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Bibliometric and Experimental Insights into Soil Liquefaction under Cyclic Loading in High-Seismicity Regions (1980–2025)

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ABSTRACT

Soil liquefaction induced by cyclic loading represents one of the most critical geotechnical hazards affecting infrastructure resilience during earthquakes and dynamic loading events. Over the past decades, extensive research has been conducted to understand liquefaction mechanisms, assessment methods, and mitigation strategies. However, a systematic evaluation of the intellectual structure and long-term evolution of this research field remains limited.

This study presents a comprehensive bibliometric analysis of global scientific publications related to liquefaction potential under cyclic loading over the period 1980–2025. Bibliographic data were extracted from the Scopus database using predefined search criteria to ensure transparency and reproducibility. Quantitative performance analysis and science mapping techniques were applied to identify publication growth patterns, leading authors, institutional collaborations, influential journals, and emerging research themes.

Results reveal a sharp increase in research output since 2015, peaking around 2025, with Earth and Planetary Sciences (41.6%) and Engineering (25.2%) as dominant disciplines. The United States emerges as the central collaboration hub, linking major producers including China, India, and European nations. Co-citation networks highlight foundational contributions from Obermeier on paleoseismic liquefaction features, Boulanger-Idriss on triggering procedures, and Moss et al. on CPT-based assessment, while keyword co-occurrence identifies three core themes: laboratory cyclic testing, seismic hazard analysis, and geological evidence.

To illustrate a gap identified in the bibliometric analysis, namely the limited representation of Mediterranean natural sands, cyclic triaxial tests were performed on a natural Algerian coastal sand under Kobe-equivalent loading conditions (CSR = 0.69). Results show density-dependent pore-pressure build-up and liquefaction resistance consistent with dominant laboratory research trends identified bibliometrically.

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Research Article

The combined bibliometric–experimental framework provides an integrated understanding of the intellectual structure, thematic evolution, and physical behaviour governing liquefaction research, highlighting future directions toward probabilistic and data-driven assessment approaches.

Keywords: Bibliometric analysis; Soil liquefaction; High seismicity; Cyclic loading; Cyclic triaxial test.

1. INTRODUCTION

Soil liquefaction induced by cyclic loading has long been recognized as one of the most critical geotechnical hazards affecting soil stability and infrastructure performance during earthquakes and other dynamic loading conditions. Since the pioneering investigations following major seismic events in the twentieth century, liquefaction has remained a central topic in earthquake geotechnical engineering due to its potential to cause severe ground deformation, foundation failure, and large-scale infrastructure damage.

The phenomenon occurs when saturated granular soils experience a progressive buildup of excess pore water pressure under cyclic stresses, leading to a temporary loss of effective stress and shear strength [1], [2], [17].

Early foundational studies established empirical relationships for liquefaction triggering assessment based on in-situ testing methods such as the Standard Penetration Test (SPT) [3], [4], [16],[18]. Over time, advances in laboratory testing, field investigation techniques, and numerical modeling [5], [6], [7],[23], have significantly expanded the scientific understanding of liquefaction mechanisms and mitigation strategies.

From the 1980s onward, research activity intensified due to improvements in geotechnical instrumentation, increased availability of post-earthquake field data, and the development of performance-based engineering approaches. Subsequent major earthquakes further accelerated scientific interest, leading to the emergence of new analytical frameworks incorporating probabilistic assessment, constitutive modeling, and more recently, data-driven and machine learning techniques [7], [8]. As a result, the research landscape related to liquefaction under cyclic loading has evolved into a highly interdisciplinary field integrating geotechnical engineering, seismology, computational mechanics, and data science.

Despite the substantial growth of scientific publications over the past four decades, the overall intellectual structure and evolution of research trends in this domain remain insufficiently synthesized. Traditional literature reviews often focus on specific technical aspects, such as triggering criteria or numerical simulations, but rarely provide a quantitative and systematic overview of global research development. Consequently, researchers and practitioners lack a comprehensive understanding of how scientific priorities, collaboration networks, and methodological approaches have evolved over time.

Bibliometric analysis offers a robust methodological framework [9], [10], [11], [26], for quantitatively evaluating scientific production, identifying influential contributors, and mapping thematic evolution within a research field. By combining performance analysis with science mapping techniques, bibliometric studies enable the identification of emerging topics, research gaps, and future development pathways. While bibliometric approaches have been widely applied in various engineering disciplines, their application to liquefaction research under cyclic loading remains limited.

