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A Decade Of Research On Ground Improvement For Road Embankments On Soft Ground: A Bibliometric And Science-Mapping Review

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Abstract
This article presents a bibliometric and science-mapping review of studies on ground improvement for road embankments on soft ground published from 2016 to 2025. Bibliographic records were obtained from Scopus and Web of Science, combined into one database, screened using a PRISMA-style procedure, and analysed using Biblioshiny. The results indicate a stable conceptual core; however, there remains limited integration across different treatment families. Embankment and geosynthetic emerged as motor themes, while prefabricated vertical drains, soft soil, and soft ground served as central but less consolidated basic themes. Thematic evolution from 2016-2020 to 2021-2025 indicates increasing specialisation toward road-embankment behaviour, geosynthetic reinforcement, load transfer, peat serviceability, and field validation. Overall, this review reframes the field as an embankment-ground improvement system and identifies hybrid, mechanism-based, and field-validated design as key priorities for future research.

Keywords: Road embankment; Soft ground; Ground improvement; Prefabricated vertical drains; Geosynthetics; Bibliometric analysis.

1. Introduction

Road embankments built on soft, or very compressible, ground continue to be an issue for roadway construction in transportation geotechnics. Such embankments may be required as part of the construction of transportation corridors that span through weak soil deposits, including soft clay, peat, organic soils, marine clays, and other weak deposits. The foundation soils are often characterized by low undrained shear strength, high compressibility, slow rates of consolidation, and significant long-term deformation, all of which have implications for embankment stability, settlement, and serviceability.

The behavior of road embankments constructed on soft soils can be affected by multiple variables, including the state of the underlying soil layers, the type of ground improvement used, construction sequencing, drainage response during and after construction, the reinforcement systems used, how loads are transferred from the embankment to the foundation beneath it, and how the embankment will perform during long-term service. Numerous research projects have examined embankments treated with columns created from deep cement mixing (DCM), widened embankments with prefabricated vertical drains (PVDs), embankments treated with dry jet mixing (DJM), reinforced with geosynthetics, and the long-term settlement of embankments constructed over peat. These studies indicate that each category of treatment focuses primarily on an individual part of the overall embankment-foundation interaction (Jamsawang et al., 2016; Jiang et al., 2020; Ghosh et al., 2021; Yamazoe et al., 2023). However, although there are many technical references available, their categorisation according to soil condition, improvement mechanism, performance criterion, and evidentiary method remains ambiguous.

Engineering issues of this type are multi-mechanism rather than focused on a single process or technique. Commonly used drainage and preloading techniques help limit post-construction settlement and speed up consolidation. For instance, Wu et al. (2021) studied an integrated application of vacuum–surcharge preloading for embankment widening over soft marine clay. Studies related to PVD have extended beyond evaluations of settlement and pore-water pressure to include numerical modeling, smear-effect assessments, and validations based on field measurements (Mamat et al., 2019a; Mamat et al., 2019b; Mamat et al., 2022; Che Mamat et al., 2024). The investigations into column-supported and deep-mixing embankments have included bearing capacity, lateral deformation, failure mechanisms, and load redistribution mechanisms (Jamsawang et al., 2016; Liyanapathirana, 2022). Geosynthetic-reinforced and pile-supported embankments provide additional mechanisms for load transfer through reinforcement platforms, soil arching, and interactions between piles and columns (Ghosh et al., 2021; Yu and Bathurst, 2017; Zhao et al., 2019). Regardless of the technical maturity of these processes, knowledge regarding them is still divided among many different overlapping bodies of literature.

A further problem in this area of study is that the field has grown beyond traditional consolidation and stability evaluation. The emphasis on peat-related behaviour, such as time-dependent behaviour, secondary consolidation, and long-term settlements, is important for maintaining road serviceability; however, these topics have historically been disconnected from the broader body of PVD, geosynthetic, and column-supported embankment research (Yamazoe et al., 2023; Cui et al., 2024). Studies focused on lightweight fills and sustainability-oriented stabilisation methods add to the solution space in terms of reducing settlement, using existing materials, and minimising environmental impact. However, many times these types of solutions are reported separately as specific materials or specific case studies rather than contributing to an overall framework for understanding embankment performance (Ahmad et al., 2021; Duda and Siwowski, 2022). Data-driven, decision-support, and monitoring-based studies reflect an increasing trend toward predicting optimal selections and validating field measurements for uncertainty associated with construction on very soft soils (Aljanabi et al., 2018; Mahdi et al., 2020; Mamat et al., 2021; Toan et al., 2023; Jablonowski et al., 2025).

Available syntheses and technical studies remain largely organised around treatment categories or individual engineering mechanisms. Such organisation is useful for design practice, but it does not reveal which concepts form the intellectual core of the field, which themes are mature or peripheral, which methods act as bridges across research streams, and whether recent research has moved toward integration or merely added new technique-specific topics. This distinction is important because a growing number of embankment projects require hybrid solutions rather than single-method treatment selection.

