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RESEARCH ARTICLE

Global Research Trends in Soft Soil Management for Infrastructure Development: Opportunities and Challenges

LAI WAH SIM[1,2], HERDA YATI BINTI KATMAN[1,2], INTAN NOR ZULIANA BINTI BAHARUDDIN[1,2], GOBINATH RAVINDRAN[3], MOHD RASDAN IBRAHIM[4], AND ADHAM MOHAMMED ALNADISH[5]

[1]Institute of Energy Infrastructure (IEI), Universiti Tenaga Nasional (UNITEN), Putrajaya Campus, Kajang, Selangor 43000, Malaysia
[2]Department of Civil Engineering, College of Engineering, Universiti Tenaga Nasional (UNITEN), Putrajaya Campus, Kajang, Selangor 43000, Malaysia
[3]Department of Civil Engineering, SR University, Warangal, Telangana 506371, India
[4]Center for Transportation Research, Department of Civil Engineering, Faculty of Engineering, Universiti Malaya, Kuala Lumpur 50603, Malaysia
[5]Department of Civil Engineering, National University of Sciences and Technology (NUST), Quetta 38000, Pakistan

Corresponding authors: Herda Yati Binti Katman (Herda@uniten.edu.my) and Lai Wah Sim (lw.sim712@gmail.com)

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ABSTRACT Soft soils present significant challenges to infrastructure development worldwide due to high compressibility, low shear strength and low permeability. Bibliometric analysis remains scarce in the soft soil management field, making it difficult to grasp global trends and contributions. This research addresses this gap by providing a novel and comprehensive bibliometric analysis of soft soil management literature to investigate the trend, opportunities and challenges. The analysis predominantly examines ground improvement methods based on 2,260 journal articles and proceeding papers from WOS core collection between 2013 and 2023 using CiteSpace. The analysis encompasses country distribution, authorship and co-cited authors, cited journals, reference co-citations and identification of research hotspots and frontiers. Findings show a growing interest and increased research focus in soft soil management, with China emerging as a prominent contributor. Reference co-citation clustering analysis reveals two dominant research themes: ground improvement methods (geosynthetic-reinforced embankments and stone columns) and sustainable practices (reuse of waste materials). The emerging word analysis reveals an evolutionary trend from investigating innovative and sustainable techniques to shear strength and failure mechanisms. Recent studies focus on the use of vertical drains, deep mixing columns, chemical stabilization, and sustainable ground improvement strategies. Opportunities lie in sustainable ground improvement methods and novel sensing technologies. Key challenges include bearing capacity, settlement, and slope stability. The study highlights the need for more research into two other key areas such as geotechnical characterization and foundation design. Overall, this bibliometric review contributes to a more thorough understanding of soft soil management studies for researchers and practitioners.

INDEX TERMS CiteSpace, energy, ground improvement, knowledge mapping, soil compaction energy, soil stabilization, soft soils.

I. INTRODUCTION

Engineering structures rest on soil irrespective of the pattern and locality it is designed and the strength of a structure directly relies on the soil it rests. Soft soils present in many parts of the world and pose significant challenges to infrastructure development worldwide due to their poor engineering characteristics, including insufficient bearing capacity, excessive post-construction settlement, and slope instability. Their specific properties such as large void ratio, high water content, high compressibility, low shear strength, low permeability and special structural features require

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careful consideration in the analysis, design, and maintenance of geotechnical structures built upon them.

Soft soil management is one primary area that is being researched by bountiful researchers across the globe. Literature review shows that significant research has been conducted in various areas of soft soil management, including ground improvement techniques, foundation design, sustainable solutions and case studies. In the field of ground improvement methods, various studies have contributed valuable insights. Zhuang and Wang [1] conducted a comprehensive analysis of the Prefabricated Vertical Drains - Deep Cement Mixing (PVD-DCM) method, combining PVDs and DCM piles, in a field case study of the Beijing-Shanghai high-speed railway. The findings showed that DCM piles enhanced bearing capacity and reduced settlement, while PVDs expedited soil consolidation by shortening drainage paths. Another study by Arulrajah et al. [2] investigated the use of fly ash and slag as alternative green binders, and observed a significant increase in the strength and stiffness of soft clay. Regarding foundation designs, Khanmohammadi and Fakharian [3] examined the feasibility of constructing piled raft foundations on soft clay, suggesting that it is promising as long as the total settlement remains within the allowable limit of 25mm. Additionally, Wang et al. [4] presented a novel pile design that combines a lower part of plain concrete rigid pile for strong bearing capacity and an upper part of crushed stone pile to enhance overburden bearing capacity and improve drainage consolidation.

Soil testing methods have also been explored. Cai et al. [5] studied the undrained shear strength of soft marine clay in Jiangsu Province using in situ piezocone penetration tests, field vane testing, and laboratory undrained triaxial testing. In a different study, Arulrajah et al. [6] compared the performance of vibrating wire and pneumatic piezometers in monitoring consolidation behaviour in a land reclamation project, finding both types to be suitable for this purpose. In terms of modelling and predicting the behaviour of soft soils, Yin et al. [7] proposed an anisotropic elastic-viscoplastic model for natural soft clays, successfully reproducing their anisotropic and viscous behaviours under different loading conditions through experimental verifications. Pham et al. [8] evaluated four machine learning methods (PANFIS, GANFIS, SVR, and ANN) for predicting the shear strength of soft soils, with PANFIS demonstrating the highest prediction capability. Seismic-related studies have also yielded valuable insights. Hokmabadi et al. [9] investigated the impact of seismic soil-pile-structure interaction (SSPSI) on the dynamic response of buildings with different heights through shaking table tests. The study revealed that SSPSI amplified maximum lateral deflections and interstory drifts in structures with end-bearing pile foundations compared to fixed-base structures. Additionally, Van Nguyen et al. [10] found out that the size and type of piles will influence the seismic response of midrise buildings in high-risk seismic zones due to the interaction happening between soil and the pile.

Hence it is very evident that analysing the path of research progress become need of the hour concerned with soft soil management, numerous works being undertaken throughout the world. To understand the research progress mostly researchers take up two methods, systematic literature review which will end up in providing information related to methods, protocols, techniques used and their related process, efficiency etc. But in this method, many concepts including who did the work, who funded the research, which country is leading in the work and related terms cannot be answered, one such technique adopted to answer that questions is bibliometric or scientometric analysis.

Scientometric analysis was first defined by Nalimov and Mulchenko [11] as 'a quantitative study of the research on the development of science. It can be regarded as a methodology that involves measuring the research impact, understanding the citation process, mapping the knowledge structure and evolutions within a specific domain based on extensive scholarly dataset [12]. Unlike traditional methods of literature evaluation such as expert or peer review, which suffer from limitations such as time-consuming and costly processes, as well as potential human bias, distortion, and lack of transparency [13], scientometrics offers a cost-effective, objective, and informative mode of analysis [14], [15]. In recent years, many researchers have conducted scientometric analysis in different subject fields, including civil engineering. For instance, scientometric studies have been conducted on topics such as global Building Information Modeling (BIM) [16], [17], construction related ontology research [18], sustainability of megaproject management [19], urban resilience research [20] and water quality indexing [21].

The bibliometric methodology is a popular way of quantitative statistical analysis that summarizes a large body of literature and sheds light on the current state of study in a certain topic. As previously discussed [22], [23], bibliometric analysis is highly valued by researchers due to its capacity to recognize research trends and hotspots, as well as provide references for future research directions and allow international collaborations. Despite the many books and articles written about soft soil management, comparatively few bibliometric studies have been conducted. As a result, the bibliometric analysis of global research trends and the amount of research contributions in the subject of soft soil management are either unclear or poorly recorded.

Moreover, novelty, defined as the fusion of established knowledge in an unconventional way, has found application in bibliometrics analysis through authors' co-citation methods. Developing a fresh array of novelty indicators holds significant importance in research evaluation, as it directs attention towards innovative breakthroughs in research. Nonetheless, evaluating research poses considerable challenges due to the fact that scientific advancements are primarily propelled by significant yet infrequent discoveries that are arduous to pinpoint and measure [24].

TABLE 1. Summary of the search details.

Source	Web of Science (WOS) Core Collection database
Citation indexes	SCIE; ESCI SSCI; CPCI-S
Years	2013-2023
Search string	TS = (soft clay OR soft soil) AND TS = (stabilized OR improved OR treated OR reinforced)
Sample size	2,260

Therefore, this research addresses the scarcity of bibliometric studies in this area through a novel approach of conducting a comprehensive bibliometric analysis of 2,260 literature from 2013 to 2023 using CiteSpace to investigate the trend, opportunities and challenges in soft soil management for infrastructure development. The analyses encompass country distribution, authorship and co-cited authors, cited journals, reference co-citations and identification of research hotspots and frontiers. The study contributes to the literature of soft soil management by identifying prominent and influential contributors (country, authorship, cited journals), dominant research themes, research hotspots and frontiers with evolutionary trends, opportunities, and key challenges in the field. The findings provide detailed information and valuable insights about the current state and ongoing efforts in the research landscape of soft soil management domain. It is hoped that the analysis offers valuable guidance and understanding to the researchers, industry practitioners and policymakers for infrastructure development in future.

The paper is structured as follows. Section II set out the data and methodology employed in this study. Section III presents the results and discussion, including quantitative analyses of the number of publications, country distribution, authorship and co-citation networks, cited journals, reference co-citation patterns, and the identification of research hotspots and frontiers. Section IV discusses the opportunities and challenges identified. Finally, Section V concludes the paper, summarizing the main findings and highlighting their implications.

II. DATA AND METHODS

A. DATA SOURCE

The Web of Science database was queried for 2,260 publications and conference papers published between 2013 and 2023 for the purpose of this review. CiteSpace was used to conduct bibliometric evaluations of the available literature in order to spot emerging topics and themes in the study of soft soil management. The search details are summarized in Table 1.

B. METHOD AND TOOL EMPLOYED

CiteSpace, a visualization information software developed jointly by Chen from the School of Information Science and Technology at Drexel University and the WISE Laboratory at Dalian University of Technology, is a powerful tool for analyzing diverse literature. It allows for the examination of various characteristics, including keywords, authors, cited research, and periodicals, to create dynamic visualizations of knowledge. CiteSpace presents the analyzed data in the form of a keyword cluster map, time zone distribution map, co-authored network, and co-cited network. Researchers in the

field of civil engineering have utilized CiteSpace to examine emerging topics and research trends in various sub-disciplines, such as environmental engineering, geotechnical engineering, and sustainable engineering.

In the context of soft soil engineering, Wang et al. [25] conducted a visualization analysis on special soil subgrade research, highlighting the concentration of international research efforts on subgrade stability and reinforcement, with China National Knowledge Infrastructure (CNKI) research emphasizing dynamic compaction methods, Cement Fly-ash Gravel (CFG) pile, and geogrids, and WOS research focusing on geosynthetics for subgrade reinforcement. CNKI research currently explored compression and deformation characteristics of lightweight foam soil fill subgrade, while WOS research concentrated on issues related to soft soil subgrade and numerical analysis methods.

In this study, data was extracted from the WOS core database prior to analysis using CiteSpace. The software was used to develop a keyword network visualization map, which revealed emerging words, popular topics, and research turning points in the field of soft soil management. This map provides valuable insights into the evolution, research frontier, and development trends within the field. Citespace is selected because of its versatility and usability concerned with data obtained from Web of Science, it is widely used by many researchers to understand the research landscape of a particular domain.

III. RESULTS AND DISCUSSION

Scientometrics works focus on analysing the rate of publication, authors contribution, country wide statistics, journals contributing and other parameters that act as indicator of the research progress. In this work, we have analysed the article production and other important parameters by the usage of Web of Science database through systematic keyword search. The rate of article production over time can give light on the trajectory of progress in a field. The number of articles published on the topic of soft soil management from 2013 to 2023 is depicted in Figure 2. There were fewer publications in 2013 and 2014, with 116 and 118 total. There was a sharp uptick in publication activity beginning about 2015, with 361 works appearing in print that year alone. An upward trajectory in the number of articles published on the subject indicates growing attention to it. Reasons for this include the topic's increasing prominence in the field and the convenience and availability of research enabled by technological developments. These advancements encompass improved computational modeling techniques, easy access to digital

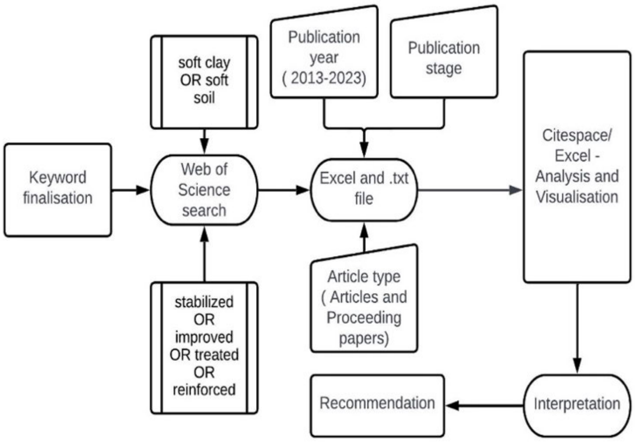


FIGURE 1. **Flowchart showing the method employed.**

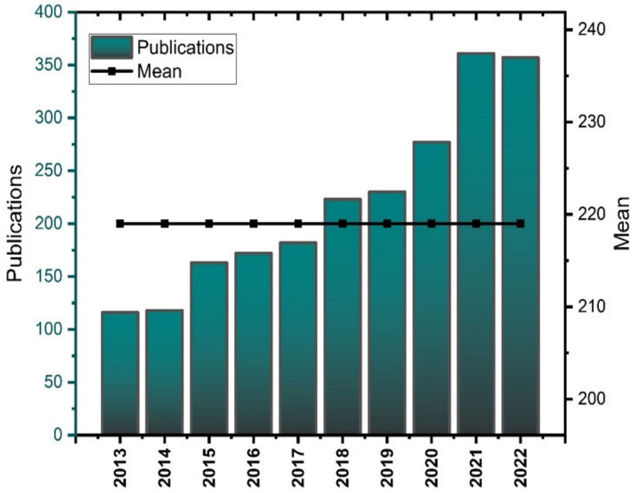


FIGURE 2. **Number of publications from 2013 to 2023.**

resources, and advancements in geotechnical instrumentation and monitoring systems. The use of improved computational modeling techniques enables researchers to simulate and analyze complex scenarios, facilitating a deeper understanding of soft soil behaviour. Additionally, researchers can easily access digital resources to build upon existing findings and stay updated with the latest advancements. Moreover, the development of advanced geotechnical instrumentation and monitoring systems such as fiber optic sensing offer real-time data on soil behaviour, aiding in the effective management of soft soil.

The number of publications did drop in 2023, but that could be because the data only covers through April of that year and the year has not yet finished. As the year continues, the volume of publications may rise. The rising tide of scholarly articles sheds light on the subject's rising profile and the field's intensifying research agenda.