To address this gap, the present study conducts a comprehensive bibliometric analysis of global research on soil liquefaction under cyclic loading covering the period **1980–2025**. The objectives of this study are to:

1. analyze the temporal evolution of scientific publications and citation patterns;
2. identify leading authors, institutions, and countries contributing to the field;
3. examine collaboration networks and knowledge dissemination structures;
4. determine dominant and emerging research themes through keyword and co-occurrence analysis;

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Research Article

5. highlight existing research gaps and future directions in liquefaction assessment research.
6. to experimentally illustrate liquefaction behaviour using a natural Algerian coastal sand identified as representative of an underexplored geological context.

By providing a structured overview of four decades of scientific development, this study aims to support researchers, engineers, and decision-makers in understanding the evolution of liquefaction research and guiding future investigations toward emerging challenges in earthquake geotechnical engineering.

2. METHODOLOGY

2.1 Research Design

This study adopts a quantitative bibliometric approach to analyze the evolution and knowledge structure of scientific research related to soil liquefaction under cyclic loading. Bibliometric analysis enables the systematic evaluation of large volumes of scientific literature through statistical and network-based techniques, allowing the identification of publication trends, influential contributors, collaboration patterns, and thematic developments within a research domain.

The methodological framework implemented in this study consists of four main stages:

1. database selection and data retrieval;
2. data screening and preprocessing;
3. bibliometric performance analysis;
4. science mapping and visualization.

This structured workflow ensures transparency and reproducibility of the analysis.

2.2 Data Source and Search Strategy

The data were extracted from the **Scopus database**, selected due to its extensive coverage of peer-reviewed journals in engineering and geosciences, as well as its compatibility with bibliometric analysis tools.

The search was conducted using a predefined query applied to titles, abstracts, and keywords to capture publications addressing liquefaction phenomena under cyclic loading conditions.

Search query:

TITLE-ABS-KEY ("soil liquefaction" OR "liquefaction potential")
AND
TITLE-ABS-KEY ("cyclic loading" OR "cyclic shear" OR "dynamic loading")
AND
TITLE-ABS-KEY ("high seismicity “)
The search covered the period **1980–2025**, ensuring a long-term perspective on the development of the research field.

2.3 Inclusion and Exclusion Criteria

To ensure consistency and relevance of the dataset, the following criteria were applied:

Inclusion criteria

- peer-reviewed journal articles;
- conference papers related to geotechnical engineering;
- publications written in English;
- studies directly related to liquefaction behavior or assessment under cyclic or dynamic loading.

Journal of Information Systems Engineering and Management
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https://www.jisem-journal.com/ **Research Article**

Exclusion criteria

- unrelated seismic hazard studies;
- purely geological studies without geotechnical relevance;
- duplicate records;
- incomplete bibliographic entries.

After screening, the final dataset consisted of **375 publications**

2.4 Data Processing and Analysis Tools

The retrieved bibliographic records were exported in CSV format and processed using bibliometric analysis software tools [27].

The analysis combined:

- **performance analysis**, evaluating publication output, citation impact, and productivity indicators;
- **science mapping**, used to visualize relationships between authors, countries, institutions, and research themes.

Network visualization and mapping analyses were conducted using:

- **VOSviewer** [29], for co-authorship, co-citation, and keyword co-occurrence networks;
- bibliometric statistical processing techniques for trend analysis.

Prior to analysis, data cleaning procedures were performed to standardize author names, institutional affiliations, and keyword variations in order to reduce indexing inconsistencies.

2.5 Bibliometric Indicators

Several indicators were employed to characterize the research landscape:

- annual publication growth;
- citation analysis;
- most productive authors and institutions;
- country collaboration networks;
- journal impact distribution;
- keyword co-occurrence frequency;
- thematic cluster identification.

These indicators allow both quantitative assessment and qualitative interpretation of research evolution.