The use of bibliometric and science-mapping techniques to address this specific knowledge-organisation issue is highly relevant. Bibliometric analysis can identify publication patterns, influential sources, highly cited documents, and citation structures, while science mapping can reveal conceptual relationships and thematic development within a defined literature (Aria and Cuccurullo, 2017; Donthu et al., 2021). In this case, co-word analysis, thematic mapping, and thematic evolution are particularly applicable, since the subject area has no single material or method defining it. Instead, there are intersecting vocabularies related to soils, earth embankments, ground improvement technologies, criteria for evaluating performance, and approaches to analysis.

As such, this study has undertaken a bibliometric and science-mapping literature analysis of soil and ground improvements for road embankments constructed over soft ground, based upon a framework of four research questions: (1) What are the primary publication, source, and citation characteristics that define the area of investigation? (2) Which documents and data sources comprise the 'visible' portion of the final dataset? (3) What conceptual themes emerged from author-keyword co-occurrences and thematic mapping? (4) How do these themes evolve over time between 2016-2020 and 2021-2025? Records were searched in Scopus and Web of Science, combined and filtered, and analysed with Biblioshiny. The final corpus consisted of 99 journal articles published between 2016 and 2025. Reporting followed a PRISMA-style identification, filtering, and inclusion procedure (Page et al., 2021).

This review makes three important contributions. Firstly, this review focuses on a very particular subset of the broad body of research into ground improvement for construction projects; that is, road embankments constructed over soft ground. Secondly, the use of bibliometric performance indicators, author-keyword co-occurrence, thematic mapping, and thematic evolution allows the conceptual structure of the body of research to be described, rather than simply counting publications. Finally, by framing the existing body of literature as an Embankment-Ground Improvement System (EGIS), this review moves away from viewing the literature as a catalogue of different treatment methods and toward an integrated framework that describes the relationship between the foundation condition, the improvement mechanism, the performance criterion, and the evidentiary method.

2 Methodology

2.1 Data Collection and Search Strategy

This study applied a bibliometric and science-mapping approach to evaluate research conducted on soil and ground improvement for road embankments on soft ground. The Boolean search was structured using the three blocks shown in Table 1. The treatment-related block was further organised into the intervention families shown in Table 2. A search query was developed matching the syntax for both Scopus and Web of Science, limited to peer-reviewed journal articles from 2016 through 2025. The overall data collection, processing, and analysis procedure is illustrated in Fig. 1.

2.2 Screening and Data Cleaning

The data collected from both Scopus and Web of Science were first combined into one single file using the tool ScientoPy to remove duplicates and manage any other entry duplication. Once the datasets were combined, they were uploaded into OpenRefine to screen out any irrelevant records. Titles, abstracts, and keywords were screened to determine if each record aligned with the research focus, specifically records related to soil and ground improvement for road embankments on soft ground. Any records dealing with an unrelated topic were eliminated at this stage. Additionally, OpenRefine was utilised to clean up any metadata fields prior to conducting an analysis. In total, 702 records were obtained (n = 513 from Scopus and n = 189 from Web of Science). Applying eligibility criteria: document type = article; publication year range 2016-2025; language = English, resulted in 188 remaining records (n = 121 from Scopus; n = 67 from Web of Science). After removing 61 duplicate records, 127 records were eligible for screening. An additional 28 records were screened out as not relevant to the study's subject area through title, abstract, and keyword screening. Thus, a total of 99 journal articles comprised the final corpus. The screening process is depicted in the PRISMA flow chart in Fig. 2.

2.3 Bibliometric Analysis Procedure

The final dataset was analysed using Biblioshiny (the web-based user interface for the bibliometrix R-package) to obtain both descriptive and structural-conceptual outputs. The descriptive phase produced: An Information Table listing all available data, a Most Relevant Sources section, and a Most Globally Cited Documents section. The conceptual phase produced the following four types of maps from author-keyword analysis: Word-Frequency Profiling; Co-Occurrence Network; Thematic Map; and Thematic Evolution Analysis. Author keywords were used as the primary unit of analysis. A Thematic Evolution Analysis was carried out in two time-slices (2016-2020 and 2021-2025) to assess whether there has been continuity, transformation, or emerging specialisation over the study period.

3 Results

3.1 Dataset Overview

Table 3 lists selected descriptive characteristics of the final cleaned dataset. The dataset includes 99 articles from journals published from 2016 to 2025 across 70 sources. The annual growth rate is 3.60%, and the average number of citations per document is 12.75. There are 312 Keywords Plus and 285 author keywords, providing terminological diversity for keyword-based analyses.

3.2 Most Relevant Sources

As shown in Fig. 3, the source distribution is specialised but not dominated by a single outlet. Three journals contributed the highest number of documents, with four papers each: Geotextiles and Geomembranes, International Journal of GEOMATE, and Transportation Infrastructure Geotechnology. Six further sources contributed three documents each, while Advances in Civil Engineering contributed two. The ten most productive sources account for 32 of the 99 documents (32.3%), suggesting that the field is concentrated in geotechnical, geosynthetics, and transportation-infrastructure outlets while remaining distributed across multiple publication venues.

3.3 Most Globally Cited Documents

The 10 most cited documents worldwide are listed in Table 4. The most cited publication is the work of Jamsawang et al. (2016), with 148 citations and 13.5 citations per year, followed by Wu et al. (2021) with 66 citations and 11.0 citations per year. The documents cited are primarily related to embankments supported by DCM, vacuum preloading and surcharge preloading, highway widening on weak foundation, soil arching and piled embankments, geosynthetic reinforcement, consolidation modelling, settlement prediction, and the performance of weak subgrade under cement stabilisation.