A. QUANTITATIVE ANALYSIS OF PRODUCTIVE COUNTRIES/ REGION

Country wide production is one of the most influencing factors in the research landscape, understanding which country is performing better gives clear picture to understand various nuances attached to the analysis. In Figure 3, we can observe how many articles various countries have published on the topic of soft soil management. In particular, China stands out as the top contributor, with 859 papers accounting for 38% of the total. In contrast, the publication outputs of countries like India and Australia and the others in the chart are far lower. Multiple causes contribute to China's prolific publication production. First, increasing economic growth and urbanization in China's coastal areas necessitate excellent soft soil management. Notably, from 2000 to 2020, the coastal zone in China underwent rapid urbanization which resulted in an expansion of 17,979.72 km^2 and an annual growth rate of 4.83% [27]. Soft clay soils are extensively distributed across China, with about one-quarter of the nation's coastline categorized as a soft clay coast [26]. Soft soil areas including soft clay and muddy clay in China are mainly located in the Bohai Bay, Yangtze River Delta, coastal Zhejiang and Fujian (and certain other coastal areas), and urban areas such as Wuhan and Kunming along major rivers (Figure 4) [28]. Second, the Chinese government has poured resources into R&D, which includes efforts to better manage soft soil. This commitment is evidenced by the significant R&D investments. For example, China's R&D investment in 2021 alone reached 2.7864 trillion yuan, marking a 14.2% increase from the previous year and reflecting the country's continuous commitment to advancing various scientific fields [29].

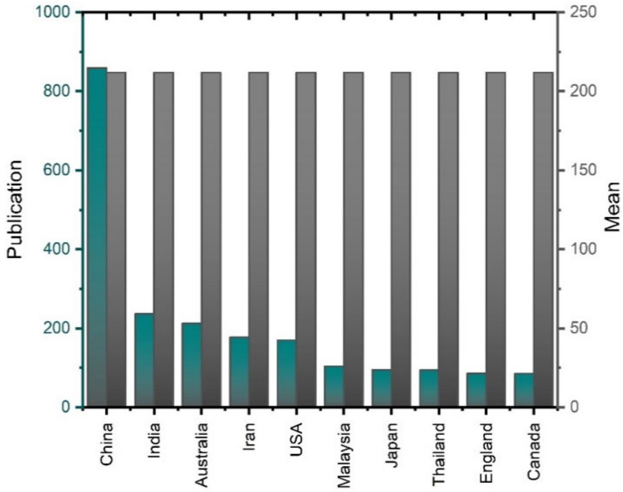


FIGURE 3. **Production of countries with mean information.**

B. ANALYSIS OF AUTHORS AND CO-CITED AUTHORS

The author and cited authors analyses conducted through CiteSpace delineate the contours of academic influence and productivity in the soft soil management domain from 2013 to 2023. After importing the document collection into CiteSpace, the time range was set to 2013 to 2023 with a 'Year Per Slice' time partition of one year. The node classes for the analyses were specified as 'Author' and 'Cited Author' respectively. The selection criterion was set to the top 50.

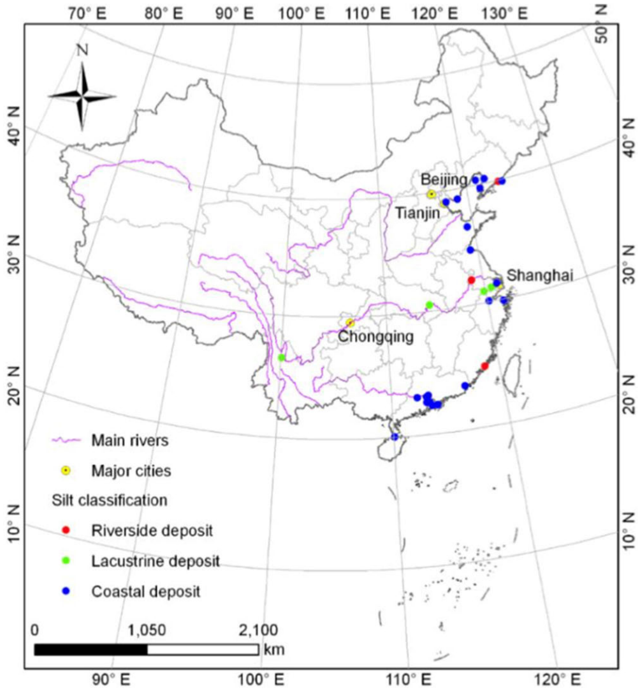


FIGURE 4. Regional distribution of typical soft clay in China [26].

TABLE 2. Top 10 most prolific authors.

Ranking	Authors	Publications
1.	Horpibulsuk, Suksun	33
2.	Indraratna, Buddhima	28
3.	Jamsawang, Pitthaya	27
4.	Jongpradist, Pornkasem	20
5.	Zheng, Gang	19
6.	Arulrajah, Arul	19
7.	Dias, Daniel	19
8.	Zhang, Zhen	16
9.	Wang, Jun	15
10.	Fatahi, Behzad	15

The author analysis reveals the research productivity within the selected timeframe. Table 2 shows the top ten most prolific authors who published on soft soil management. Horpibulsuk, Suksun had the highest number of publications (33), followed by Indraratna, Buddhima (28) and Jamsawang, Pitthaya (27). The prominence of these authors in this table underscores their extensive contribution to the body of literature within the decade.

TABLE 3. Top 11 most cited authors.

Ranking	Cited Authors	Centrality	Citation Counts
1.	[Anonymous]	0.01	840
2.	Han J	0.17	362
3.	Indraratna B	0.08	306
4.	Chai JC	0.1	294
5.	Bergado DT	0.06	254
6.	ASTM	0.16	251
7.	Horpibulsuk S	0.17	250
8.	Terzaghi K	0.02	235
9.	Consoli NC	0.06	154
10.	Liu HL	0.01	151
11.	Castro J	0.05	149

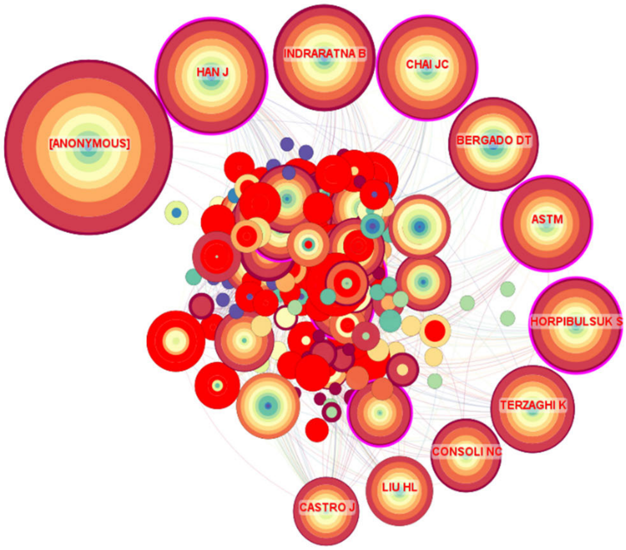


FIGURE 5. Authors' co-citation network.

Parallel to this, the cited author analysis indicates broader academic impact. Figure 5 visualises the authors' co-citation network. The nodes represent cited authors, and the connections between nodes represent the relationships between the authors and cited authors. Table 3 presents the top 11 most cited authors in this field. Excluding the anonymously cited authors ('Anonymous'), Han J stands out not only for the citation count but also for the centrality within the scholarly network. The centrality measure suggests Han J's work is a pivotal reference within the network, serving as a foundational or highly influential set of works for other researchers. The visualization also underscores the prominence of specific authors like Terzaghi K that have the lasting impact of their work across the years.

The cross-analysis of these datasets elucidates a dichotomy between prolific output and citation impact. The presence of Indraratna, Buddhima and Horpibulsuk, Suksun in both tables underscore their dual role as significant contributors and influential authorities within the academic discourse. This duality is less apparent for other authors, indicating a potential divergence between quantity of publications and their scholarly influence.

C. ANALYSIS OF CITED JOURNALS

To provide a clear overview of the research orientations involved in the soft soil management, a citation network of journals was drawn using CiteSpace as shown in Figure 6. The same time range, 'Year Per Slice' time partition and selection criterion were selected as per those of analyses of

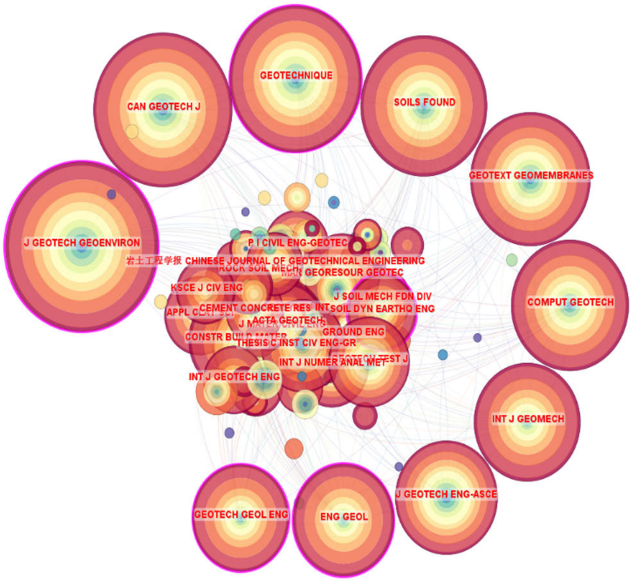


FIGURE 6. Journals in the cited network.

TABLE 4. Top 10 most cited journals.

Ranking	Cited Journals	Centrality	Citation Counts	*JIF (2022)
1.	Journal of Geotechnical and Geoenvironmental Engineering	0.21	1517	3.9
2.	Canadian Geotechnical Journal	0.05	1252	3.6
3.	Géotechnique	0.1	1142	5.8
4.	Soils and Foundations	0.07	1068	3.7
5.	Geotextiles and Geomembranes	0.07	955	5.2
6.	Computers and Geotechnics	0.05	927	5.3
7.	International Journal of Geomechanics	0.02	770	3.7
8.	Journal of Geotechnical Engineering - ASCE	0.08	710	1.009 (As of 1998)
9.	Engineering Geology	0.15	697	7.4
10.	Geotechnical and Geological Engineering	0.1	615	1.7

*The data were taken from www.webofknowledge.com on 17 November 2023. JIF – Journal Impact Factor.

authors and cited authors. The node type for the analysis was specified as 'Cited Journal'.

Table 4 presents the top 10 most-cited journals. It can be seen that the core journals in the domain are highly concentrated. Within this citation network, 'Journal of Geotechnical and Geoenvironmental Engineering' emerges as the foremost high-cited journal with 1517 citations which indicates its foundational role in the literature. This journal's centrality of 0.21 with a Journal Impact Factor (JIF) of 3.9, establishes its position as a principal node through which a significant portion of research dialogue is filtered. Similarly, 'Engineering Geology' with 697 citations, the second highest centrality of 0.15 and the highest JIF of 7.4, and 'Géotechnique' with 1142 citations, a high centrality of 0.1 and JIF of 5.8, are both pivotal in disseminating influential research as evidenced by their strong presence in the citation network.

In contrast, 'Geotechnical and Geological Engineering' presents a centrality score on par with 'Géotechnique', yet a lower JIF of 1.7. This suggests a specialized impact within the network that might not be captured solely by citation frequency. Its role may be essential for niche areas within soft soil management, highlighting that centrality and JIF are not always directly correlated. Additionally, an interesting and important observation concerns the 'Journal of Geotechnical Engineering – ASCE' which has a centrality of 0.08. This journal maintained its influence in the field despite its publications only being until 1998. Wherein, this journal later evolved into the 'Journal of Geotechnical and Geoenvironmental Engineering', signifying its continuous impact and adaptation in the evolving domain of soft soil management.

D. ANALYSIS OF REFERENCE CO-CITATION

For the analysis of reference co-citation, the same time range and 'Year Per Slice' time partition were selected as per those of analysis of cited journals. The node type for the analysis was specified as 'Cited Reference'. And the selection criteria were set to 'TOP 10%' with a maximum of 100 items per segment being chosen. Table 5 lists the top 10 most cited references in the research of soft soil management.

The clustering of similar references resulted in co-citation clusters that can provide insight into the main research topics in the intellectual base. In the soft soil management literature, the main research themes are classified into the top 17 largest clusters as listed in Table 6. Figure 7 illustrates the details of the reference co-citation clusters.

From Figure 7 and Table 6, several major observations can be drawn. Firstly, most soft soil management studies focused heavily on two types of ground improvement methods, i.e. 'geosynthetic-reinforced pile-supported embankment' (Clusters #0) and 'stone column' (Clusters #1) which emerge as the two largest clusters within the field. The size of the clusters suggests a significant volume of studies and citations. On top of that, the inter-cluster relevance of stone columns is also observed. Where, the stone column method is a recurring theme across multiple clusters, i.e. Cluster # 0, 1, 2, 3, 4, and 14 which highlights its central importance in the field and its applicability to various ground improvement contexts.

Additionally, the focus on sustainability within this field is evidenced by dedicated clusters for 'calcium carbide residue' (Clusters #3), 'recycled basanite' (Clusters #7) and 'sludge ash' (Clusters #8). These clusters are defined by main research topics that are directly related to sustainable practices and the reuse of waste materials in soil stabilization. Moreover, the 'analytical solution' cluster in the co-citation analysis indicates that analytical solutions are a significant aspect of soft soil management research. This cluster reflects a significant research effort focused on theoretical models and computational methods that predict the behavior and properties of ground improvement techniques and materials used. As evidenced by the emergence of the 'case study'

TABLE 5. Top 10 most cited references.

Ranking	Cited References	Authors	Citation Counts
1	An Analytical Model for Arching in Piled Embankments	van Eekelen et al.	70
2	Studies on the Behavior of Single and Group of Geosynthetic Encased Stone Columns	Murugesan and Rajagopal	62
3	Performance of Pile-Supported Embankment over Soft Soil: Full-Scale Experiment	Briançon and Simon	61
4	Improvement of Soft Soils Using Geogrid Encased Stone Columns	Gniel and Bouazza	59
5	Bearing Capacity of Geosynthetic Encased Stone Columns	Ghazavi and Nazari Afshar	53
6	3D Coupled Mechanical and Hydraulic Modeling of a Geosynthetic-Reinforced Deep Mixed Column-Supported Embankment	Huang and Han	51
7	Performance of a Geogrid-Reinforced and Pile-Supported Highway Embankment over Soft Clay: Case Study	Liu et al.	46
8	Behavior of Stone Columns Based on Experimental and FEM Analysis	Ambily and Gandhi	45
9	Model Experiments on Piled Embankments. Part I	van Eekelen et al.	44
10	Failure Mechanism of Geosynthetic-Encased Stone Columns in Soft Soils Under Embankment	Chen et al.	43

TABLE 6. Top 17 reference co-citation clusters.

