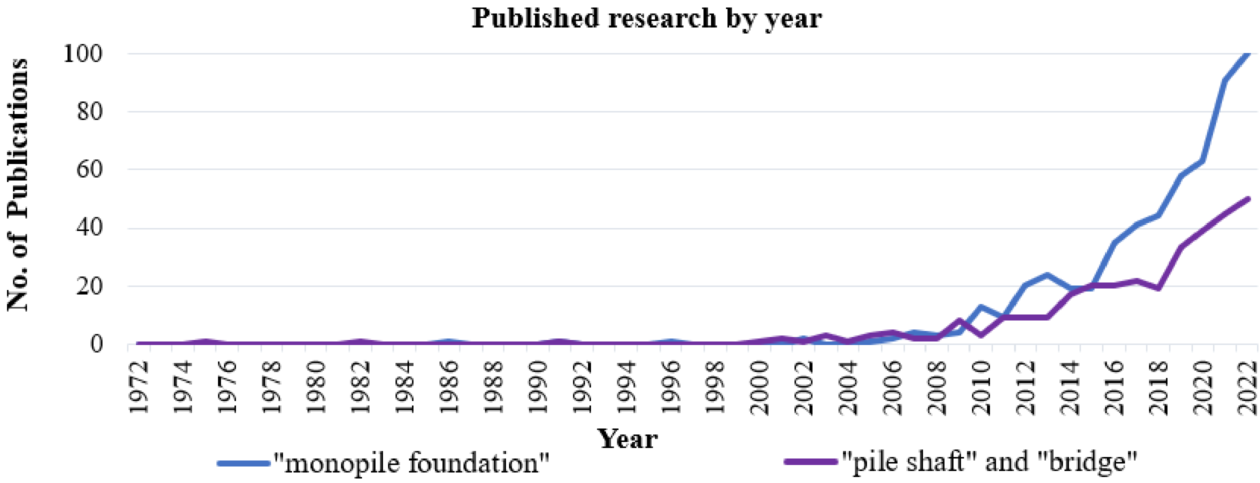

Figure 7. Graphical presentation of published research by year for monopile foundation.

2.8. Published Research for Monopile Foundation by Country

The bar chart in Figure 8 displays the top 10 countries for the materials collected from the 1964–2022 search, using World Wide Science only because Science Direct and BASE did not provide data. Using the keywords "monopile foundation", the leading countries publishing their research are the United States of America with 238 documents, the Czech Republic with 105, Germany with 100, Russia with 98, India with 90, Japan with 57, the United Kingdom with 50, Korea with 26, Norway with 15, and Canada with 4. The chart shows that the United States of America is the most significant source of published studies on the monopile foundation and pile shaft related to bridges. However, most monopile foundation studies are related to offshore structures such as wind turbine foundations and oil well supports. In comparison, the pile shaft is mostly for highway bridges.

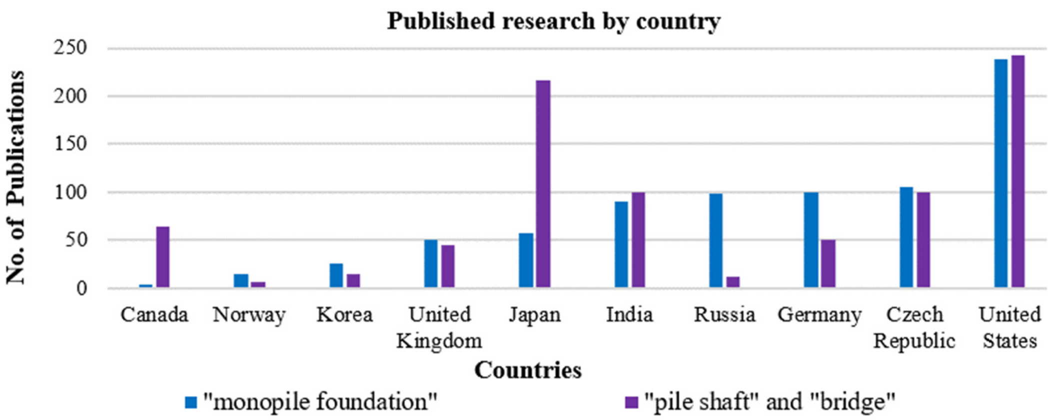

Figure 8. Bar chart presentation of published research by country for monopile foundation.

2.9. Published Research for Monopile Foundation Bibliometric Map

The bibliometric map, in Figure 9, presents the latest trend in monopile foundation published studies using the 1239 collected materials from the 1964–2022 search using Science Direct, BASE, and the World Wide Science. The VOSviewer software generated this map using the keywords "monopile foundation" and the combination of "pile shaft" and "bridge". The limitation of the analysis is the minimum occurrences of 30 of the 7580 captured keywords, and only 99 documents met the threshold. After verifying and excluding the generic words unrelated to the topic, the resulting map has 5 clusters, with 3953 links and a total link strength of 41,202.