3.4 Co-Occurrence Network Analysis

The co-occurrence network was built from author keywords of the final corpus of 99 documents published from 2016 to 2025. Co-occurrence means that two concepts were mentioned by authors in the same publication, revealing how authors conceptually relate soil type, embankment performance, improvement technique, and analytical method. The co-occurrence network of author keywords is shown in Fig. 4.

The network shows that the field is conceptually coherent at the problem level, but segmented at the method level. The centrality of the term 'embankment' is confirmed by its being the most frequent term in the corpus (28 occurrences) and the most structurally important node in the co-occurrence network, with the highest PageRank value (0.134) and betweenness centrality (220.77). The term 'soft soil' was used 18 times and had the second highest PageRank value (0.086), with similar terms such as 'soft clay', 'soft ground', 'peat', and 'compressible soil' contributing to the centrality of problematic foundation conditions. 'Settlement' was used 12 times, associated with soft soil, embankment, ground improvement, and drainage-related methods, indicating that deformation control is still the main technical issue for road embankment construction over soft ground.

Prefabricated vertical drain (PVD) was found 12 times and exhibited high structural importance, with a PageRank value of 0.079 and betweenness centrality of 101.40, suggesting that PVD is not just a common treatment technique but a concept linking soft-ground conditions, field measurement, numerical analysis, slope stability, and road embankment performance. The finite element method was mentioned 10 times but had the second-highest betweenness centrality (150.06), confirming it as an integrative language connecting drainage-based treatment, deep mixing, stone columns, geosynthetic reinforcement, basal reinforcement, and stability analysis.

The cluster structure indicates five major conceptual areas: (1) embankment stability and soil-improvement response; (2) settlement control, geosynthetic reinforcement, and load transfer mechanism; (3) PVD, road embankment, consolidation, and field measurement; (4) finite element method, geosynthetic, and numerical modelling; and (5) peat and corduroy road. Overall, the co-occurrence network exhibits a stable core of well-connected but not fully integrated concepts. Fragmentation is caused by terminological inconsistency, where related concepts such as deep mixing, DCM, cement deep mixing, dry jet mixing, and soil-cement columns are spread across various keyword expressions.

3.5 Thematic Map Analysis

The thematic map was created from author keywords of the final corpus of 99 documents, arranging keyword clusters based on Callon centrality (connections to the rest of the field) and Callon density (internal cohesion and development). The thematic map is shown in Fig. 5, and cluster metrics are summarised in Table 5.

In the motor-theme quadrant, two themes are present: 'embankment' and 'geosynthetic', both with high degree of relevance and relatively high internal development. In the basic-theme quadrant, 'prefabricated vertical drain (PVD)' has the highest Callon centrality but insufficient density to surpass the motor-theme threshold, indicating it is highly interconnected but not tightly defined. 'Soft soil' and 'soft ground' serve as broad, transversal problem domains. The niche-theme quadrant features 'factor of safety' and 'displacement' as highly internally cohesive but weakly connected to the broader field. 'Peat' and 'lightweight fill material' are under-integrated rather than merely declining, representing specific foundation-condition and material-innovation literatures that have not yet been well linked to the mainstream PVD, geosynthetic, and column-supported embankment research domains.

3.6 Thematic Evolution Analysis

Thematic evolution analysis was performed on the final set of 99 documents to examine how author keywords changed across two time-slices: 2016-2020 and 2021-2025. The output in Biblioshiny connects themes from earlier periods to themes from later periods based on common words, using the weighted inclusion index and the inclusion index to show the degree of conceptual overlap. The thematic evolution is shown in Fig. 6.

The analysis suggests continuity rather than sudden changes in direction. The first period was structured around general problem-defining and performance-oriented themes: 'soft ground', 'embankment', 'prefabricated vertical drain (PVD)', 'soft soil', 'settlement', and 'numerical analysis'. During the second period, the field maintained several of these anchors but reorganised into a more differentiated thematic structure: 'embankment', 'peat', 'soft ground', 'road embankment', 'settlement', 'load transfer mechanism', 'geosynthetic', and 'soil improvement'. The 'embankment' family shows the best general continuity (weighted inclusion index 0.538, 14 shared occurrences), while settlement continuity is also strong (weighted inclusion index 0.556, inclusion index 0.500). PVD illustrates conceptual absorption rather than disappearance, with weighted inclusion index values of 0.333 for transitions to 'embankment' and 'road embankment'. The 'soft soil' lineage shows the most significant conceptual diversification, linking to later 'geosynthetic' and 'load transfer mechanism' themes.