Cluster ID	Clusters	Main Including Labels
0	Geosynthetic-reinforced pile-supported embankment	geosynthetic-reinforced pile-supported embankment; pile-supported embankment; load transfer mechanism; analytical model; stone column
1	Stone column	stone column; bearing capacity; geosynthetic-encased stone column; granular blanket; encased stone column
2	Soil stabilization	soil stabilization; clayey soil; stone column; unifying industrial by-product; generic framework
3	Calcium carbide residue	calcium carbide residue; soft highway subgrade soil; stone column; strength development; cement-stabilized clayey soil
4	Analytical solution	analytical solution; stone column; soil-cement column; numerical modeling; composite ground
5	Case study	case study; preloading method; soft bangkok clay; soil wall; vacuum consolidation
6	Bending effect	bending effect; stability analysis; subgrade strength; geocell-reinforced foundation system; bearing capacity calculation method
7	Recycled bassanite	recycled bassanite; soft clay soil; marine soft clay; blastfurnace slag; coal ash
8	Sludge ash	sludge ash; steel fibre; polypropylene fiber; liquid polymer; using fiber
9	Cemented stone column	cemented stone column; infinite beam; moving load; geosynthetic-reinforced granular bed; extensible geosynthetics
10	Ballasted rail track	ballasted rail track; performance assessment; synthetic inclusion; australian perspective; track geomechanics
11	Using cationic reagent grout	using cationic reagent grout; electrokintic method; microfabric change; exchange behavior; electro-osmotic consolidation
12	Land reclamation sand	land reclamation sand; deep vibratory compaction technique; bat permeameter; in-situ hydraulic conductivity; land reclamation
13	Extraction test	extraction test; cyclic full-flow penetration; free fall sphere projectile; curvilinear penetration; marine clay
14	Ultra-soft kaolin	ultra-soft kaolin; strength properties; soft soil; soft clay; stone column
15	Continuous drainage boundary	continuous drainage boundary; double-layered soil; analysis; non-darcian flow; soft soil
16	Uncertainty analysis	uncertainty analysis; soft soil site; soft alluvial soil; railway embankment; field studies

cluster, empirical research using specific examples or scenarios is another significant aspect of soft soil management research. The case studies are particularly centered on specific techniques (such as preloading method, vacuum consolidation and retaining structures) and local soil conditions (such as soft Bangkok clay) that are critical to the practical application of research.

E. RESEARCH HOTSPOT

Keywords are the best way to summarize the subject of a document, there are two keywords used one is author keywords, second is indexed keywords. Therefore, by analyzing keywords, one can determine the research foci over time. After importing the document collection into CiteSpace, the time range was set to 2013 to 2023 with a 'Year Per Slice' time partition of one year. 'Keyword' has been chosen as the node class. And the selection criteria were set to 'TOP 10%' with a maximum of 100 items per segment being chosen. In the analysis of WOS keyword distribution, each node within the keyword knowledge map represents a keyword, the node size indicates the frequency of keyword occurrence, and the thickness of the lines connecting the nodes indicates the intensity of correlation. The investigation revealed 397 network nodes and 3008 connecting connections. On the

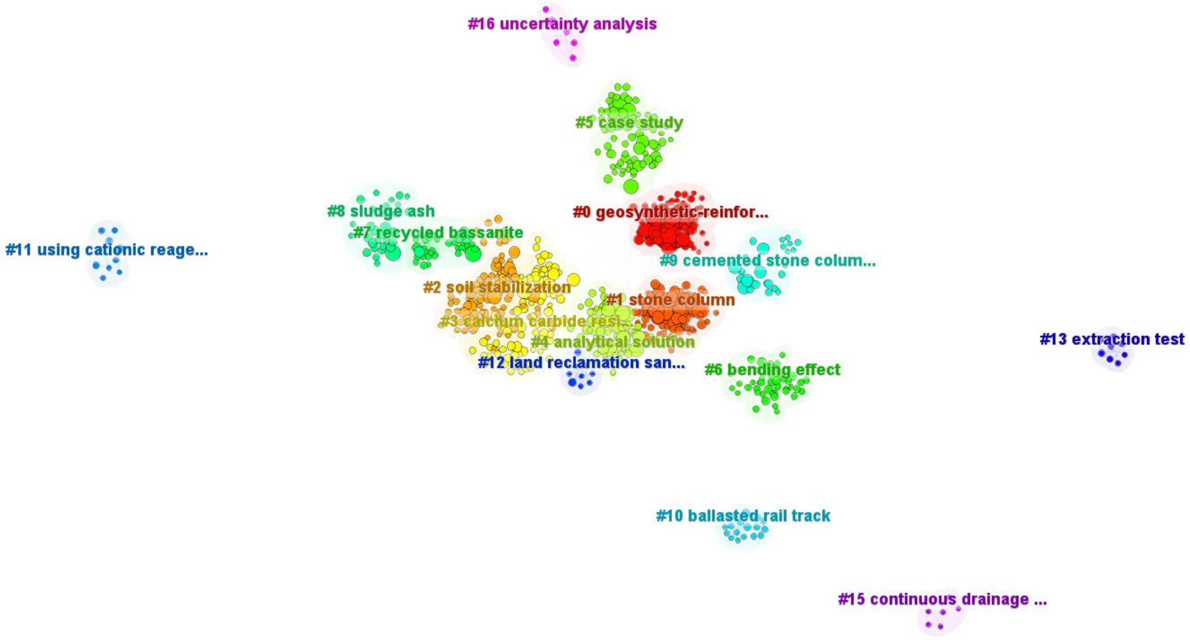


FIGURE 7. Cluster graphs of reference co-citations in soft soil management.

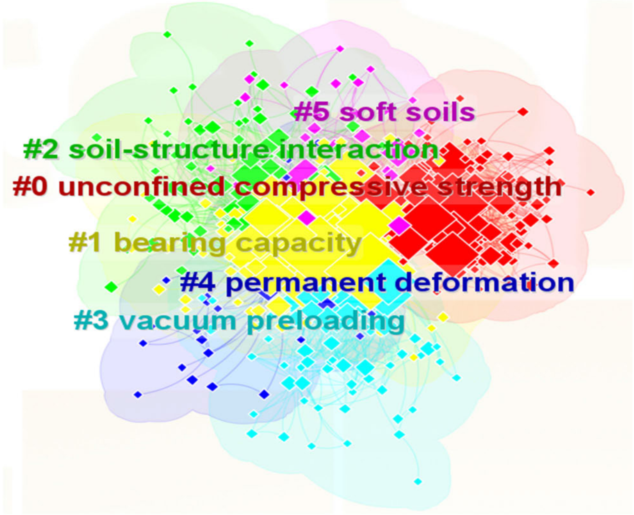


FIGURE 8. Cluster graph of soft soil management research keywords.

knowledge map of keywords, a cluster analysis was then conducted. Using a similarity-based algorithm, cluster analysis classifies objects into various groups in order to identify the most prominent research topics in a given field [30]. As shown in Figure 8, the software has classified the keywords into six cluster groupings. According to Table 7, nodes with the same color imply a cluster group named after the node containing the primary keyword.

Unconfined compressive strength was the most common theme among the topics in Cluster-ID #0, which also included microstructure, soil stabilization, geopolymer, and cement. The unconfined compressive strength (UCS) is the most widely used parameter for assessing subgrade or foundation soil strength for cohesive soils. It is defined as the maximum vertical load or stress a soil sample can withstand before collapse or failure [31]. In the context of soft soil, UCS is influential in determining the effectiveness of soil stabilizers. The UCS testing allows determination of type, quantity, and ratio of specific binders, as well as assessing the suitability of the water-to-cement (w/c) ratio for desired soil stabilization outcomes [32]. In order to improve the soil's engineering properties at a low cost, chemical stabilization has been shown to be effective. The addition of lime or cement to weak soil is the most typical way of stabilization. Multiple studies have reported the drawbacks of using cement for soil stabilization, including increased carbon dioxide emissions [33], [34], damage to ground water and vegetation [35], [36], and the potential for sulfate-induced heave in coastal regions [37], [38], [39]. The use of geopolymer as an alternative to cement has been the subject of extensive research in recent years. To stabilize soft clay, for instance, Zheng and Wu [40] investigated the viability of utilizing a one-part geopolymer as an alternative to ordinary Portland cement (OPC). The unconfined compressive strength (UCS) values achieved through geopolymerization were observed to rise noticeably with increasing fly ash concentration in the precursor mixture. With a mass ratio of 10% fly ash to 90% ground granulated blast furnace slag (GGBFS), the highest UCS values were attained. Analysis of the soil's microstructure and mineralogy revealed that abundant hydration products helped strengthen the soft clay by constructing the soil's skeleton and filling in the spaces between clay particles.

Cluster-ID #1 was the second, and it was labelled as bearing capacity. This cluster included topics such as bearing

TABLE 7. **Six cluster groups of the keyword nodes.**

Cluster ID	Clusters	Main Including Labels
0	Unconfined compressive strength	unconfined compressive strength; microstructure; soil stabilization; geopolymer; cement
1	Bearing capacity	bearing capacity; stone column; ground improvement; finite element analysis; stone columns
2	Soil-structure interaction	soil-structure interaction; soil arching; reinforced concrete; seismic design; ground improvement
3	Vacuum preloading	vacuum preloading; prefabricated vertical drain; vertical drain; land reclamation; vacuum consolidation
4	Permanent deformation	permanent deformation; pvd-improved ground; soft soil subgrade; piles & piling; monte carlo simulation
5	Soft soils	soft soils; shield tunnel; geosynthetics; tunnelling; soil -structure interaction

capacity, stone columns, ground improvement and finite element analysis. When assessing the long-term viability and safety of structures constructed on soft soil, bearing capacity is a critical element. The use of stone columns to fortify weak clay soil has recently gained popularity as a practical and efficient method. Soil settling is decreased and bearing capacity is increased [41]. Elsawy [42], for instance, used a numerical analysis to compare the performance of conventional stone columns versus geogrid-encased stone columns in a full-scale model of Bremerhaven clay subjected to embankment loads. The stone columns improved the foundation's bearing capacity and accelerated the reduction of excess pore water pressure, with even greater improvement observed when the columns were encased with geogrid. Soil consolidation can be sped up with the help of stress concentration in the stone columns, as was shown in the study.

The third was Cluster-ID #2, with a tag of soil-structure interaction, primarily including soil-structure interaction, soil arching, reinforced concrete, seismic design and ground improvement. Soil-Structure Interaction (SSI) has emerged as a crucial aspect of structural engineering, following the development of large-scale constructions on soft soils such as nuclear power plants, concrete and earth dams. Particular attention to SSI issues may also be necessary for buildings, bridges, tunnels, and underground structures [43]. It is crucial to incorporate the soil-structure interaction (SSI) in the analysis of structures on soft soils to ensure accurate seismic assessment [44], [45]. SSI significantly impacts the seismic response of structures, particularly those situated on soft soils. SSI can detrimentally impact a flexible secondary system linked to the primary soil-structure system by filtering out high-frequency content while amplifying low-frequency content motions in the secondary system. Additionally, as the soft soil beneath a structure act as a flexible pad, excessive displacement can occur in the structure [46]. The significant impact of SSI is further evidenced by the study of Fatahi et al. [47], who demonstrated that considering SSI substantially increased inter-storey drifts and changed the performance levels of structures from life safe to near collapse. In another study, Carbonari et al. [48] investigated the seismic response of reinforced concrete structures supported by monopile foundation systems and found that SSI had a notable effect on the seismic response of the building by increasing structural deformation and inter-story drifts, especially in the lower parts of the building. The study also observed a considerable increase in pile rotations due to SSI.

The fourth was Cluster-ID #3, with a tag of vacuum preloading, mainly including vacuum preloading, prefabricated vertical drain, vertical drain, land reclamation and vacuum consolidation. The combination of vertical drains and vacuum preloading has emerged as a viable and cost-effective ground improvement solution. This method speeds up the consolidation process by facilitating fast radial flow that decreases excess pore pressure and increases the effective stress. Over the past few decades, numerous experimental, analytical, and numerical methods have been developed to simulate the mechanics of prefabricated vertical drains (PVDs) and vacuum preloading, including two-dimensional and three-dimensional analyses, as well as advanced design approaches. These innovative techniques have been put into practice in a range of real-world projects across Australia and Southeast Asia. For example, Saowapakpiboon et al. [49] examined the effectiveness of vacuum preloading in accelerating the consolidation of PVD improved soft Bangkok clay through laboratory test and field data analyses. The addition of vacuum pressure increased undrained shear strength and resulted in relatively shorter preloading time due to the increase of horizontal coefficient of consolidation. Furthermore, the field monitoring at the Brisbane Port, Australia, confirmed that the PVD system subjected to vacuum combined surcharge preloading is an effective method for accelerating radial consolidation and controlling lateral displacement [50], [51].

The fifth was Cluster-ID #4, with the tag of permanent deformation, primarily including permanent deformation, PVD-improved ground, soft soil subgrade, piles & piling and Monte Carlo simulation. Soft soil subgrades are prone to excessive permanent deformation when exposed to moisture. This deformation is intensified under repetitive traffic wheel loads, eventually resulting in surface rutting along the wheel paths of the pavement which endangers road users.

Geosynthetic reinforcement, such as geogrids, has been widely used to minimise pavement rutting by distributing the wheel loads more evenly across the subgrade. Excess pore pressure caused by traffic loading in soft subgrades can also be mitigated by using vertical drains to facilitate rapid dissipation of excess pore pressures. For example, PVDs have demonstrated effectiveness in preventing the accumulation of excess pore pressures to critical values for clay-like soils that are susceptible to cyclic softening [52].

Several significant findings have emerged from the cluster analysis of soft soil management. Unconfined compressive strength, bearing capacity, and soil-structure interaction are only a few of the factors that have been highlighted by the analysis as being particularly important. In addition, geopolymer has been praised for its potential to improve the strength and longevity of weak soils. Besides, the analysis has uncovered a number of widely used soil stabilization methods, like stone columns and vacuum preloading with prefabricated vertical drains, that warrant further investigation. Finally, the analysis has focused on the issue of permanent deformation in soft subgrades, which is a critical concern for road construction and other infrastructure projects. In sum, the results provide valuable insights into the management of soft soils and can direct future studies and developments in this field.

Building upon these individual findings, interrelationships can be identified among the clusters in soft soil management research. Notably, unconfined compressive strength (Cluster-ID #0) and bearing capacity (Cluster-ID #1) both play critical roles. The UCS is a key metric for assessing soil strength characteristics, and soil bearing capacity is directly dependent on the shear strength, where greater shear strength implies an enhanced capacity to support loads without shear failure. In this context, California Bearing Ratio (CBR) which is used as a direct measure of bearing capacity, is commonly measured together with the UCS to evaluate the effectiveness of stabilization techniques.

Soil-Structure Interaction (SSI) in Cluster 2 also demonstrates a significant connection to bearing capacity (Cluster-ID #1). The dynamic response of a structure during severe seismic events is influenced by both the behavior of the superstructure and the characteristics of the soil in and around the substructure. This implies that the soil's bearing capacity can significantly influence Soil-Structure Interaction (SSI). This relationship is further exemplified in the study by Akkar and Metin [53], where the effect of SSI is more pronounced on soft soil compared to medium and hard soil.