2.6 Experimental investigation on Algerian coastal sand

The tested soil consists of a natural coastal sand collected from the Boumerdès shoreline in northern Algeria, cyclic triaxial tests were conducted under isotropic effective confining pressure $\sigma c'$=100 kPa

Three relative densities were investigated:

- Dr = 20% (loose)
- Dr = 45% (medium dense)
- Dr = 70% (dense)

Journal of Information Systems Engineering and Management
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Research Article

Saturation was achieved with Skempton B-values between 96% and 98%, and a sinusoidal cyclic loading was applied at a frequency of 1.44 Hz with a cyclic stress ratio CSR=0.69 , corresponding to strong seismic loading derived from the Kobe (1995) earthquake record using the Seed–Idriss framework [1], [2],[22].

2.7 Analytical Framework

The analytical framework integrates descriptive statistics with network-based visualization techniques to reveal the intellectual structure of liquefaction research. Keyword co-occurrence analysis was used to identify dominant research themes and emerging topics, while collaboration networks provided insights into global scientific interaction patterns.

The methodological workflow adopted in this study is illustrated in **Figure 1**, summarizing data collection, preprocessing, analysis, and interpretation stages.

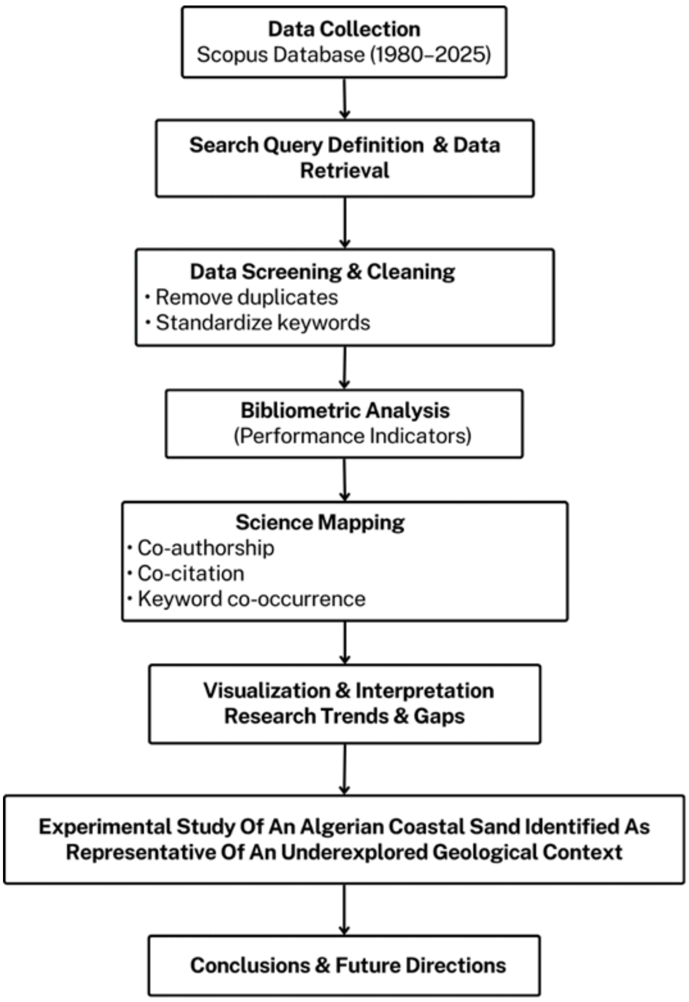

Figure 1: Methodological workflow adopted for the Study

3. RESULTS:

3.1 Evolution of publications by year:

The annual distribution of publications reveals a clear long-term growth pattern in research related to soil liquefaction under cyclic loading between 1980 and 2025 (Figure 2). During the initial period (1980–1995), scientific production remained limited, with only a small number of publications per year, reflecting the early exploratory phase of liquefaction research dominated by post-earthquake observations and empirical triggering approaches.

Journal of Information Systems Engineering and Management
2026, 11(2s)
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https://www.jisem-journal.com/

Research Article

A transition phase is observed between 1995 and 2010, characterized by a steady increase in publication output. This period coincides with the expansion of laboratory cyclic testing techniques and the development of improved in-situ investigation methods, particularly CPT-based and probabilistic assessment procedures. The gradual increase suggests a shift from empirical evaluation toward mechanistic interpretation of liquefaction behaviour.