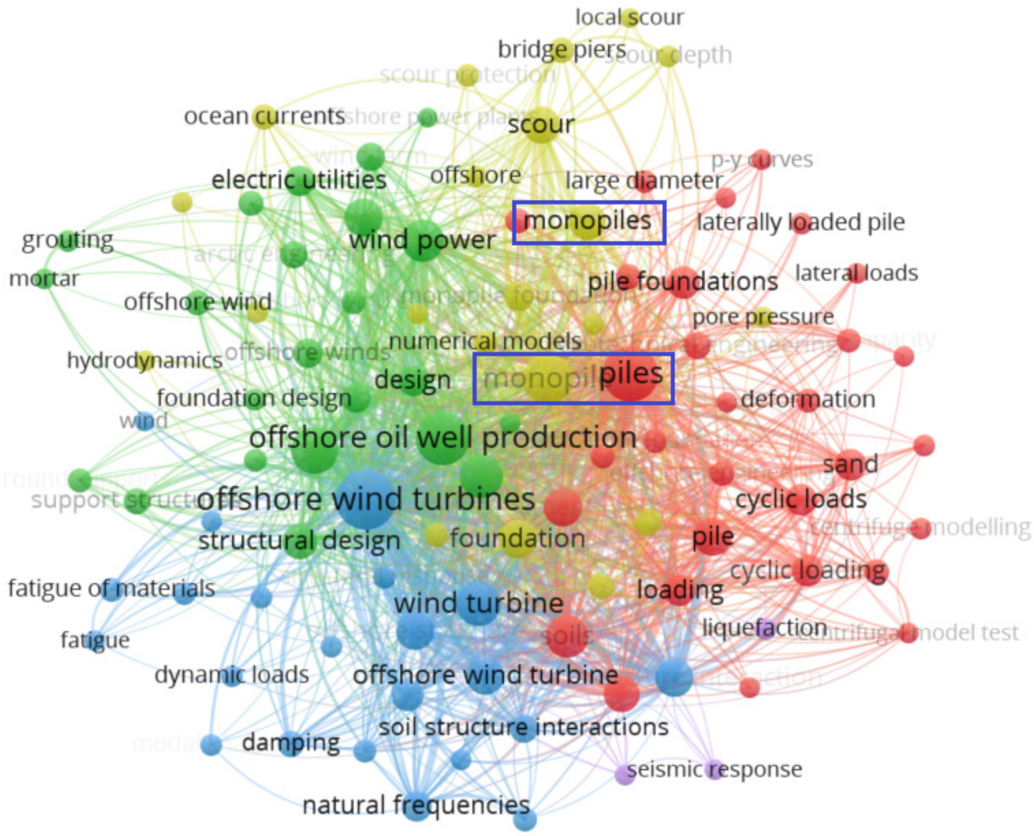

Figure 9. Bibliometric map of published research for monopile foundation.

Cluster no. 1, in red color, highlights the keywords "monopile foundation" linkages to laterally loaded piles, large diameter piles, cyclic loading, p-y curve, and deformation. This cluster links to other clusters, but most connections are related to offshore structures.

Cluster no. 2, in yellow color, shows the linkages of monopile foundation to bridge piers, scour, pore pressure, ocean currents, and hydrodynamics. This cluster connects to other clusters, but most connections are related to offshore structures.

Cluster no. 3, in green color, highlights more linkages of monopile foundation to offshore oil well production, wind power, electric utilities, grouting, and mortar. This cluster links to other clusters but has fewer connections to bridges.

Cluster no. 4, in blue color, represents the studies of monopile foundations supporting offshore wind turbines. These studies link to natural frequencies, damping, dynamic loads, soil-structure interactions, and fatigue of materials. However, no linkages to bridges are shown for this cluster.

Cluster no. 5, in violet color, is the smallest of all the clusters but is nonetheless important, representing the studies linking monopile foundations to the dynamic seismic response of the pile and liquefaction phenomenon.

Overall, this bibliometric map shows the application of a monopile foundation more in offshore structures than in bridges. Further published studies are needed on monopile foundations that support bridges, especially for HSR.

2.10. Extraction of Information from Published Research on Monopile Foundations

The extraction of information from the latest studies is achieved by summarizing the essential objectives, useful methodologies, and notable findings that might apply to future studies relating to monopile foundations for bridges. Table 8 summarizes some of the latest published studies from 2020 to 2022 searched for with the keywords "monopile foundation" and the combination of the keywords "pile shaft" and "bridge" using multiple systems.

Table 8. Extraction of information from latest studies on monopile foundations.