Regarding Cluster 3, vacuum preloading proves to be a highly effective method for enhancing the bearing capacity of soft clay layers. This technique minimizes post-construction settlement and increases the original ground's bearing capacity [54]. Additionally, the link between permanent deformation and bearing capacity becomes apparent when observing how a pavement subgrade with adequate bearing capacity can manage and stabilize permanent deformations. These deformations, even if minor in each loading cycle, can lead to structural deterioration due to severe rutting. Therefore, maintaining adequate bearing capacity is essential to prevent premature failure and ensure a stable and resilient response over the pavement subgrade's service life.

In short, the SSI analysis needs to incorporate considerations of bearing capacity as it significantly influences the structural response. Furthermore, vacuum preloading is effective in reducing settlement and improving the bearing capacity of soft soil. The capacity to accumulate and stabilize permanent deformation is intrinsically linked to the bearing capacity. Lastly, the importance of bearing capacity is rooted in its direct dependence on the shear strength of the soil.

F. RESEARCH FRONTIER IDENTIFICATION

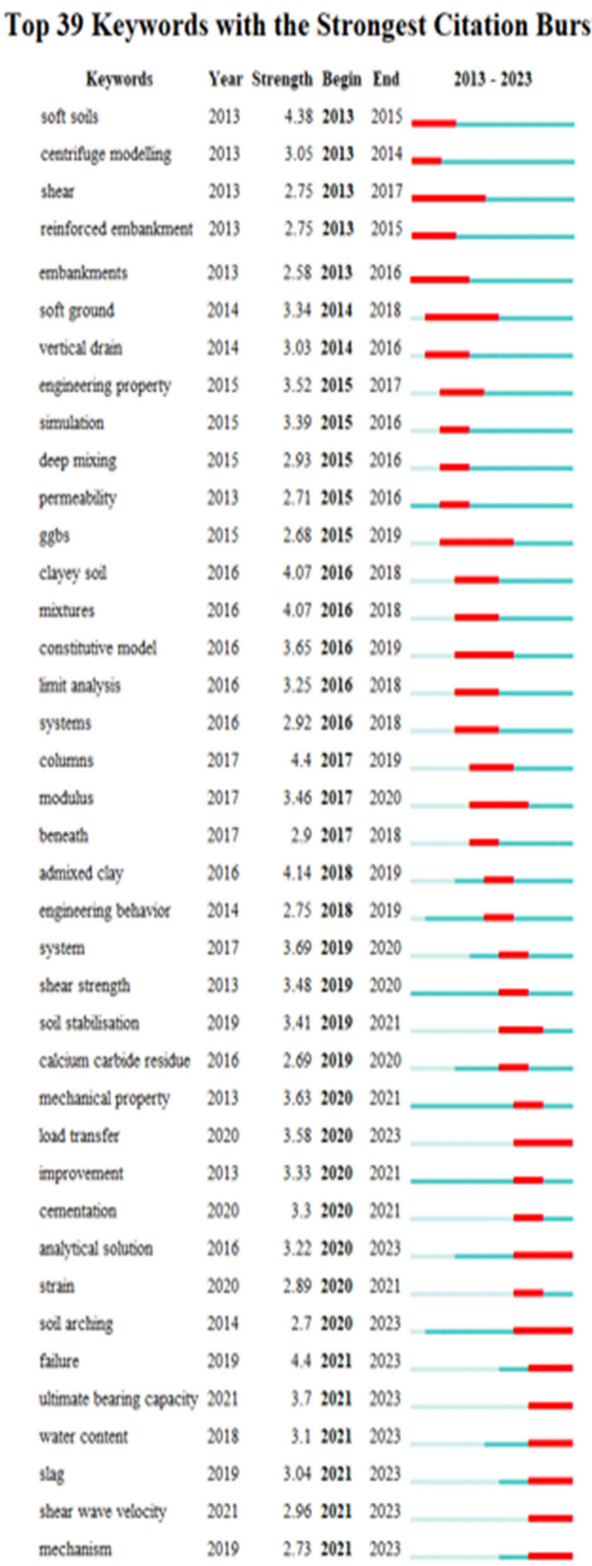
Figure 9 showed the analysis of emergence words using CiteSpace's burst detection capabilities to identify cutting edge topics in the soft soil management field. A list of emerging words was obtained, sorted by their year of appearance. The strength of each keyword corresponds to the degree of its emergence. The position and length of the red block represents the highlighted interval of the keyword.

From Figure 9, the analysis of the WOS research trends revealed several key areas across four distinct time periods, as outlined below:

1) From 2013 to 2015, the key emerging words were found to be 'centrifuge modelling' and 'vertical drains'. During this time, centrifuge modelling had been widely used to test models of geotechnical problems such as slope stability, earth retaining structures, tunnel stability, embankment settlement and strength, stiffness and capacity of foundations for bridges and buildings. Liu et al. [55] performed a series of centrifuge model tests to understand the deformation and failure characteristics of slopes reinforced with various pile layouts.

   During the same period, the use of vertical drains had been studied as an active research area to address the challenges of infrastructure development in soft soil areas. Numerous studies focused on the development of efficient drain designs and performance assessment methods. For example, Estabragh et al. [56] examined the effect of electro-osmosis on the chemical, physical and mechanical behaviour of a clay soil using designed apparatus with electrical vertical drains (EVD). The study found that electro-osmosis induced changes in the soil properties, including increased settlement and undrained strength, as well as changes in pH, electrical conductivity (EC), and Atterberg limits. Another study by Chen et al. [57] presented a case study on the effective depth of PVDs under embankment loading on a very soft clay deposit in central China. The analysis indicated that the effective depth of PVDs for this case was between 10 and 12.8 m.

   Interestingly, the emerging word analysis from Figure 5 reveals that 'shear' was a persistent keyword in soft soil management research from 2013 to 2017. This persistence indicates a continuous focus on how



Top 39 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End
soft soils	2013	4.38	**2013**	2015
centrifuge modelling	2013	3.05	**2013**	2014
shear	2013	2.75	**2013**	2017
reinforced embankment	2013	2.75	**2013**	2015
embankments	2013	2.58	**2013**	2016
soft ground	2014	3.34	**2014**	2018
vertical drain	2014	3.03	**2014**	2016
engineering property	2015	3.52	**2015**	2017
simulation	2015	3.39	**2015**	2016
deep mixing	2015	2.93	**2015**	2016
permeability	2013	2.71	**2015**	2016
ggbs	2015	2.68	**2015**	2019
clayey soil	2016	4.07	**2016**	2018
mixtures	2016	4.07	**2016**	2018
constitutive model	2016	3.65	**2016**	2019
limit analysis	2016	3.25	**2016**	2018
systems	2016	2.92	**2016**	2018
columns	2017	4.4	**2017**	2019
modulus	2017	3.46	**2017**	2020
beneath	2017	2.9	**2017**	2018
admixed clay	2016	4.14	**2018**	2019
engineering behavior	2014	2.75	**2018**	2019
system	2017	3.69	**2019**	2020
shear strength	2013	3.48	**2019**	2020
soil stabilisation	2019	3.41	**2019**	2021
calcium carbide residue	2016	2.69	**2019**	2020
mechanical property	2013	3.63	**2020**	2021
load transfer	2020	3.58	**2020**	2023
improvement	2013	3.33	**2020**	2021
cementation	2020	3.3	**2020**	2021
analytical solution	2016	3.22	**2020**	2023
strain	2020	2.89	**2020**	2021
soil arching	2014	2.7	**2020**	2023
failure	2019	4.4	**2021**	2023
ultimate bearing capacity	2021	3.7	**2021**	2023
water content	2018	3.1	**2021**	2023
slag	2019	3.04	**2021**	2023
shear wave velocity	2021	2.96	**2021**	2023
mechanism	2019	2.73	**2021**	2023

FIGURE 9. Emerging words of soft soil management research. Note: "Begin" and "End" in the figure are the starting and ending time of keyword emergence.

soils respond to shear forces. This extended interest likely reflects ongoing challenges in predicting and improving shear behavior in soft soils. For example, Indraratna et al. [58] employed the coupled DEM and FDM approach to study stone column deformation in soft soil. The approach captured the contact force distribution and shear stress contour developed in the stone column and surrounding clay for a better understanding of the load-deformation behaviour of the stone column.

2) From 2015 to 2019, the key emerging words were 'engineering property', 'simulation' and 'constitutive model', highlighting the importance of accurate characterization of soft soil properties for effective design and construction of infrastructure on these problematic soils. To better understand the behaviour of soft soils and to improve the accuracy of predictions, researchers used laboratory testing techniques, field instrumentation, and numerical simulations involving constitutive models. For example, Weidong et al. [59] conducted statistical and numerical analyses to investigate the physical and mechanical properties of marine coastal soft soil samples collected near an ancient seawall in Wenzhou, Zhejiang. The researchers established relationships between these properties through linear regression analysis and explored variations with depth based on data from field and laboratory tests.

Building upon these traditional approaches, advanced AI methodologies have brought significant advancements in the fields of geotechnical characterization in cohesive soils. Comparative analyses have been conducted on various machine learning models and soft computing techniques to predict key soil properties such as soil compaction parameters [60], [61], [62], shear strength properties [63], [64], [65], [66], [67] and the suitable percentage of waste materials for soil improvement [68]. In these studies, the proposed models showed superior performance with high prediction accuracy. For example, Länsivaara et al. [66] demonstrated that machine learning models surpass traditional transformation methods in predicting the undrained shear strength of Finnish soft clays. The study identified preconsolidation pressure and effective vertical stress as key variables in the transformation model.

Between 2016 to 2019, the key emerging words were found to be 'mixtures', 'columns', and 'admixed clay', which are closely related to ground improvement methods. The admixed clay and mixtures were associated with chemical stabilisation and sustainable ground improvement method such as lime, cement, fly ash, recycled plaster admixture, reuse of geo composite waste etc. For example, Arulrajah et al. [2] investigated the use of fly ash (FA) and slag (S) as alternative green binders for ground-improvement projects, compared to traditional cement and lime binders. Results showed that the FA + S binders significantly increased the strength and stiffness of the soft clay, and the optimum binder content was found to be 20%. They proposed correlations between unconfined compression strength (UCS) and modulus of elasticity (E50) and modulus of rupture (R) for the geopolymer mixtures. Jahandari et al. [69] investigated the effects of curing time on geotechnical properties of lime and geogrid-stabilized kaolinitic clay. The results indicated significant improvements in the geotechnical properties of clay through the addition of lime and geogrid, although an increase in lime percentage led to increased brittleness.

While the columns may refer to piles, deep mixing columns and stone columns. For example, Ye et al. [70] conducted finite element analyses to investigate the load transfer effect of Stiffened Deep Mixed (SDM) column-reinforced ground under an embankment. The study showed that the column spacing, and embankment height significantly affected the load transfer between SDM column and surrounding soil. In another study, Alkhorshid et al. [71] investigated the performance of encased columns on soft soil using different types of encasements and fill materials. The results of load capacity tests conducted on large scale models indicated that the displacement method used during column installation could enhance shear strength in the smear zone. Additionally, breakage of the column fill material was found to affect the load-settlement response of gravel and recycled construction and demolition waste columns.

3) Building on the foundational studies on 'shear' spanning 2013-2017, the subsequent period from 2019 to 2021 expanded the scope to rigorously explore the shear strength and mechanical properties of porous soils due to the need for efficient and sustainable methods for their stabilization and reinforcement. During this time period, the terms 'shear strength', 'soil stabilization', 'mechanical property', and 'improvement' were prominent. In one study, Pham et al. [72] proposed a Multi-Layer Perceptron neural network and Biogeography-based Optimization (MLP-BBO) hybrid approach for predicting the coefficient of consolidation of soft soil (Cv). Their research demonstrated that the MLP-BBO model can enhance the prediction of Cv values, which can then be utilized in the design of foundations and slopes. Kassou et al. [73] compared numerous correlations between undrained shear strength and overconsolidation ratio to estimate the increase in undrained shear strength during consolidation. Some correlations matched field measurements well, making them exceptional tools for predicting the increase in undrained shear strength of soft soils during consolidation.

4) From 2021 to 2023, 'load transfer', 'ultimate bearing capacity', and 'failure' were the most prominent emerging terms. The load transmission mechanism influences the distribution of loads within the soil, which, in turn, influences the ultimate bearing capacity. The ultimate bearing capacity is related to the soil and foundation's failure mechanism. Among the identified keywords, 'failure' stands out as the fastest growing area of research as it has the most significant burst with a strength of 4.4 that only started in 2021. This shows a very recent and rapid growth in interest and research activity around this topic. For instance, Jamsawang et al. [74] reported the failure of a composite soil-cement retaining wall in Bangkok due to an unexpected porous clay thickness of 7 meters, causing shear and tensile failure points to develop in the entire soil bodies and wall structures, respectively. Rehabilitation measures were implemented by extending the embedded wall structure lengths and soil-cement segments to reinforce the wall, resulting in no visible wall failure. Similarly, Li et al. [75] investigated the cause and treatment of a highway embankment slope sliding disaster in China. The slope was then strengthened with a loading berm, steel pipe grouting, and steel sheet piles. Through numerical simulation, the stability of the reinforced embankment was analyzed, and a scheme for time-dependent slurry diffusion was proposed.

At the same time, shear wave velocity (Vs) has also attracted increasing attention among researchers, not only for assessing the dynamic properties of stabilized soils but also for its application beyond traditional seismic evaluations. The use of Vs has been extended to the determination of strength and compressibility parameters through empirical correlations. This development builds upon and contributes to the existing literature on shear strength to predict unconfined compressive strength (UCS) and other critical soil parameters. For example, Min et al. [76] proposed the UCS prediction of soft clay stabilized by one-part geopolymer (OPG) under the curing stress based on the shear wave velocity.

Researchers in the field of soft soil management have switched their attention over time. Shear strength, mechanical property, and failure mechanism studies have taken precedence over those that focused on novel and sustainable methods in more recent work. There is continued prevalence in recent soft soil literature on some ground improvement methods, particularly in the applications of vertical drains, deep mixing columns, chemical stabilization, and sustainable ground improvement approaches. When simulating geotechnical issues, researchers at first primarily favored centrifuge models. The employment of simulation methods, especially constitutive models, has undergone a significant shift, however. Researchers are increasingly interested in analytical solutions as a means to more effectively evaluate and comprehend the behaviour of soft soils.

However, it is noteworthy that 'Removal and Replacement' (R&R) does not appear in the emerging word analysis despite its popularity in treating soft soil. This may be attributed to depth and cost limitations associated with this method. According to Tan [77], the R&R is effectively limited to a depth of 4.5m in terms of cost and practicality as observed in highway construction project. While partial removal and replacement is an option for deeper soft materials, it requires careful consideration of stability and long-term settlement. Furthermore, high groundwater levels pose additional challenges, necessitating the use of underwater replacement materials when pumping of water is not practical. The main disadvantage of this method is the amount of soft soil that needs to be disposal. Moreover, Idrus et al. [78] emphasize the high cost of this method as a critical factor which has prompted the consideration of alternative techniques for highway construction. These combined operational and cost issues likely explain the method's reduced emphasis in recent research trends.