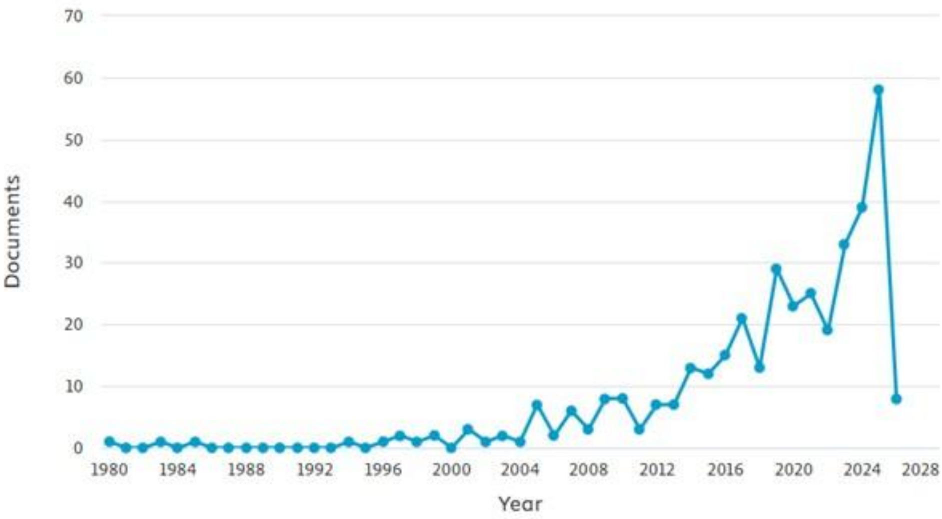

Figure 2: publications by year

After 2010, publication growth accelerates markedly, indicating a maturation phase of the research field. This increase corresponds to the wider availability of strong-motion databases, advances in numerical modelling capabilities, and the adoption of performance-based geotechnical design frameworks. The rapid expansion observed after 2015 highlights the integration of interdisciplinary approaches, including computational mechanics and data-driven methodologies.

This temporal evolution indicates not only an increase in publication volume but also a structural transformation of liquefaction research, shifting from post-earthquake observational studies toward predictive and performance-based frameworks. The acceleration observed after 2015 therefore reflects a paradigm transition rather than simple growth in scientific output.

3.2 Development of Subject areas by disciplines:

The disciplinary distribution of publications (Figure 3) indicates that Earth and Planetary Sciences account for approximately 41.6% of the total output, followed by Engineering with 25.2%. This distribution confirms the dual scientific nature of liquefaction research, positioned at the interface between geosciences and engineering applications.

The dominance of Earth sciences reflects the strong dependence of liquefaction studies on seismic hazard characterization, sedimentary environment analysis, and paleoseismic investigations. In contrast, the engineering contribution emphasizes laboratory experimentation, constitutive modelling, and infrastructure performance assessment.

The presence of Environmental Science (11.5%) and Agricultural and Biological Sciences (6.7%) suggests an increasing expansion toward environmental and land-use considerations, particularly in coastal and deltaic environments susceptible to liquefaction. Smaller contributions from Computer Science and Materials Science indicate the growing incorporation of numerical simulation and data-driven approaches, highlighting an ongoing diversification of methodological tools within the field.

This distribution illustrates a progressive transition from purely geotechnical analysis toward multidisciplinary seismic risk research.

Journal of Information Systems Engineering and Management
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Research Article

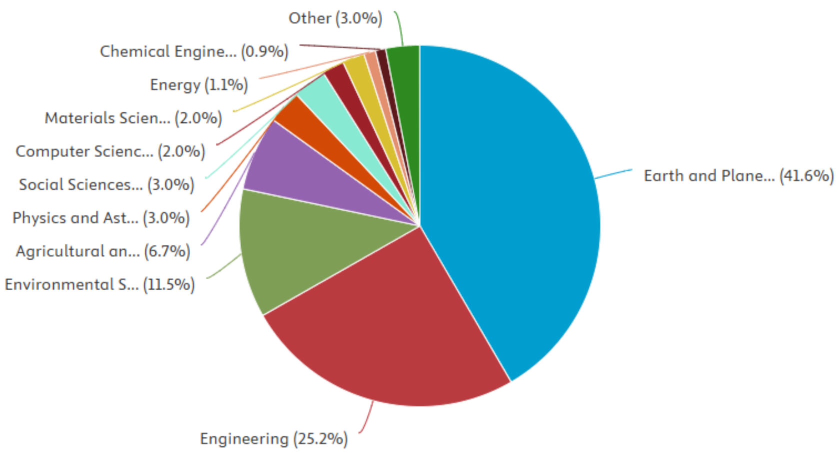

Figure 3: Development of Subject areas by disciplines

3.3 Keyword co-occurrence and thematic structure:

Keyword co-occurrence analysis reveals the conceptual organization of liquefaction research into three main thematic clusters (Figure 4).