Year	Research Description	Keywords
2022	The study presented the liquefaction effect of a single large-diameter pile and pile group with a pile cap on ground level and sloping ground. The analysis used the finite difference method in FLAC 3D. The single large-diameter pile analysis showed that its existence is like a stiff barrier that opposes the soil's movement. Moreover, the pile's top displacement is less than the soil's movement, all measured at ground level. On the other hand, the pile group with pile cap analysis indicates that a pile cap prevents the soil's displacement in the sloping ground more than the displacement on the level ground due to lateral spreading [113]. However, the considered single large pile model carries a pile cap for the weight. The model should consider extending the pile shaft above ground level to carry part of the load, such as in the comparative relation of the bridge superstructure.	"monopile foundation"
2021	The study investigated a single pile in liquefiable soil under axial and lateral load combinations in different earthquake motions using FLAC 2D software. The numerical investigation focused on the pile head's vertical displacement and soil surface, the lateral displacement of the pile along its length, and the pore water pressure ratio within the soil model. The soil shake table test later verified the numerical investigation results. The study concluded that adding the lateral load at the pile head notably reduces the pile's lateral displacement. On the other hand, lateral loading variations do not cause pile settlement and vertical soil movement, even during stronger earthquakes of high magnitudes [114]. However, the considered pile model carries a pile cap for the weight. The model should consider extending the pile shaft above ground level to carry part of the load, such as in the comparative relation of the bridge superstructure.	"pile shaft" and "bridge"
2020	The study theoretically investigated the lateral force resisted by the pile foundation in liquefiable soil during earthquakes. The investigation used a vector symbol operation method to analyze the liquefaction velocity field and solve the dynamic field using the principle of fluid mechanics. Moreover, the investigation carried out a sensitivity analysis to obtain the sensitivity degree of design parameters. The results show that the stress field of the pile contains pressure and friction resistances when the liquefied soil moves laterally. The composition of these forces is mainly inertial and damping because of soil density, fluid viscosity, pile radius, and frequency of vibration [115]. However, as these factors gradually increase, any increase in mass and damping is sensitive to vibration.	"pile shaft" and "bridge"

3. Discussion

3.1. Review of Published Studies on HSR Bridges, MSE, SSI, DBD, and PBSD

The search systems used in this review are Science Direct, BASE, and World Wide Science. The graphical presentation and bar chart using the Microsoft Excel spreadsheet visualize the 6004 documents related to HSR bridges, MSE, SSI, DBD, and PBSD published studies. The results reveal that SSI has the highest published studies, followed by HSR bridges, PBSD, DBD, and MSE. The number of published studies on SSI is far higher than those on HSR bridges, PBSD, DBD, and MSE. It is evident from the results that more researchers dedicated their time to conducting and publishing studies on SSI, HSR bridges, PBSD, and DBD from 2020 to 2021 due to COVID-19 restrictions. However, there was a drop in published studies for MSE during this period. Meanwhile, the review identifies the top 10 countries that are publishing their studies. The United States of America is leading in HSR bridges, MSE, SSI, DBD, and PBSD studies. However, the authors of the HSR bridge studies are mostly Chinese. This information was extracted from World Wide Science only, because Science Direct and BASE could not provide any themselves. This issue may bias the results for published studies by country.

The VOSviewer software generated the bibliometric map in 4 different clusters. On the cluster for the HSR bridges, there is a big gap between it and other clusters, showing there were more published studies relating to serviceability than there were relating to the ultimate bridge requirements because of fewer linkages to seismic design. Moreover, this bibliometric map shows that the studies on PBSD and SSI are closely linked, but there is a wide gap between both these studies and the HSR bridges. It is evident that the research topic DBD is a portion of PBSD, and there are no linkages between MSE and HSR bridges. There is therefore a need for further research to fill the wide gap in the studies related to the SSI phenomenon considering a PBSD of HSR bridges.

3.2. Review of Published Studies on Monopile Foundation

For monopile foundation, the number of searched documents is 1522, which were visualized using a graphical format, bar chart, and bibliometric map. The results reveal that the United States of America is the most significant source of published monopile foundation studies. However, this information was extracted from World Wide Science only, because Science Direct and BASE could not provide data. This issue may bias the results for published studies by country. Moreover, the bibliometric map shows monopile foundations applied more in offshore structures than in bridges. More studies therefore need to be published on monopile foundations that support bridges, especially HSR bridges.

4. Conclusions

This paper revisits the published studies on HSR bridges and pile foundations through a bibliometric review. All the results indicate the need for further research to fill the knowledge gap related to the soil–structure interaction phenomenon considering the performance-based seismic design of a high-speed railway bridge with the innovation of monopile foundation in areas with liquefiable soil because of lateral spreading during earthquakes.

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