IV. OPPORTUNITIES AND CHALLENGES

A. OPPORTUNITIES

In particular, sustainable ground improvement approaches, new foundation systems, and unique sensing technologies to monitor the soft soil's behaviour present interesting and diversified potential in the field of soft soil management. The need for effective and environmentally responsible solutions to the problems caused by soft soils is growing in tandem with the demand for new infrastructure. This section will further explore these opportunities in detail.

1) DEVELOPMENT OF SUSTAINABLE GROUND IMPROVEMENT METHODS

One of the potentials in the field of soft soil management is the development of sustainable ground improvement approaches, as evidenced by the research frontiers in this area. Deep foundation systems and soil replacement are two examples of conventional ground improvement approaches that can be beneficial, but are also resource-intensive and potentially harmful to the environment. Sustainable ground improvement techniques have received more attention in recent years. These strategies are developed with the goal of providing efficient soil stabilization with minimal negative effects on the environment and consumption of resources. One promising approach studied by researchers is to use waste materials for soil stabilization. Many types of waste, such as industrial, agricultural, mineral, domestic, and natural fibers, have shown potential for modifying the engineering properties of soft soils. Unfortunately, much of this waste is currently mishandled, leading to environmental and health problems. However, if these wastes were to be reused for soil stabilization, it would help to minimize the usage of traditional stabilizers such as lime or cement, thereby reducing the costs of civil engineering projects. Additionally, using waste materials for soil stabilization can help to mitigate environmental pollution caused by their improper disposal. For example, Changizi and Haddad [79] reported that the addition of recycled polyester fiber produced from polyethylene (PET) bottles improved the mechanical properties of soils when stabilized with nano-SiO_2. Industrial solid wastes such as fly ash has shown promise as effective stabilizing materials for pavement subgrades, with notable benefits including the reduction of clay soil swelling potential, enhancement of shear strength in fine-grained soils, and settlement reduction in foundation fills [80].

While some waste materials, such as fly ash, have been used in some nations, their widespread implementation into the field is still in its infancy at best. Several factors, including the absence of clearly documented guidelines by governing bodies on their usage, the lack of established standards or optimum quantities for effective soil stabilization, and the inadequate data published by independent researchers or organizations regarding the use of waste materials for soil stabilization, have contributed to their limited use [81]. To fully exploit the potential of sustainable ground improvement technologies and meet the challenges of soft soil management, more study and collaboration among scholars, practitioners and governing bodies is required.

2) DEVELOPMENT OF INNOVATIVE FOUNDATION SYSTEM

Despite their widespread use throughout the years, traditional foundation methods like shallow and deep foundations may not always be suitable for soft soil conditions. New foundation systems that can meet the challenges of various soil conditions, building loads, and site limits have been explored and implemented due to the demand for more effective and cost-efficient solutions. The creation of novel foundation systems is a potentially fruitful avenue for advancement in the field of soft soil management, as these systems have the potential to serve as a viable alternative to more conventional approaches. These innovative systems are adaptable to various soil types and site specifications, lowering construction time and expenses.

Low and medium-rise buildings on thick, soft, compressible subsoil can benefit from the floating piled raft foundation method. This system is cost-effective compared to conventional piled foundation. The settlement reducing piles, which are designed to minimize settlement, are attached to a strip-raft foundation. Differential settlement can lead to cracks in walls and partitions and stress on structural members, both of which can be mitigated with the help of these settlement-reducing piles. Before implementing the concept of settlement-reducing piles, it is essential to ensure that the foundation raft provides sufficient bearing capacity [82]. Local stresses at concentrated load points and overall stresses for the entire residential block must be taken into account during a detailed analysis of the foundation system in order to identify the stresses acting on the structural member. Successful application of the floating piled raft foundations has been reported for a residential and commercial development at Bukit Tinggi, Klang [82].

When dealing with soft soils, screw piles are another novel option for foundation system. In recent years, screw piles' utilization as a deep foundation choice for a wide range of weights has skyrocketed. These loads range from small applications such as residential housing, solar farms, utilities, retrofit projects, to larger applications like commercial structures, power transmission lines, oil facilities, and industrial projects [83]. In deep foundations, screw piles (also known as screw anchors or helical piles) are used to resist tensile, compressive and lateral loads. These piles feature a central shaft of lower diameter with one or more circular helix plates affixed to it [84]. Screw piles are distinct from other types of piles due to their use of high-strength steel, fixed helices and a pointed toe for improved ground installation [85]. Furthermore, screw piles vary in shaft and helix diameters, helix spacings and embedment depths to meet the requirements of a wide range of applications.

It is essential to weigh the benefits and drawbacks of screw piles in relation to more conventional piling methods before deciding whether or not to use them. There are many benefits to using screw piles, including their low cost, ease of installation, ability to work on slopes, high tensile and acceptable compressive capacities, low noise and vibration during installation, and quick installation after which loading can begin [86], [87], [88], [89], [90]. Multiple studies have consistently demonstrated the superior effectiveness of screw piles in soft clay, providing strong evidence and endorsing their utilization as an innovative piling system. This is particularly evident in high clay depths where screw piles outperform other pile types due to the challenges associated with drilling [91].

Within this context, the use of advanced AI methodologies has shown significant promise, particularly in enhancing the design and implementation of foundation systems in cohesive soils. These machine learning and soft computing techniques have been extended to various foundation design applications, including estimating the settlement of pile groups [92], assessing the seismic bearing capacity of strip footings on slopes [93], designing energy piles based on CPT data [94], [95], and evaluating the reliability of shallow foundations on clayey soil based on settlement criteria [96].

For example, Kumar and Samui [95] designed energy piles based on Cone Penetration Test (CPT) data from the Perniö test site in Finland. Various soft computing algorithms including Random Forest (RF), Support Vector Machine (SVM), Gradient Boosting Machine (GBM), and Extreme Gradient Boosting (XGB) are employed for predicting the group capacity of energy piles. Among the evaluated models, the GBM model demonstrated the lowest system error and the best performance. The comparative analysis of models in these studies has demonstrated that the proposed models are effective and offering superior performance in prediction capabilities for each specific application. Across all applications, it is important to recognize the factors that affect performance and to consider the limitations of each study, despite the superior performance of the models.

In conclusion, the investigation of novel foundation systems has emerged as a promising opportunity to address the challenges posed by soft soil conditions in construction. Floating piled raft foundations and screw piles are two methods that stand out among the others due to their demonstrated efficacy. However, the selection of the appropriate foundation system should be based on careful consideration of criteria such as soil properties, building loads, site conditions, construction constraints, cost-effectiveness, and environmental impact. By evaluating these criteria, engineers and designers can make informed decisions to ensure the selection of a foundation system that optimally meets the specific requirements of soft soil conditions, leading to enhanced stability and performance of structures.

3) DEVELOPMENT OF NOVEL SENSING TECHNOLOGIES FOR MONITOR THE BEHAVIOUR OF SOFT SOILS

Soft soil conditions necessitate careful subsurface study for optimal foundation construction and ground improvement. Understanding the soil qualities, assessing bearing capacity, and determining settlement potential are all important tasks for engineers to complete to guarantee the safety, stability, and long-term performance of structures. Advancements in sensing technologies have opened up new avenues for monitoring the behaviour of soft soil.

Soil spectroscopy in the VNIR-SWIR region (400–2500 nm) has been evaluated as a possible alternative method for soil parameter monitoring to address the need for continuous information about soil's condition, while reducing the cost of soil analysis [97], [98], [99]. The nondestructive nature of this technique enables simultaneous and repeatable measurements to be made, giving it a significant advantage over conventional laboratory measurements [100]. Another potential application in this field is Proximal Soil Sensing (PSS), which involves the use of field-based sensors positioned in close proximity to the ground, generally within a maximum distance of two meters [101]. PSS allows rapid and inexpensive collection of precise, quantitative data at fine (spatial and temporal) resolutions, which can be used in more meaningful analyses to better understand soils and the spatiotemporal variability of their properties. Various soil properties, including soil water content, clay mineralogy and soil strength, can be measured using different proximal soil sensors, such as active γ-ray attenuation for soil water content, portable XRD and XRF instruments for clay mineralogy and mechanical sensors for soil strength assessment.

In short, the advancements in sensing technologies hold great potential for monitoring the behaviour of soft soil. Two promising approaches, soil spectroscopy in the VNIR-SWIR region and Proximal Soil Sensing (PSS), have been explored in this context. To further advance the practical implementation of these sensing technologies, future research should prioritize the investigation of underlying mechanisms that enable accurate prediction of soil properties.

B. CHALLENGES

As mentioned in the research frontier identification in Section III, one of the most recent research focuses in this field is the issue of soil failure. Soft soil is typically characterized as having low shear strength, high compressibility, and low permeability. This soil type presents significant challenges in construction and requires special attention to avoid engineering problems such as bearing capacity failure, excessive settlement and slope instability. These challenges can occur during or after the construction phase due to the strength and compressibility characteristics of the soft soil. This section will further explore these challenges in detail.

1) BEARING CAPACITY

Bearing capacity, or the ability of soil to sustain a structure without excessive settlement or shear failure, is an important factor in the construction of embankments and foundations. When the shear stress exerted on a structure is greater than the shear strength of the soil, bearing capacity failure can occur. Terzaghi, Vesic, Meyerhof, and Hansen are only a few of the experts who have discovered new ways to evaluate soil bearing capacity.

The factors that affect soil's carrying capacity have been the subject of a lot of research. Soil bearing capacity is determined by a number of factors, including cohesion, soil unit weight, foundation width and depth, and the angle of internal friction, as noted by Dixit and Patil [102]. According to their research, deeper foundations have a greater ultimate bearing capability of soil, and this is mostly owing to the increased surcharge weight. The relationship between water table depth and soil carrying capacity was also studied by Tahmid et al. [103], who discovered that when the water table depth increased, the soil bearing capacity also increased.

Stone columns, deep mixing method, geocell reinforcement, and chemical stabilization are just some of the ground improvement approaches that have been investigated by scientists to increase the bearing capacity of soft soil [42], [104], [105], [106]. The selection of soil improvement methods depends on several factors such as soil characteristics, load requirements, project duration, cost, environmental impact, site access and logistics. The effectiveness of the chosen soil enhancement approach can be maximized by taking into account the aforementioned factors.

2) SETTLEMENT

As previously stated, soft soils display a variety of characteristics, including low strength, high water content, high compressibility and poor permeability. These characteristics make soft soils susceptible to substantial settlement under long-term loading. In infrastructure projects, the magnitude of settlement plays a crucial role in determining the serviceability of structures and construction equipment. Engineers typically conduct settlement analysis, which entails evaluating both the total and differential settlements of a soil mass under external loads, to evaluate settlement. Total settlement is the overall vertical movement of a foundation or soil surface due to applied loads or other external factors, whereas differential settlement is the variation in settlement between different points on the foundation. Total settlement can be further divided into three components: immediate settlement, consolidation settlement and secondary compression settlement. Immediate settlement occurs instantly upon load application with little drainage taking place in soils with low permeability. It is also known as undrained or elastic settlement. When pore pressure is gradually dissipated due to external loads, a process called consolidation settlement takes place. This process results in water being expelled from the loaded soil mass, leading to volume changes and shear deformations. Secondary compression settlement, also known as drained creep, takes place after complete dissipation of excess pore water pressures at practically constant effective stresses. This type of settlement is the same as compaction and occurs due to the rearrangement of particles.

Differential settlement is described by settlement across a horizontal distance and may be characterized by distortion, as stated by LaGatta et al. [107]. The Leaning Tower of Pisa is a famous example of differential settlement, with the south side sinking 2.8 meters and the north side sinking 0.8 meters over the course of 800 years. This has resulted in a total differential settlement of 2 m and a tilt of 5°, 11', and 20' [108]. The tower leaning was due primarily to inadequate construction foundation and unfavorable soil conditions. Several significant stabilization efforts involved soil extraction, anchoring the tower with weights and cables, and installing drainage systems.

In geotechnical engineering, Terzaghi's 1-D classical method is a foundational approach for estimating total settlement and settlement rate. Primary consolidation of a fully saturated soil occurs due to excess pore water pressure dissipation from the soil as a result of the gradual transition of applied load from water to the soil particles, as described by Terzaghi's one-dimensional consolidation theory [109], [110], [111]. Terzaghi assumed a linear stress-strain relationship of the soil to simplify its practical implementation [112]. Terzaghi's consolidation theory is often criticized for its assumptions about constant compressibility and permeability coefficients and its failure to account for the impact of large deformations and secondary consolidation.

The ability of numerical approaches to account for heterogeneous anisotropic elastic materials and complex nonlinear stress-strain behaviours has led to their increased use in the prediction of settlements in recent years. Engineers tend to have confidence in the findings of finite elements due to their strength and flexibility, but they may overlook the inherent idealization and assumptions within these models. The accuracy of settlement predictions largely depends on the quality of data inputs, thus evaluating and controlling experimental constraints is crucial for high quality data to be used in numerical analysis. The development of settlement prediction methods has undergone a revolution, transitioning from the classic 1D to numerical methods. With advanced parameters and testing ground, numerical methods are capable of solving a wide range of complex issues, and the sophistication of computing technology has contributed to their popularity and further development.

3) SLOPE STABILITY

The management of slope stability in soft soil environments presents significant challenges in geotechnical engineering. Soft soils exhibit unique complexities that demand careful attention and specialized techniques to ensure slope stability. In a study conducted by Yalcin [113] in Kanlica Village, Turkey, the effect of clay on landslides was investigated. The findings revealed that clays containing illite and montmorillonite minerals are more prone to landslides compared to clays with kaolinite and chlorite minerals, primarily due to their lower shear strengths and higher swelling potentials. These observations align with a previous study conducted by Underwood [114]. The consequences of slope failure can be severe, resulting in the loss of life and extensive damage to property and infrastructure, as demonstrated by Gjerdrum quick clay landslide in Norway in 2020. Therefore, it is crucial to effectively address these challenges to ensure the stability and safety of constructed embankments and slopes in soft soil environments.

Current research on slope failure in soft soils primarily focuses on analyzing historical cases and academic studies. For example, Hussein and Mustapha [115] identified the causes of a collapse in Malaysia where a 25m high fill slope failed due to inadequate compaction during construction, the presence of a thin layer of soft clay, an increase in groundwater level, and heavy rainfall. The presence of the soft layer could have caused settlement and instability to occur. Another study by Rahardjo [116] discussed various case histories of embankment failures on soft soils. The findings revealed that embankment failures on soft soils in Indonesia are often attributed to bearing capacity failures of the foundation soils and the increase in excess pore water during loading. Additionally, a lack of awareness among contractors about these phenomena and the significant difference in stiffness between embankment and foundation soils also contribute to these failures. The study also emphasized that soil softening is a major factor in slope failures. Even though expansive soils are well compacted, they are prone to water absorption, resulting in a significant decrease in strength. For instance, a study conducted by Rahardjo and Meilani [117] in Padalarang demonstrated that saturation has a highly significant effect on reducing soil shear strength. Slope stability problems can also arise when dispersive soils, such as silts, are used in embankments due to limited budget and local availability. This was observed in the case of the Samboja Dam in East Kalimantan, which experienced multiple failures during construction. The stability of the dam was endangered by erosion caused by soil dispersion in the upstream area.