4 Discussion

4.1 Summary of Key Findings

The science-mapping results show that research on soil and ground improvement for road embankments on soft ground is organised around a stable problem core, but remains segmented by treatment method, soil condition, and evidentiary approach. Embankment performance, soft soil, settlement, PVDs, finite element modelling, and geosynthetic reinforcement were found to be the key conceptual pillars of the co-occurrence network. The thematic map further identified 'embankment' and 'geosynthetic' as motor themes, whereas 'prefabricated vertical drain (PVD)', 'soft soil', and 'soft ground' are more basic themes, highly connected but less internally consolidated. Thematic evolution demonstrated continuity, with broad early themes being maintained in 2021-2025 but regrouped around more specific themes of embankment, peat, load transfer mechanism, geosynthetic, and soil improvement. The central finding is that the field is moving from method-specific soil treatment toward performance-based embankment systems.

4.2 Interpretation of Findings

The strong dominance of embankment and soft-ground terms reflects that the engineering problem involves interaction between embankment loading and weak foundation response. Ground improvement is not considered a single material or treatment, but a way of achieving outcomes at embankment scale, including settlement, slope stability, bearing capacity, pore-water pressure, and long-term serviceability. PVD remains very central but is a transversal technology linking consolidation, settlement prediction, field measurement, and staged construction across numerous design contexts (Jiang et al., 2020; Wu et al., 2021; Mamat et al., 2019a; Mamat et al., 2019b; Mamat et al., 2022; Che Mamat et al., 2024; Gui et al., 2020; Liang et al., 2020; Nazir et al., 2018).

Geosynthetic and load-transfer themes are more mature and developed than other themes, suggesting a move from treatment-based stabilisation to system behaviour. The question of how embankment loads are redistributed through improved ground is conceptually related to geosynthetic reinforcement, pile-supported embankments, concrete injected columns, and column-supported platforms. FEM and numerical analysis serve as a shared language for comparing different improvement methods, generalising them, and relating them to mechanism concepts. However, the relatively weaker integration of field-test and monitoring themes suggests that modelling maturity has advanced faster than systematic field validation, an imbalance that matters because embankment performance depends on construction sequencing, drainage boundaries, installation disturbance, and long-term soil response, all of which require calibration evidence.

The peripheral placement of peat and lightweight-fill themes does not indicate unimportance, but rather loose connection to the core vocabulary of PVD, geosynthetics, and column-supported systems. Their under-integration suggests that the field has not yet fully linked material or soil-specific solutions to the broader performance framework of embankment design (Yamazoe et al., 2023; Cui et al., 2024; Ahmad et al., 2021; Duda and Siwowski, 2022).

4.3 Theoretical Implications

The first theoretical implication is that the field should be referred to as an embankment-ground improvement system rather than a catalogue of ground improvement techniques. The bibliometric structure indicates four interacting constructs: (1) foundation condition (soft soil, soft ground, soft clay, peat, organic soil, sensitive clay); (2) improvement mechanism (PVD, preloading, deep mixing, stone columns, pile-supported systems, geosynthetics, lightweight fills, hybrid reinforcement); (3) performance criterion (settlement, stability, bearing capacity, pore pressure, displacement, load transfer); and (4) evidentiary method (numerical modelling, field measurement, physical modelling, monitoring, data-driven prediction). This four-part structure is non-obvious because traditional reviews often classify the field by treatment method.

The second implication is the theoretical link between consolidation-based and load-redistribution-based streams. A theory combining consolidation and load redistribution is needed to design embankments over soft ground, particularly when PVDs are used in conjunction with geosynthetics, columns, piles, or lightweight fills. The third implication is that long-term serviceability, creep, secondary consolidation, traffic-induced cyclic loading, and seismic response remain less integrated than construction-stage settlement and stability, indicating a need to shift focus toward life-cycle embankment behaviour. The fourth implication is terminological: inconsistent keyword uses across related concepts (deep mixing, DCM, CDM, cement deep mixing, dry jet mixing, soil-cement columns) reduces the apparent maturity and interconnectedness of technically related research streams.

4.4 Engineering Synthesis of the Embankment-Ground Improvement System

The bibliometric results indicate that embankments treated with ground improvements should be viewed as one embankment-ground improvement system rather than as separate treatment families. For engineering use, the primary focus for practitioners needs to be on how each treatment modifies the embankment's behaviour, that is, the dominant mechanism, and not merely what method was used, that is, the treatment type. Table 6 summarises the main treatment families found in the corpus and links them to soil condition, dominant mechanism for improving embankment performance, performance criterion, and design implication. This synthesis provides a bridge between the science-mapping results discussed herein and practical geotechnical decision-making.

4.5 Implications for Practice and Policy

The results suggest a transition from method selection to selection of a performance system. PVD, stone columns, deep mixing, geosynthetics, lightweight fills, and rigid inclusions should not be considered as stand-alone solutions. Rather, each should be evaluated on the basis of the governing foundation condition, construction sequence, target performance criterion, uncertainty level, and monitoring feasibility (Aljanabi et al., 2018; Mahdi et al., 2020; Toan et al., 2023). The results also suggest that the practice of field validation should be reinforced; large embankment projects on soft ground should be treated as monitored geotechnical systems, not just earthworks (Ghosh et al., 2021; Jablonowski et al., 2025; Wang et al., 2022).

Policy implications are most clearly seen in the areas of sustainability and risk management. Policy guidance should require evaluation of low-carbon or recycled materials not only based on material strength or laboratory indices but also based on settlement performance, durability, environmental safety, constructability, and maintenance implications at embankment scale (Ahmad et al., 2021; Duda and Siwowski, 2022; Mokhtar et al., 2025; Ramirez et al., 2024). This is especially important for transport agencies operating in peat, marine clay, sabkha, and sensitive clay areas where long-term deformation and failure effects can be significant.