The use of limit equilibrium (LE) methods is prevalent in both the slope stability analysis and engineered slopes design. LE methods are simple and flexible, assuming that the potential failure surface of a slope is known in advance and that the slope can be divided into finite vertical slices. The stability of each slice is analyzed based on the principles of force and/or moment equilibrium. Several LE methods have been developed over the past century to assess slope stability by considering different equations of equilibrium and assumptions made for inter-slice forces, as described by Bishop, Morgenstern and Price, Spencer and Duncan [118], [119], [120], [121].

In the past several decades, numerical methods have been extensively used in slope stability analysis because they can provide a more accurate and detailed analysis of complex geometries and material behaviour. Unlike limit equilibrium methods, which assume that failure occurs along a predetermined failure surface, numerical methods allow for a more realistic representation of the stability and behaviour of the slope, including factors such as stress and deformation patterns, failure mechanisms, and potential failure modes. Additionally, numerical methods can also be used to evaluate the effects of various slope design and remediation strategies, allowing engineers to optimize their designs and reduce potential risks.

The factor of safety (FOS) serves as a key indicator for assessing slope stability. It is commonly defined as the ratio of the resisting shear force to the driving shear force along a failure surface [122]. A slope stability analysis typically considers soil mechanical properties, slope geometry and groundwater conditions to determine the factor of safety [123]. For example, Rahardjo et al. [124] analyzed the stability of residual soil slope under rainfall infiltration considering different groundwater levels, rainfall intensities and soil properties. The findings demonstrated that a shallower groundwater table position relative to the ground surface resulted in a lower initial FOS. Moreover, higher rainfall intensities caused a more rapid decrease in the FOS. Additionally, the FOS decreased at a faster rate for soils with coarser particles and higher permeability under rainfall infiltration with varying intensities. In another study, Shiferaw [125] investigated the influence of slope height and angle on the FOS and shape of slope failure based on strength reduction analysis. The study found that the dominant failure mode for clayey soils was toe slide. It was also found that the FOS increased nearly linearly as the slope angle decreased, while decreased slope height leads to different rates of increase in the FOS. The observations are consistent with Tan [126], who suggested that the reduction of slope angle or construction of counterweight berms enhanced the stability of the embankment by increasing the length of potential failure surfaces in the soft soils.

Although the presence of water and rainfall are commonly recognized as primary factors that contribute to slope failure, it’s worth noting that slope failure is a complex phenomenon that can be caused by a combination of factors, and the relative contribution of each factor can vary depending on the specific situation. Therefore, it’s crucial to conduct a thorough analysis that takes into account various factors such as soil properties, slope geometry, groundwater conditions and other external forces such as earthquakes, heavy rainfall or anthropogenic to determine the root causes of slope failure.

V. CONCLUSION

This paper presents a novel approach of conducting a comprehensive bibliometric review on soft soil management literature based on 2,260 journal articles and proceeding papers from 2013 to 2023 from the WOS core collection. The identified articles were processed by the CiteSpace Visualization software, which enabled the creation of knowledge maps to investigate the research development and trends in the field. Analyses of country distribution, authorship and co-cited authors, cited journals, reference co-citations and identification of research hotspots and frontiers were conducted. The study reveal significant findings on prominent and influential contributors (country, authorship, cited journals), dominant research themes, research hotspots and frontiers with evolutionary trends, opportunities, and key challenges in the field.

The quantitative analyses reveal a discernible upward trend in the number of publications, indicating a growing interest in soft soil management and an intensified research emphasis. Notably, China has the maximum number of publications in soft soil management research, making it a prominent contributor. Author and cited author analysis show that Horpibulsuk, Suksun is the most productive author and Han J is the most influential author with both high citation count and centrality in the co-citation network. Through cross analysis, some authors like Indraratna and Horpibulsuk demonstrate both high productivity and influence, while others show a gap between publication volume and impact. Furthermore, reference co-citation clustering analysis reveals two dominant research themes in soft soil management: ground improvement methods (particularly geosynthetic-reinforced embankments and stone columns) and sustainable practices (reuse of waste materials). The analysis also highlights the importance of analytical solutions for theoretical modeling and case studies for practical applications.

In addition, a cluster analysis was performed on the keyword knowledge map, which resulted in the classification of keywords into six distinct clusters: unconfined compressive strength, bearing capacity, soil-structure interaction, vacuum preloading, permanent deformation, and soft soils. Among the emerging research topics, failure has been identified as the fastest growing areas of research starting from 2021. Recent research has placed a greater emphasis on shear strength, mechanical properties, and failure mechanisms, as opposed to the initial emphasis on investigating innovative and sustainable techniques. There is continued prevalence in recent soft soil literature on some ground improvement methods, particularly in the applications of vertical drains, deep mixing columns, chemical stabilization, and sustainable approaches. In terms of research methods, there has been a transition from centrifuge modeling to simulation utilizing constitutive modeling, as well as an increase in the use of analytical solutions in contemporary studies.

In addition to the difficulties inherent in soft soil management, there are significant opportunities for advancement. These opportunities include the development of sustainable ground improvement techniques, such as the use of waste materials for soil stabilization, the implementation of innovative foundation systems, such as the floating piled raft and screw piles, and the use of novel sensing technologies, such as soil spectroscopy and proximal soil sensing, to effectively monitor the behaviour of soft soils. However, it is also essential to address the main challenges of bearing capacity, settlement, and slope stability in order to successfully manage soft soils and prevent engineering issues. These findings provide researchers and practitioners with a clearer understanding of the evolution of soft soil management research.

It is essential to underscore the limitations of this study and the open questions that must be addressed in future research. As stated in Section II-A, the analysis was conducted solely with WoS-indexed publications, which may have resulted in incompletion as some significant publications on soft soil management may not have been included in the WoS database. It is important to note, however, that the WoS database adheres to the highest quality standards. In a broader sense, investigating the remaining issues could add to the existing body of knowledge. While this study was predominantly concerned with mapping knowledge pertaining to ground improvement methods in soft soil management, there is a need for further investigation into the broader implications of these keywords. This includes expanding the scope to include different performance models, samples, annual observations, and methods. In addition, it is necessary to investigate other facets of soft soil management, such as geotechnical characterization of soft soils, foundation design and construction techniques, and slope stability analysis. Researchers can identify factors that contribute to indirect links or attributes that enhance the overall performance of soft soil management by conducting exhaustive studies in these areas.

REFERENCES

[1] Y. Zhuang and K. Wang, "Numerical simulation of high-speed railway foundation improved by PVD-DCM method and compared with field measurements," *Eur. J. Environ. Civil Eng.*, vol. 21, no. 11, pp. 1363–1383, Nov. 2017, doi: 10.1080/19648189.2016.1170728.

[2] A. Arulrajah, M. Yaghoubi, M. M. Disfani, S. Horpibulsuk, M. W. Bo, and M. Leong, "Evaluation of fly ash- and slag-based geopolymers for the improvement of a soft marine clay by deep soil mixing," *Soils Found.*, vol. 58, no. 6, pp. 1358–1370, Dec. 2018, doi: 10.1016/j.sandf.2018.07.005.

[3] M. Khanmohammadi and K. Fakharian, "Evaluation of performance of piled-raft foundations on soft clay: A case study," *Geomech. Eng.*, vol. 14, no. 1, pp. 43–50, Jan. 2018, doi: 10.12989/gae.2018.14.1.043.

[4] X. Wang, Y. Cui, S. Zhang, W. Yu, and F. Wang, "Research on construction technology of bulk material and concrete upper-lower integrated composite pile for thick overburden and deep-buried soft soil based on experimental analysis," in *Proc. Int. Conf. Smart Grid Electr. Autom. (ICSGEA)*, Aug. 2016, pp. 222–225, doi: 10.1109/ICSGEA.2016.34.

[5] G. J. Cai, S. Y. Liu, L. Y. Tong, and G. Y. Du, "Field evaluation of undrained shear strength from piezocone penetration tests in soft marine clay," *Mar. Georesources Geotechnol.*, vol. 28, no. 2, pp. 143–153, May 2010, doi: 10.1080/10641191003780906.

[6] A. Arulrajah, M. W. Bo, M. Leong, and M. M. Disfani, "Piezometer measurements of prefabricated vertical drain improvement of soft soils under land reclamation fill," *Eng. Geol.*, vol. 162, pp. 33–42, Jul. 2013, doi: 10.1016/j.enggeo.2013.05.005.

[7] Z.-Y. Yin, C. S. Chang, M. Karstunen, and P.-Y. Hicher, "An anisotropic elastic–viscoplastic model for soft clays," *Int. J. Solids Struct.*, vol. 47, no. 5, pp. 665–677, Mar. 2010, doi: 10.1016/j.ijsolstr.2009.11.004.

[8] B. T. Pham, L. H. Son, T.-A. Hoang, D.-M. Nguyen, and D. T. Bui, "Prediction of shear strength of soft soil using machine learning methods," *Catena*, vol. 166, pp. 181–191, Jul. 2018, doi: 10.1016/j.catena.2018.04.004.

[9] A. S. Hokmabadi, B. Fatahi, and B. Samali, "Physical modeling of seismic soil-pile-structure interaction for buildings on soft soils," *Int. J. Geomechan.*, vol. 15, no. 2, 2014, doi: 10.1061/(ASCE)GM.1943-5622.0000396.

[10] Q. Van Nguyen, B. Fatahi, and A. S. Hokmabadi, "Influence of size and load-bearing mechanism of piles on seismic performance of buildings considering soil-pile-structure interaction," *Int. J. Geomechan.*, vol. 17, no. 7, 2017, doi: 10.1061/(ASCE)GM.1943-5622.000086.

[11] V. V. Nalimov and Z. M. Mulchenko, "Measurement of science. Study of the development of science as an information process," *Proc. Natl. Acad. Sci. USA*, vol. 405, no. 4, p. 210, 1971.

[12] K. Börner, C. Chen, and K. W. Boyack, "Visualizing knowledge domains," *Annu. Rev. Inf. Sci. Technol.*, vol. 37, no. 1, pp. 179–255, Jan. 2005, doi: 10.1002/aris.1440370106.

[13] J. Mingers and L. Leydesdorff, "A review of theory and practice in scientometrics," *Eur. J. Oper. Res.*, vol. 246, no. 1, pp. 1–19, Oct. 2015, doi: 10.1016/j.ejor.2015.04.002.

[14] G. Abramo and C. A. D'Angelo, "Evaluating research: From informed peer review to bibliometrics," *Scientometrics*, vol. 87, no. 3, pp. 499–514, Jun. 2011, doi: 10.1007/s11192-011-0352-7.

[15] A. van Raan, "Measuring science: Basic principles and application of advanced bibliometrics," in *Springer Handbook of Science and Technology Indicators*. Springer, 2019, pp. 237–280, doi: 10.1007/978-3-030-02511-3_10.

[16] X. Zhao, "A scientometric review of global BIM research: Analysis and visualization," *Autom. Construction*, vol. 80, pp. 37–47, Aug. 2017, doi: 10.1016/j.autcon.2017.04.002.

[17] Z. Liu, Y. Lu, and L. C. Peh, "A review and scientometric analysis of global building information modeling (BIM) research in the architecture, engineering and construction (AEC) industry," *Buildings*, vol. 9, no. 10, Oct. 2019, doi: 10.3390/buildings9100210.

[18] B. Zhong, H. Wu, H. Li, S. Sepasgozar, H. Luo, and L. He, "A scientometric analysis and critical review of construction related ontology research," *Autom. Construction*, vol. 101, pp. 17–31, May 2019, doi: 10.1016/j.autcon.2018.12.013.

[19] G. Wang, P. Wu, X. Wu, H. Zhang, Q. Guo, and Y. Cai, "Mapping global research on sustainability of megaproject management: A scientometric review," *J. Cleaner Prod.*, vol. 259, Jun. 2020, Art. no. 120831, doi: 10.1016/j.jclepro.2020.120831.

[20] L. Wang, X. Xue, Y. Zhang, and X. Luo, "Exploring the emerging evolution trends of urban resilience research by scientometric analysis," *Int. J. Environ. Res. Public Health*, vol. 15, no. 10, p. 2181, Oct. 2018, doi: 10.3390/ijerph15102181.

[21] S. Dash and A. S. Kalamdhad, "Science mapping approach to critical reviewing of published literature on water quality indexing," *Ecological Indicators*, vol. 128, Sep. 2021, Art. no. 107862, doi: 10.1016/j.ecolind.2021.107862.

[22] C. Boudry, C. Baudouin, and F. Mouriaux, "International publication trends in dry eye disease research: A bibliometric analysis," *Ocular Surf.*, vol. 16, no. 1, pp. 173–179, Jan. 2018, doi: 10.1016/j.jtos.2017.10.002.

[23] Y. Geng, W. Chen, Z. Liu, A. S. F. Chiu, W. Han, Z. Liu, S. Zhong, Y. Qian, W. You, and X. Cui, "A bibliometric review: Energy consumption and greenhouse gas emissions in the residential sector," *J. Cleaner Prod.*, vol. 159, pp. 301–316, Aug. 2017, doi: 10.1016/j.jclepro.2017.05.091.

[24] L. Bornmann, A. Tekles, H. H. Zhang, and F. Y. Ye, "Do we measure novelty when we analyze unusual combinations of cited references? A validation study of bibliometric novelty indicators based on F1000Prime data," *J. Informetrics*, vol. 13, no. 4, Nov. 2019, Art. no. 100979, doi: 10.1016/j.joi.2019.100979.

[25] H. Wang, W. Zhang, Y. Zhang, and J. Xu, "A bibliometric review on stability and reinforcement of special soil subgrade based on CiteSpace," (English Edition), *J. Traffic Transp. Eng.*, vol. 9, no. 2, pp. 223–243, Apr. 2022, doi: 10.1016/j.jtte.2021.07.005.

[26] J. Xiao, B. Wang, R. Wei, S. Wu, and H. Cai, "Study on the geometry and spatial distribution characteristics of physical and mechanical indexes of soft clay," *IOP Conf. Ser., Earth Environ. Sci.*, vol. 861, no. 4, Oct. 2021, Art. no. 042094, doi: 10.1088/1755-1315/861/4/042094.

[27] P. Du, X. Hou, and H. Xu, "Dynamic expansion of urban land in China's coastal zone since 2000," *Remote Sens.*, vol. 14, no. 4, p. 916, Feb. 2022, doi: 10.3390/rs14040916.

[28] *Code for Engineering Geological Exploration in Soft Soil Area*, document JGJ83-91, China Construction Ind. Press, Beijing, China, 1992.