4.6 Future Research Directions

Future theoretical studies should formulate a unified conceptual model for soft ground road embankment improvement, connecting consolidation, load transfer, reinforcement, inclusion-soil interaction, and long-term serviceability. The best prospects are hybrid systems where the families of treatment in the field are merged and compared based on common performance criteria (Jiang et al., 2020; Ghosh et al., 2021; Singh and Mishra, 2025; Kartawiria et al., 2025; Phutthananon et al., 2025). The priority directions and their associated open problems are summarised in Fig. 7.

Methodologically, future science-mapping studies should go beyond simple co-occurrence of author keywords and include controlled keyword normalisation, sensitivity analysis of thresholds, full-text or abstract-level text mining, and separate maps of methods, soil types, and performance outcomes. Future technical studies should also focus on further integration of model and data, including FEM, physical modelling, field instrumentation, and data-driven prediction. From an empirical perspective, more long-term, comprehensive, and regionally representative evidence is needed, particularly for peat, soft marine clay, sensitive clay, sabkha soil, and organic soil contexts (Yu et al., 2017; Gui et al., 2020; Liang et al., 2020; Dai et al., 2017; Lindgard et al., 2025).

5 Conclusions

The present investigation analyzed ten years of research on improving ground conditions for road embankments built on poor-quality or compressible soils using bibliometric performance indicators, author-keyword co-occurrence analysis, thematic mapping, and thematic evolution analysis. The final corpus was made up of 99 journal articles published during 2016-2025 and distributed across 70 different scientific sources. The study also found that the field has been organized around one consistent geotechnical problem: settlement control, stability, load transfer, and long-term serviceability of road embankments over weak or compressible foundation materials.

The conceptual structure of the field can best be seen as comprising four interdependent constructs of knowledge: foundation condition, improvement mechanism, performance criterion, and evidentiary method. Foundation conditions refer to soil types such as soft soil, soft ground, peat, organic soil, and marine clay. Interventions include prefabricated vertical drains, preloading, geosynthetics, deep mixing, stone columns, lightweight fills, and pile-supported systems. Performance measures include settlement, stability, bearing capacity, pore-water pressure, displacement, and load transfer. Finally, the evidentiary base includes numerical modelling, field measurement, monitoring, physical modelling, and data-driven prediction.

The thematic evidence shows continuity rather than complete change in research focus: embankment, soft ground, soft soil, settlement, and PVD-related concepts are all strong anchors, but the more recent literature shows stronger differentiation toward road-embankment specificity, geosynthetic reinforcement, load-transfer mechanisms, peat serviceability, hybrid improvement systems, and field validation. This indicates that the field is transitioning from single-method treatment studies toward a mechanism-performance-based approach for embankment systems, a transition that is important because real embankment projects rarely depend on one isolated treatment. They require combinations of drainage, reinforcement, inclusions, staged construction, monitoring, and long-term serviceability control.

The results are presented for practice, emphasising a change from the selection of ground-improvement methods individually to the design and evaluation of ground-improvement systems based on embankment-scale performance targets. In particular, the under-integration of peat, lightweight-fill materials, sustainability-oriented stabilisation, and monitoring-based evidence indicates that future practice should evaluate how a treatment performs over time, under construction sequencing, traffic loading, environmental exposure, and site-specific soil behaviour, not only whether it works.

Limitations include the selection of databases (Scopus and Web of Science), publication window, article-type filtering, restriction to English-language papers, and a Boolean strategy. Thematic visibility is also largely determined by author keywords. Conceptual association, knowledge structure, and conceptual links shown in co-occurrence, thematic-map, and thematic-evolution outputs do not imply technical superiority, causal relationships, or design effectiveness.

Future work should combine consolidation-based treatment with geosynthetic- and column-supported systems, combine numerical modelling with long-term monitoring, and provide performance comparisons across problematic soils including peat, marine clay, organic soil, and sensitive clay. Greater keyword standardisation and more systematic reporting of soil type, treatment mechanism, performance criterion, and validation method would also improve future bibliometric reproducibility and technical synthesis.

Declarations

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Tables

Table 1. Search String used for literature retrieval.

Search block	Purpose	Terms included in the Search String
A. Soft-ground condition	Captures problematic foundation materials and weak or compressible ground conditions.	"soft soil*" OR "soft-soil*" OR "soft clay*" OR "soft-clay*" OR "soft ground" OR "soft foundation*" OR "soft subsoil*" OR "compressible soil*" OR "compressible clay*" OR "weak soil*" OR "weak ground" OR "marine clay*" OR "alluvial clay*" OR "organic soil*" OR peat OR "peat soil*"
B. Road-embankment context	Restricts the corpus to road, highway, and related transportation embankment applications.	"road embankment*" OR "highway embankment*" OR "roadway embankment*" OR "expressway embankment*" OR "motorway embankment*" OR "freeway embankment*" OR road* within five words of embankment* OR highway* within five words of embankment* OR roadway* within five words of embankment* OR expressway* within five words of embankment* OR motorway* within five words of embankment* OR freeway* within five words of embankment*

Search block	Purpose	Terms included in the Search String
C. Ground-improvement or treatment method	Identifies ground-improvement, stabilisation, reinforcement, drainage, column-supported, piled, and lightweight-fill interventions.	The third block comprised the treatment-related terms grouped in Table 2.

Table 2. Ground-improvement and treatment terms included in the third Search string.

Treatment or intervention family	Terms included
Generic improvement, treatment, stabilisation, and reinforcement	"ground improvement" OR "ground treatment" OR "ground reinforcement" OR "soil improvement" OR "soil treatment" OR "soil reinforcement" OR "soil stabilization" OR "soil stabilisation" OR "ground stabilization" OR "ground stabilisation" OR "foundation improvement" OR "foundation treatment" OR "soft foundation treatment"
Preloading and consolidation	preload* OR pre-load* OR surcharge OR "surcharge loading" OR "vacuum preloading" OR "vacuum consolidation"
Vertical drains	"vertical drain*" OR "prefabricated vertical drain*" OR PVD OR "wick drain*" OR "band drain*" OR "sand drain*"
Deep mixing and stabilised columns	"deep soil mixing" OR "deep mixing method" OR "cement deep mixing" OR "dry jet mixing" OR "soil-cement column*" OR "soil cement column*" OR "cement column*" OR "lime column*"
Granular columns and compaction piles	"stone column*" OR "granular column*" OR "gravel column*" OR "sand compaction pile*" OR "cement-fly ash-gravel pile*" OR "cement fly ash gravel pile*"
Rigid inclusions and jet grouting	"rigid inclusion*" OR "controlled modulus column*" OR "jet grouting" OR "jet grout*"
Geosynthetics and basal reinforcement	geosynthetic* OR geogrid* OR geotextile* OR geocell* OR "basal reinforcement" OR "reinforced embankment*" OR "geosynthetic reinforced*" OR "geosynthetic-reinforced*" OR "geosynthetic encased column*"
Piled and column-supported embankments	"piled embankment*" OR "pile-supported embankment*" OR "pile supported embankment*" OR "column-supported embankment*" OR "column supported embankment*"
Lightweight fill and lightweight embankments	"lightweight fill*" OR "lightweight embankment*" OR geofoam OR "EPS geofoam" OR "expanded polystyrene" OR "foamed concrete" OR "lightweight concrete"

Table 3. Main information of the bibliometric dataset.

Indicator	Value
Timespan	2016-2025
Sources	70
Documents	99
Annual growth rate (%)	3.60

Indicator	Value
Average citations per document	12.75
Keywords Plus	312
Author keywords	285
Document type	Article (99)

Table 4. Top 10 globally cited documents in the final corpus.

No.	Document	Source	TC	TC/Y	NTC
1	Jamsawang et al. (2016)	Computers and Geotechnics	148	13.5	4.39
2	Wu et al. (2021)	Geotextiles and Geomembranes	66	11.0	4.20
3	Yu H. et al. (2017)	Arabian Journal for Science and Engineering	53	5.3	2.59
4	Lai et al. (2016)	Journal of Zhejiang University-SCIENCE A	50	4.5	1.48
5	Zhao et al. (2019)	Journal of Geotechnical and Geoenvironmental Engineering	45	5.6	3.79
6	Yu and Bathurst (2017)	Geotextiles and Geomembranes	42	4.2	2.06
7	Ghosh et al. (2021)	Geotextiles and Geomembranes	40	6.7	2.54
8	Zhang et al. (2020)	Int. J. Numer. Anal. Methods Geomech.	38	5.4	2.40
9	Wang et al. (2018)	International Journal of Geomechanics	37	4.1	1.81
10	Ifediniru and Ekeocha (2022)	International Journal of Geo-Engineering	31	6.2	3.62

Note. TC = total citations; TC/Y = citations per year; NTC = normalised total citations.

Table 5. Thematic-map cluster metrics for author keywords (Callon centrality and density).

Cluster	Callon Centrality	Callon Density	Cluster Frequency	Quadrant
Embankment	0.685	51.32	67	Motor
Geosynthetic	0.714	54.55	41	Motor
Prefabricated vertical drain (PVD)	1.568	38.13	46	Basic
Soft soil	0.876	30.48	39	Basic
Soft ground	0.411	42.78	21	Basic
Factor of safety	0.000	75.00	12	Niche
Displacement	0.000	62.50	4	Niche

Cluster	Callon Centrality	Callon Density	Cluster Frequency	Quadrant
Field test	0.000	50.00	2	Niche (boundary)
Peat	0.075	47.22	10	Emerging/declining
Lightweight fill material	0.000	50.00	2	Emerging/declining (boundary)

Note. Quadrant assignments follow the median centrality and median density used to partition the thematic map. The 'field test' and 'lightweight fill material' clusters lie on the density boundary and each comprise only two keyword occurrences, so their positions should be interpreted with caution.

Table 6. Engineering synthesis of ground-improvement treatment families for road embankments on soft ground.