[29] National Bureau of Statistics of China. (2021). *China's R&D Expenditure Reached 2.79 Trillion Yuan in 2021*. Accessed: Nov. 9, 2023. [Online]. Available: http://www.stats.gov.cn/english/PressRelease/202201/t20220127_1827065.html

[30] M. Zheng, H.-Z. Fu, and Y.-S. Ho, "Research trends and hotspots related to ammonia oxidation based on bibliometric analysis," *Environ. Sci. Pollut. Res.*, vol. 24, no. 25, pp. 20409–20421, Sep. 2017, doi: 10.1007/s11356-017-9711-0.

[31] M. A. M. Al-Bared and A. Marto, "A review on the geotechnical and engineering characteristics of marine clay and the modern methods of improvements," *Malaysian J. Fundam. Appl. Sci.*, vol. 13, no. 4, pp. 825–831, Dec. 2017.

[32] S. Topolinski, "Unconfined compressive strength properties of a cement-organic soil composite," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 471, Feb. 2019, Art. no. 042018, doi: 10.1088/1757-899X/471/4/042018.

[33] L. Barcelo, J. Kline, G. Walenta, and E. Gartner, "Cement and carbon emissions," *Mater. Struct.*, vol. 47, no. 6, pp. 1055–1065, Jun. 2014.

[34] S. J. Davis et al., "Net-zero emissions energy systems," *Science*, vol. 360, no. 6396, Jun. 2018, doi: 10.1126/science.aas9793.

[35] A. J. Puppala, L. R. Hoyos, and A. K. Potturi, "Resilient moduli response of moderately cement-treated reclaimed asphalt pavement aggregates," *J. Mater. Civil Eng.*, vol. 23, no. 7, pp. 990–998, Jul. 2011, doi: 10.1061/(asce)mt.1943-5533.0000268.

[36] T. Zhang, G. Cai, and S. Liu, "Reclaimed lignin-stabilized silty soil: Undrained shear strength, Atterberg limits, and microstructure characteristics," *J. Mater. Civil Eng.*, vol. 30, no. 11, Nov. 2018, doi: 10.1061/(ASCE)MT.1943-5533.0002492.

[37] N.-J. Jiang, Y.-J. Du, and K. Liu, "Durability of lightweight alkali-activated ground granulated blast furnace slag (GGBS) stabilized clayey soils subjected to sulfate attack," *Appl. Clay Sci.*, vol. 161, pp. 70–75, Sep. 2018, doi: 10.1016/j.clay.2018.04.014.

[38] G. Rajasekaran and S. N. Rao, "Sulphate attack in lime-treated marine clay," *Mar. Georesources Geotechnol.*, vol. 23, nos. 1–2, pp. 93–116, Jan. 2005, doi: 10.1080/10641190590944926.

[39] R. S. Rollings, J. P. Burkes, and M. P. Rollings, "Sulfate attack on cement-stabilized sand," *J. Geotechnical Geoenvironmental Eng.*, vol. 125, no. 5, pp. 364–372, May 1999, doi: 10.1061/(asce)1090-0241(1999)125:5(364).

[40] X. Zheng and J. Wu, "Early strength development of soft clay stabilized by one-part ground granulated blast furnace slag and fly ash-based geopolymer," *Frontiers Mater.*, vol. 8, Apr. 2021, doi: 10.3389/fmats.2021.616430.

[41] A. Madun, S. A. Meghzili, S. Tajudin, M. F. Yusof, M. H. Zainalabidin, A. A. Al-Gheethi, M. F. M. Dan, and M. A. M. Ismail, "Mathematical solution of the stone column effect on the load bearing capacity and settlement using numerical analysis," *J. Phys., Conf. Ser.*, vol. 995, Apr. 2018, Art. no. 012036, doi: 10.1088/1742-6596/995/1/012036.

[42] M. B. D. Elsawy, "Behaviour of soft ground improved by conventional and geogrid-encased stone columns, based on FEM study," *Geosynthetics Int.*, vol. 20, no. 4, pp. 276–285, Aug. 2013, doi: 10.1680/gein.13.00017.

[43] P. M. Yesane, Y. M. Ghugal, and R. L. Wankhade, "Study on soil-structure interaction: A review," *Int. J. Eng. Res.*, vol. 5, no. 3, pp. 737–741, 2016, doi: 10.17950/ijer/v5i3/047.

[44] R. Figini and R. Paolucci, "Integrated foundation–structure seismic assessment through non-linear dynamic analyses," *Earthq. Eng. Structural Dyn.*, vol. 46, no. 3, pp. 349–367, Mar. 2017, doi: 10.1002/eqe.2790.

[45] N. Sharma, K. Dasgupta, and A. Dey, "Natural period of reinforced concrete building frames on pile foundation considering seismic soil-structure interaction effects," *Structures*, vol. 27, pp. 1594–1612, Oct. 2020, doi: 10.1016/j.istruc.2020.07.010.

[46] S. Kwag, B. Ju, and W. Jung, "Beneficial and detrimental effects of soil-structure interaction on probabilistic seismic hazard and risk of nuclear power plant," *Adv. Civ. Eng.*, vol. 2018, pp. 1–18, Jul. 2018, doi: 10.1155/2018/2698319.

[47] B. Fatahi, H. R. Tabatabaiefar, and B. Samali, "Performance based assessment of dynamic soil-structure interaction effects on seismic response of building frames," in *Proc. GeoRisk*, 2011.

[48] S. Carbonari, F. Dezi, F. Gara, and G. Leoni, "Seismic response of reinforced concrete frames on monopile foundations," *Soil Dyn. Earthq. Eng.*, vol. 67, pp. 326–344, Dec. 2014, doi: 10.1016/j.soildyn.2014.10.012.

[49] J. Saowapakpiboon, D. T. Bergado, S. Youwai, J. C. Chai, P. Wanthong, and P. Voottipruex, "Measured and predicted performance of prefabricated vertical drains (PVDs) with and without vacuum preloading," *Geotextiles Geomembranes*, vol. 28, no. 1, pp. 1–11, Feb. 2010, doi: 10.1016/j.geotexmem.2009.08.002.

[50] B. Indraratna, C. Rujikiatkamjorn, J. Ameratunga, and P. Boyle, "Performance and prediction of vacuum combined surcharge consolidation at port of Brisbane," *J. Geotechnical Geoenvironmental Eng.*, vol. 137, no. 11, pp. 1009–1018, Nov. 2011, doi: 10.1061/(asce)gt.1943-5606.0000519.

[51] B. Indraratna, C. Rujikiatkamjorn, P. Baral, and J. Ameratunga, "Performance of marine clay stabilised with vacuum pressure: Based on Queensland experience," *J. Rock Mech. Geotechnical Eng.*, vol. 11, no. 3, pp. 598–611, Jun. 2019, doi: 10.1016/j.jrmge.2018.11.002.

[52] B. Indraratna, A. Attya, and C. Rujikiatkamjorn, "Experimental investigation on effectiveness of a vertical drain under cyclic loads," *J. Geotechnical Geoenvironmental Eng.*, vol. 135, no. 6, pp. 835–839, Jun. 2009, doi: 10.1061/(asce)gt.1943-5606.0000006.

[53] S. Akkar and A. Metin, "Assessment of improved nonlinear static procedures in FEMA-440," *J. Structural Eng.*, vol. 133, no. 9, pp. 1237–1246, Sep. 2007, doi: 10.1061/(asce)0733-9445(2007)133:9(1237).

[54] T. L. Gouw and A. Gunawan, "Vacuum preloading, an alternative soft ground improvement technique for a sustainable development," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 426, no. 1, 2020, doi: 10.1088/1755-1315/426/1/012003.

[55] S. Liu, F. Luo, and G. Zhang, "Centrifuge model tests on pile-reinforced slopes subjected to drawdown," *J. Rock Mech. Geotechnical Eng.*, vol. 12, no. 6, pp. 1290–1300, Dec. 2020, doi: 10.1016/j.jrmge.2020.02.006.

[56] A. R. Estabragh, M. Naseh, and A. A. Javadi, "Improvement of clay soil by electro-osmosis technique," *Appl. Clay Sci.*, vol. 95, pp. 32–36, Jun. 2014, doi: 10.1016/j.clay.2014.03.019.

[57] J. Chen, S.-L. Shen, Z.-Y. Yin, Y.-S. Xu, and S. Horpibulsuk, "Evaluation of effective depth of PVD improvement in soft clay deposit: A field case study," *Mar. Georesources Geotechnol.*, vol. 34, no. 5, pp. 420–430, Jul. 2016, doi: 10.1080/1064119x.2015.1016638.

[58] B. Indraratna, N. T. Ngo, C. Rujikiatkamjorn, and S. W. Sloan, "Coupled discrete element–finite difference method for analysing the load-deformation behaviour of a single stone column in soft soil," *Comput. Geotechnics*, vol. 63, pp. 267–278, Jan. 2015, doi: 10.1016/j.compgeo.2014.10.002.

[59] Z. Weidong, W. Wenshuang, Z. Yingying, and Z. Xiaoyue, "Numerical analysis on engineering characteristics of costal soft soil in the area of ancient seawall in Wenzhou based on soil test," in *Proc. 6th Int. Conf. Measuring Technol. Mechatronics Autom.*, Jan. 2014, pp. 435–438, doi: 10.1109/ICMTMA.2014.106.

[60] J. Khatti and K. S. Grover, "Prediction of compaction parameters for fine-grained soil: Critical comparison of the deep learning and standalone models," *J. Rock Mech. Geotechnical Eng.*, vol. 15, no. 11, pp. 3010–3038, Nov. 2023, doi: 10.1016/j.jrmge.2022.12.034.

[61] J. Khatti and K. S. Grover, "Assessment of fine-grained soil compaction parameters using advanced soft computing techniques," *Arabian J. Geosci.*, vol. 16, no. 3, p. 208, Mar. 2023, doi: 10.1007/s12517-023-11268-6.

[62] A. Bardhan, R. K. Singh, S. Ghani, G. Konstantakatos, and P. G. Asteris, "Modelling soil compaction parameters using an enhanced hybrid intelligence paradigm of ANFIS and improved grey wolf optimiser," *Mathematics*, vol. 11, no. 14, p. 3064, Jul. 2023, doi: 10.3390/math11143064.

[63] J. Khatti and K. S. Grover, "Prediction of UCS of fine-grained soil based on machine learning Part 2: Comparison between hybrid relevance vector machine and Gaussian process regression," *Multiscale Multidiscip. Model. Exp. Des.*, vol. 7, pp. 123–163, Jul. 2023, doi: 10.1007/s41939-023-00191-8.

[64] J. Khatti and K. S. Grover, "Prediction of UCS of fine-grained soil based on machine learning Part 1: Multivariable regression analysis, Gaussian process regression, and gene expression programming," *Multiscale Multidisciplinary Model., Exp. Design*, vol. 6, no. 2, pp. 199–222, Jun. 2023, doi: 10.1007/s41939-022-00137-6.

[65] A. Rabbani, P. Samui, and S. Kumari, "Implementing ensemble learning models for the prediction of shear strength of soil," *Asian J. Civil Eng.*, vol. 24, no. 7, pp. 2103–2119, Nov. 2023, doi: 10.1007/s42107-023-00629-x.

[66] T. T. Länsivaara, M. S. Farhadi, and P. Samui, "Performance of traditional and machine learning-based transformation models for undrained shear strength," *Arabian J. Geosci.*, vol. 16, no. 3, p. 183, Mar. 2023, doi: 10.1007/s12517-022-11173-4.

[67] A. Rabbani, P. Samui, and S. Kumari, "Optimized ANN-based approach for estimation of shear strength of soil," *Asian J. Civil Eng.*, vol. 24, no. 8, pp. 3627–3640, Dec. 2023, doi: 10.1007/s42107-023-00739-6.

[68] J. Khatti and K. S. Grover, "Prediction of suitable percentage of waste materials for improving geotechnical properties of black cotton soil using AI approaches," in *Soil Behavior and Characterization of Geomaterials*, 2023, pp. 43–57, doi: 10.1007/978-981-19-6513-5_4.

[69] S. Jahandari, M. Saberian, F. Zivari, J. Li, M. Ghasemi, and R. Vali, "Experimental study of the effects of curing time on geotechnical properties of stabilized clay with lime and geogrid," *Int. J. Geotechnical Eng.*, vol. 13, no. 2, pp. 172–183, Mar. 2019, doi: 10.1080/19386362.2017.1329259.

[70] G. Ye, Y. Cai, and Z. Zhang, "Numerical study on load transfer effect of stiffened deep mixed column-supported embankment over soft soil," *KSCE J. Civil Eng.*, vol. 21, no. 3, pp. 703–714, Mar. 2017, doi: 10.1007/s12205-016-0637-8.

[71] N. R. Alkhorshid, G. L. S. Araujo, E. M. Palmeira, and J. G. Zornberg, "Large-scale load capacity tests on a geosynthetic encased column," *Geotextiles Geomembranes*, vol. 47, no. 5, pp. 632–641, Oct. 2019, doi: 10.1016/j.geotexmem.2019.103458.

[72] B. T. Pham, M. D. Nguyen, K.-T.-T. Bui, I. Prakash, K. Chapi, and D. T. Bui, "A novel artificial intelligence approach based on multilayer perceptron neural network and biogeography-based optimization for predicting coefficient of consolidation of soil," *Catena*, vol. 173, pp. 302–311, Feb. 2019, doi: 10.1016/j.catena.2018.10.004.

[73] F. Kassou, J. B. Bouziyane, A. Ghafiri, and A. Sabihi, "Slope stability of embankments on soft soil improved with vertical drains," *Civil Eng. J.*, vol. 6, no. 1, pp. 164–173, Jan. 2020, doi: 10.28991/cej-2020-03091461.

[74] P. Jamsawang, P. Voottipruex, P. Jongpradist, and S. Likitlersuang, "Field and three-dimensional finite element investigations of the failure cause and rehabilitation of a composite soil-cement retaining wall," *Eng. Failure Anal.*, vol. 127, Sep. 2021, Art. no. 105532, doi: 10.1016/j.engfailanal.2021.105532.

[75] X. Li, Z. Dong, W. Chen, J. Wang, Z. Liu, and X. Li, "Back analysis of a collapsed highway embankment—A numerical study on the rigid reinforcement and time-dependent grouting," *Eng. Failure Anal.*, vol. 131, Jan. 2022, Art. no. 105863, doi: 10.1016/j.engfailanal.2021.105863.

[76] Y. Min, J. Wu, B. Li, and J. Zhang, "Effects of fly ash content on the strength development of soft clay stabilized by one-part geopolymer under curing stress," *J. Mater. Civil Eng.*, vol. 33, no. 10, Oct. 2021, doi: 10.1061/(ASCE)MT.1943-5533.0003887.