Treatment family	Typical soft-ground context	Dominant mechanism	Main performance criterion	Design implication	Representative studies
Prefabricated vertical drains, vacuum preloading, and surcharge preloading	Soft clay, soft marine clay, compressible deposits	Drainage-path shortening, excess pore-water pressure dissipation, accelerated consolidation	Settlement rate, residual settlement, pore-water pressure, construction-stage stability	Design should account for smear effect, drain spacing, staged loading, field instrumentation, and consolidation model calibration	Mamat et al. (2019a, 2019b); Wu et al. (2021); Mamat et al. (2022); Che Mamat et al. (2024)
Deep cement mixing, dry jet mixing, and soil–cement columns	Soft clay, deep compressible deposits, embankment widening zones	Strength and stiffness increase, load sharing between columns and soil, reduction of lateral deformation	Bearing capacity, lateral displacement, total and differential settlement, global stability	Design should consider column spacing, replacement ratio, column yielding, strain softening, and interaction with surrounding soil	Jamsawang et al. (2016); Jiang et al. (2020); Liyanapathirana (2022)
Geosynthetic-reinforced and pile-supported embankments	Soft soil requiring load transfer and differential-settlement control	Tensioned membrane action, soil arching, load transfer to inclusions or piles	Reinforcement strain, differential settlement, pile/column load sharing, serviceability under traffic loading	Design should evaluate reinforcement stiffness, platform geometry, pile spacing, arching assumptions, and cyclic loading	Yu and Bathurst (2017); Zhao et al. (2019); Ghosh et al. (2021); Xu et al. (2024)
Stone columns and encased stone columns	Soft clay, sabkha soil, weak subgrade	Drainage, lateral confinement, composite stiffness, reinforcement of weak foundation	Settlement reduction, stability improvement, column bulging control	Encased systems may be required where lateral confinement is insufficient; design should check drainage, column spacing, and encasement stiffness	Al-Shukur and Al-Khafajy (2017); Debbabi et al. (2020, 2021); Ullah et al. (2022)
Lightweight fills and geofoam systems	Very soft deposits where embankment load reduction is critical	Reduction of vertical stress applied to foundation soil	Settlement reduction, slope stability, long-term deformation, constructability	Material selection should consider density, durability, creep, drainage, fire/environmental constraints, and	Duda and Siwowski (2022); Ozer and Akinay (2022); Chaiyaput et al. (2023)

Treatment family	Typical soft-ground context	Dominant mechanism	Main performance criterion	Design implication	Representative studies
				maintenance implications	
Peat and organic-soil embankment systems	Peat, organic soil, highly compressible natural deposits	Long-term compression, secondary consolidation, time-dependent serviceability response	Long-term settlement, differential settlement, pavement serviceability	Monitoring and long-term prediction are essential; design should not rely only on construction-stage settlement	De Guzman and Alfaro (2016, 2018); Yamazoe et al. (2023); Cui et al. (2024)

Figures

Fig. 1 Methodological workflow for data collection, screening, cleaning, and bibliometric analysis.

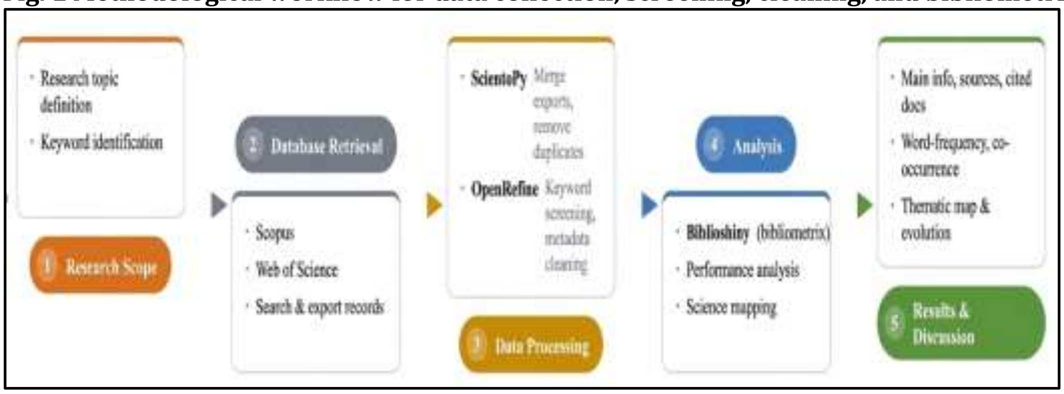

Fig. 2 PRISMA-style flow diagram for identification, filtering, screening, and inclusion of records.

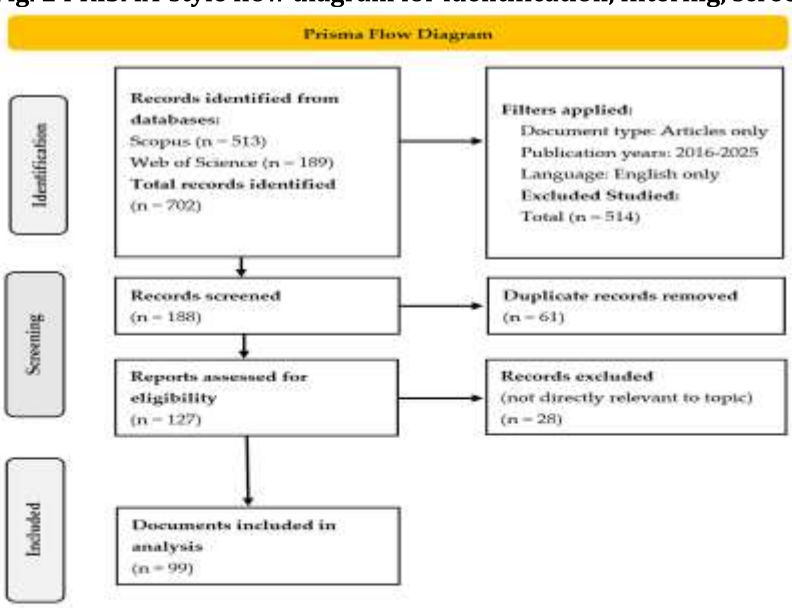

Fig. 3 Most relevant sources in research on soil and ground improvement for road embankments on soft ground.

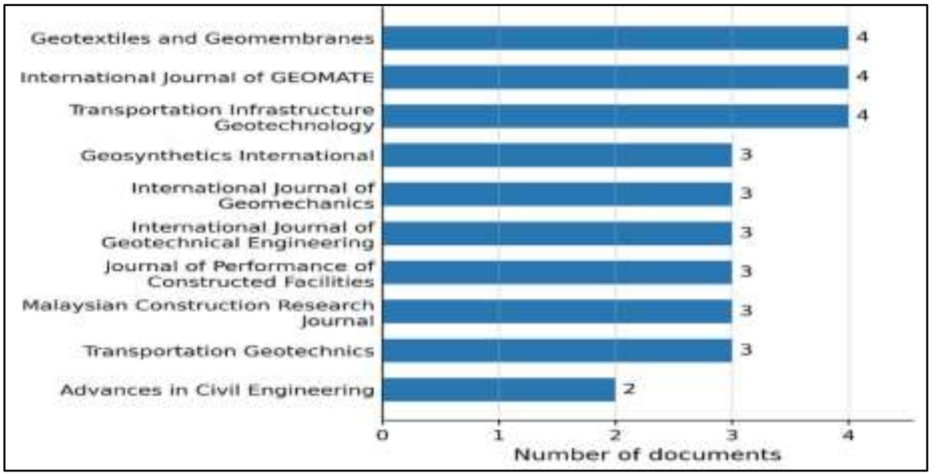

Fig. 4 Author-keyword co-occurrence network for ground improvement of road embankments on soft ground.

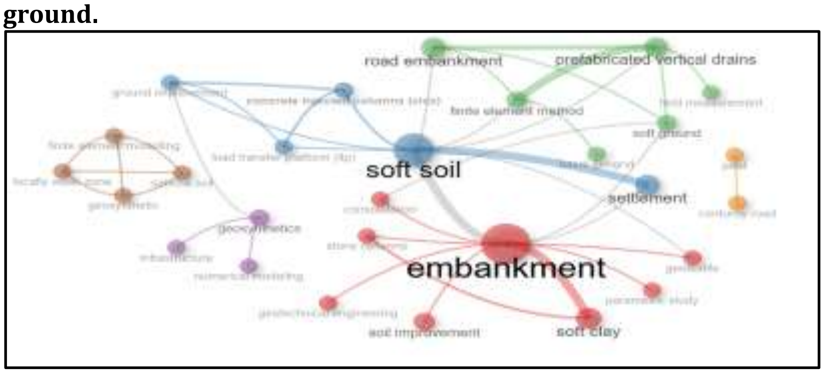

Fig. 5 Thematic map of author keywords based on Callon centrality and Callon density.

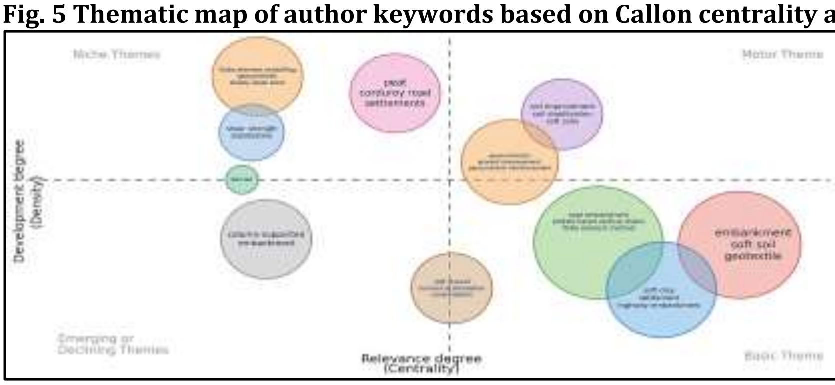

Fig. 6 Thematic evolution of author keywords across 2016-2020 and 2021-2025.

Fig. 7 Priority future research directions toward an integrated Embankment-Ground Improvement System (EGIS).

Abbreviations

DCM	Deep cement mixing
DJM	Dry jet mixing
EGIS	Embankment-Ground Improvement System
FEM	Finite element method
NTC	Normalised total citations
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PVD	Prefabricated vertical drain
TC	Total citations
TC/Y	Citations per year
WoS	Web of Science