[77] Y. C. Tan. (2016). *Design and Construction of Road Embankment on Soft Ground.* [Online]. Available: https://www.gnpgroup.com.my

[78] M. M. M. Idrus, J. S. M. Singh, A. L. A. Musbah, and D. C. Wijeyesekera, "Investigation of stabilised batu pahat soft soil pertaining on its CBR and permeability properties for road construction," *IOP Conf. Ser., Mater. Sci. Eng.*, vol. 136, Jul. 2016, Art. no. 012026, doi: 10.1088/1757-899x/136/1/012026.

[79] F. Changizi and A. Haddad, "Strength properties of soft clay treated with mixture of nano-SiO_2 and recycled polyester fiber," *J. Rock Mech. Geotechnical Eng.*, vol. 7, no. 4, pp. 367–378, Aug. 2015, doi: 10.1016/j.jrmge.2015.03.013.

[80] *Standard Practice for Design of Stabilization of Soil and Soil-Like Materials With Self-Cementing Fly Ash*, ASTM Standard D7762-18, ASTM Int., West Conshohocken, PA, USA, 2018.

[81] J. B. Niyomukiza, S. P. R. Wardani, and B. H. Setiadji, "Recent advances in the stabilization of expansive soils using waste materials: A review," *IOP Conf. Ser., Earth Environ. Sci.*, vol. 623, Jan. 2021, Art. no. 012099, doi: 10.1088/1755-1315/623/1/012099.

[82] Y. C. Tan, C. M. Chow, and S. S. Gue, "A design approach for piled raft with short friction piles for low rise buildings on very soft clay," *Geotech. Eng.*, vol. 36, no. 1, pp. 84–90, 2005. [Online]. Available: https://www.gueandpartners.com.my

[83] H. Likhitha, H. N. Raghavendra, K. P. Rakesh, and U. P. Shrihari, "The compression bearing capacity of helical piles in black cotton soil," *Int. J. Innov. Res. Sci. Eng. Technol.*, vol. 6, no. 7, pp. 14959–14964, 2017, doi: 10.15680/IJIRSET.2017.0607030.

[84] H. O. Abbase, "Pullout capacity of screw piles in sandy soil numerical and experimental studies on deep foundations view project improving difficult soils for foundation purposes view project pullout capacity of screw piles in sandy soil," *J. Geotech. Eng.*, vol. 4, no. 1, pp. 8–12, 2017.

[85] *Design of Screw Piles: Assessment of Pile Design Methodology*, Arup Geotechnics, London, U.K., 2005.

[86] B. Livneh and M. H. El Naggar, "Axial testing and numerical modeling of square shaft helical piles under compressive and tensile loading," *Can. Geotechnical J.*, vol. 45, no. 8, pp. 1142–1155, Aug. 2008, doi: 10.1139/t08-044.

[87] M. Sakr, "Performance of helical piles in oil sand," *Can. Geotechnical J.*, vol. 46, no. 9, pp. 1046–1061, Sep. 2009, doi: 10.1139/t09-044.

[88] M. Sakr, "Installation and performance characteristics of high capacity helical piles in cohesionless soils," *DFI J., J. Deep Found. Inst.*, vol. 5, no. 1, pp. 39–57, Jun. 2011.

[89] R. Schmidt and M. Nasr, "Screw piles: Uses and considerations," *Struct. Mag.*, pp. 29–31, Jan. 2004.

[90] D. J. Y. Zhang, R. Chalaturnyk, P. K. Robertson, D. C. Sego, and G. Cyre, "Screw anchor test program (Part I & II): Instrumentation, site characterisation and installation," in *Proc. 51st Can. Geotechnical Conf.*, Edmonton, AB, Canada, 1998.

[91] T. A. Chapel, *Field Investigation of Helical and Concrete Piers in Expansive Soil*. Fort Collins, CO, USA: Colorado State Univ., 1998.

[92] J. Khatti, H. Samadi, and K. S. Grover, "Estimation of settlement of pile group in clay using soft computing techniques," *Geotechnical Geological Eng.*, vol. 42, no. 3, pp. 1729–1760, Sep. 2023, doi: 10.1007/s10706-023-02643-x.

[93] D. R. Kumar, P. Samui, W. Wipulanusat, S. Keawsawasvong, K. Sangjinda, and W. Jitchaijaroen, "Soft-computing techniques for predicting seismic bearing capacity of strip footings in slopes," *Buildings*, vol. 13, no. 6, p. 1371, May 2023, doi: 10.3390/buildings13061371.

[94] P. Kumar and P. Samui, "Reliability-based load and resistance factor design of an energy pile with CPT data using machine learning techniques," *Arabian J. Sci. Eng.*, vol. 49, no. 4, pp. 4831–4860, Sep. 2023, doi: 10.1007/s13369-023-08253-2.

[95] P. Kumar and P. Samui, "Design of an energy pile based on CPT data using soft computing techniques," *Infrastructures*, vol. 7, no. 12, p. 169, Dec. 2022, doi: 10.3390/infrastructures7120169.

[96] R. Ray, P. Samui, and L. B. Roy, "Reliability analysis of a shallow foundation on clayey soil based on settlement criteria," *J. Current Sci. Technol.*, vol. 13, no. 1, pp. 91–106, 2023, doi: 10.14456/jcst.2023.9.

[97] D. J. Brown, K. D. Shepherd, M. G. Walsh, M. Dewayne Mays, and T. G. Reinsch, "Global soil characterization with VNIR diffuse reflectance spectroscopy," *Geoderma*, vol. 132, nos. 3–4, pp. 273–290, Jun. 2006, doi: 10.1016/j.geoderma.2005.04.025.

[98] M. Nocita et al., "Soil spectroscopy: An alternative to wet chemistry for soil monitoring," in *Advances in Agronomy*, vol. 132. Amsterdam, The Netherlands: Elsevier, 2015, pp. 139–159, doi: 10.1016/bs.agron.2015.02.002.

[99] J. M. Soriano-Disla, L. J. Janik, R. A. Viscarra Rossel, L. M. Macdonald, and M. J. McLaughlin, "The performance of visible, near-, and mid-infrared reflectance spectroscopy for prediction of soil physical, chemical, and biological properties," *Appl. Spectrosc. Rev.*, vol. 49, no. 2, pp. 139–186, Feb. 2014, doi: 10.1080/05704928.2013.811081.

[100] C. Pasquini, "Near infrared spectroscopy: A mature analytical technique with new perspectives—A review," *Analytica Chim. Acta*, vol. 1026, pp. 8–36, Oct. 2018, doi: 10.1016/j.aca.2018.04.004.

[101] R. A. V. Rossel, V. I. Adamchuk, K. A. Sudduth, N. J. McKenzie, and C. Lobsey, "Proximal soil sensing: An effective approach for soil measurements in space and time," in *Advances in Agronomy*. Amsterdam, The Netherlands: Elsevier, 2011, pp. 243–291, doi: 10.1016/B978-0-12-386473-4.00005-1.

[102] M. Dixit and K. A. Patil, "Study of effect of different parameters on bearing capacity of soil," in *Proc. Indian Geotechnical Conf.*, 2010. [Online]. Available: https://www.researchgate.net/publication/268353924

[103] A. Tahmid, S. Junaed, and A. S. M. F. Hossain, "Variation in bearing capacity of soil due to changes in water table depth in Dhaka, Bangladesh," *Malaysian J. Civ. Eng.*, vol. 33, no. 2, Jul. 2021, doi: 10.11113/mjce.v33.16552.

[104] M. A. Ozdemir, "Improvement in bearing capacity of a soft soil by addition of fly ash," *Proc. Eng.*, vol. 143, pp. 498–505, Jan. 2016, doi: 10.1016/j.proeng.2016.06.063.

[105] A. S. A. Rashid, J. A. Black, H. Mohamad, and N. M. Noor, "Behavior of weak soils reinforced with end-bearing soil-cement columns formed by the deep mixing method," *Mar. Georesources Geotechnol.*, vol. 33, no. 6, pp. 473–486, Nov. 2015, doi: 10.1080/1064119x.2014.954174.

[106] L. Zhang, M. Zhao, C. Shi, and H. Zhao, "Bearing capacity of geocell reinforcement in embankment engineering," *Geotextiles Geomembranes*, vol. 28, no. 5, pp. 475–482, Oct. 2010, doi: 10.1016/j.geotexmem.2009.12.011.

[107] M. D. LaGatta, B. T. Boardman, B. H. Cooley, and D. E. Daniel, "Geosynthetic clay liners subjected to differential settlement," *J. Geotechnical Geoenvironmental Eng.*, vol. 123, no. 5, pp. 402–410, May 1997.

[108] J. K. Mitchell, V. Vivatrat, and T. W. Lambe, "Foundation performance of tower of Pisa," *J. Geotechnical Eng. Division*, vol. 103, no. 3, pp. 227–249, Mar. 1977, doi: 10.1061/ajgeb6.0000393.

[109] K. Terzaghi, *Erdbaumechanik Auf Bodenphysikalischer Grundlage*. F. Deuticke, 1925.

[110] K. Terzaghi, *Theoretical Soil Mechanics*. New York, NY, USA: Wiley, 1943, doi: 10.1002/9780470172766.

[111] K. Terzaghi and R. B. Peck, *Soil Mechanics in Engineering Practice*. New York, NY, USA: Wiley, 1948.

[112] Q. Liu, Y.-B. Deng, and T.-Y. Wang, "One-dimensional nonlinear consolidation theory for soft ground considering secondary consolidation and the thermal effect," *Comput. Geotechnics*, vol. 104, pp. 22–28, Dec. 2018, doi: 10.1016/j.compgeo.2018.08.007.

[113] A. Yalcin, "The effects of clay on landslides: A case study," *Appl. Clay Sci.*, vol. 38, nos. 1–2, pp. 77–85, Dec. 2007, doi: 10.1016/j.clay.2007.01.007.

[114] L. B. Underwood, "Classification and identification of shales," *J. Soil Mech. Found. Div.*, vol. 93, pp. 97–116, Nov. 1967.

[115] A. N. Hussein and A. H. Mustapha, "Failure investigation of a fill slope in Putrajaya, Malaysia," in *Proc. Int. Conf. Case Hist. Geotech. Eng.*, 2004. [Online]. Available: https://scholarsmine.mst.edu/icchge/5icchge/session07/5

[116] P. P. Rahardjo, "Geotechnical failures case histories of construction on soft soils, forensic investigations and counter measures in Indonesia," *Int. J. Integr. Eng.*, vol. 6, no. 2, pp. 11–23, 2014.

[117] P. P. Rahardjo and I. Meilani, "Effect of saturation on the strength of natural and compacted padalarang clays," Rep., 1999.

[118] A. W. Bishop, "The use of pore-pressure coefficients in practice," *Géotechnique*, vol. 4, no. 4, pp. 148–152, Dec. 1954, doi: 10.1680/geot.1954.4.4.148.

[119] J. M. Duncan, "State of the art: Limit equilibrium and finite-element analysis of slopes," *J. Geotechnical Eng.*, vol. 122, no. 7, pp. 577–596, Jul. 1996, doi: 10.1061/(asce)0733-9410(1996)122:7(577).

[120] N. R. Morgenstern and V. E. Price, "The analysis of the stability of general slip surfaces," *Géotechnique*, vol. 15, no. 1, pp. 79–93, Mar. 1965, doi: 10.1680/geot.1965.15.1.79.

[121] E. Spencer, "A method of analysis of the stability of embankments assuming parallel inter-slice forces," *Géotechnique*, vol. 17, no. 1, pp. 11–26, Mar. 1967, doi: 10.1680/geot.1967.17.1.11.

[122] S. Oh and N. Lu, "Slope stability analysis under unsaturated conditions: Case studies of rainfall-induced failure of cut slopes," *Eng. Geol.*, vol. 184, pp. 96–103, Jan. 2015, doi: 10.1016/j.enggeo.2014.11.007.

[123] C. J. Shepheard, P. J. Vardanega, E. A. Holcombe, and K. Michaelides, "Analysis of design choices for a slope stability scenario in the humid tropics," *Proc. Inst. Civil Eng. Eng. Sustainability*, vol. 171, no. 1, pp. 37–52, Feb. 2018, doi: 10.1680/jensu.16.00081.

[124] H. Rahardjo, A. S. Nio, E. C. Leong, and N. Y. Song, "Effects of groundwater table position and soil properties on stability of slope during rainfall," *J. Geotechnical Geoenvironmental Eng.*, vol. 136, no. 11, pp. 1555–1564, Nov. 2010, doi: 10.1061/(asce)gt.1943-5606.0000385.

[125] H. M. Shiferaw, "Study on the influence of slope height and angle on the factor of safety and shape of failure of slopes based on strength reduction method of analysis," *Beni-Suef Univ. J. Basic Appl. Sci.*, vol. 10, no. 1, Dec. 2021, doi: 10.1186/s43088-021-00115-w.

[126] Y. C. Tan, "Embankment over soft clay—Design and construction control," in *Proc. Geotech. Eng.*, 2012, pp. 1–15.

LAI WAH SIM received the bachelor's degree in civil engineering from Universiti Kebangsaan Malaysia. She is currently pursuing the master's degree in civil engineering with Universiti Tenaga Nasional (UNITEN), Malaysia. Her research interests include geotechnical engineering, soft ground improvement, and pavement engineering.

HERDA YATI BINTI KATMAN received the Ph.D. degree in transportation engineering from the University of Malaya, Malaysia, in 2016. She is currently a Senior Lecturer with the Department of Civil Engineering, College of Engineering, Universiti Tenaga Nasional (UNITEN), Malaysia. Her research interests include sustainable construction materials, waste material utilization, pavement engineering, and highway engineering.

INTAN NOR ZULIANA BINTI BAHARUDDIN received the master's degree in geotechnical engineering from Universiti Teknologi MARA, Malaysia, in 2010. She is currently a Lecturer with the Department of Civil Engineering, College of Engineering, Universiti Tenaga Nasional (UNITEN), Malaysia. Her research interests include slope stability, characterization of rocks and soils, waste materials for soil stabilization, and infrastructure health monitoring.

GOBINATH RAVINDRAN received the Ph.D. degree in environmental geotechnology—disaster management from VIT University, India, in 2018. He is currently the Dean of research and ranking with SR University, India. He is also a Professor with the Department of Civil Engineering, SR University. His research interests include environmental chemistry, geotechnology, environmental geotechnology, wastewater treatment, and soil bioengineering.

MOHD RASDAN IBRAHIM received the Ph.D. degree in pavement engineering from the University of Malaya, Malaysia. He is currently a Senior Lecturer with the Department of Civil Engineering, Faculty of Engineering, University of Malaya. His research interests include crumb rubber-modified asphalt, recycled asphalt pavement, waste plastic-modified asphalt, and traffic and transportation management and modeling.

ADHAM MOHAMMED ALNADISH received the Ph.D. degree in transportation engineering from Universiti Tun Hussein Onn Malaysia (UTHM), in 2019. He is currently an Assistant Professor with the Department of Civil Engineering, National University of Sciences and Technology (NUST), Pakistan. His research interests include sustainable pavement materials, utilization of waste material, pavement engineering, and highway engineering.