The first cluster is centred on laboratory and experimental soil mechanics, including keywords such as *cyclic loading*, *cyclic triaxial test*, *shear modulus*, and *pore pressure*. This cluster reflects the dominant role of controlled laboratory investigations in understanding cyclic stress response and pore-pressure generation mechanisms.

A second cluster groups seismological and hazard-related terms such as *earthquake magnitude*, *peak ground acceleration*, and *seismic response*, representing studies that translate ground-motion characteristics into equivalent cyclic loading conditions for liquefaction triggering assessment.

The third cluster includes geological and environmental concepts such as *sediments*, *paleoseismicity*, and *soft-sediment deformation*, highlighting the importance of field evidence and stratigraphic interpretation in reconstructing past seismic events.

The coexistence and strong interconnection between these clusters demonstrate that modern liquefaction research integrates soil mechanics, earthquake engineering, and geological analysis within a unified framework.

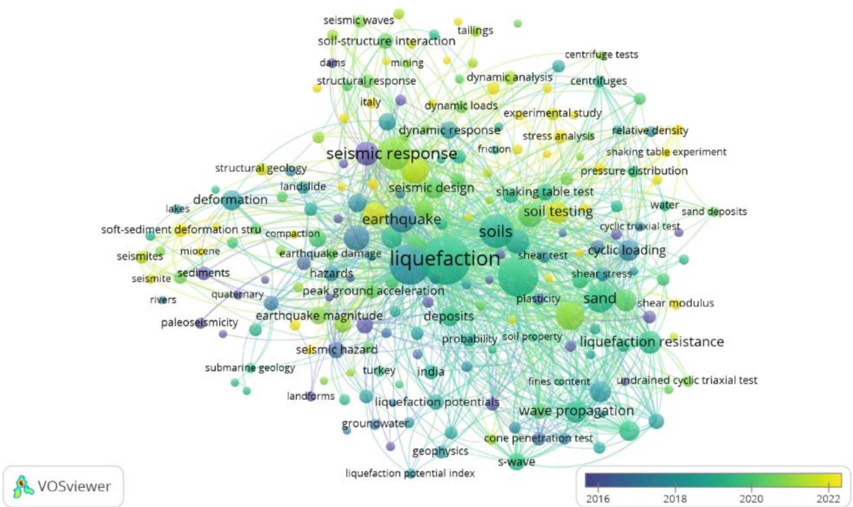

Figure 4: Keyword co-occurrence and thematic structure

Journal of Information Systems Engineering and Management
2026, 11(2s)
e-ISSN: 2468-4376
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3.4 Global bibliographic network of documents:

The bibliographic coupling network (Figure 5) provides insight into the structural organization of the scientific literature through relationships established between frequently co-cited documents. In this network, node size reflects citation influence, while link density represents thematic proximity among studies.

Several highly influential works emerge as central nodes, including Moss (2006), Obermeier (1996) [7], [12], [13], Bažant (2010), Judd (2007), Boulanger (2016), Dashti (2010), and Fan (2019). The prominence of these references indicates their integrative role in connecting multiple research directions related to liquefaction potential assessment, cyclic loading behaviour, and earthquake case-history analysis.

Older contributions, particularly Obermeier (1996), Vucetic (1994), and Hempton (1983), form the historical core of the network. These studies established fundamental interpretations of liquefaction-induced deformation and paleoseismic indicators, which continue to underpin contemporary research. Their persistent centrality demonstrates the long-term stability of foundational concepts within the field.

More recent publications, including Fan (2019) and Debbarma (2017), appear within younger clusters characterized by shorter citation paths and higher temporal proximity. These works are associated with advances in numerical modelling, centrifuge experimentation, and machine-learning-based prediction approaches. The spatial transition from older to newer nodes within the network therefore reflects a gradual evolution from empirical and observational studies toward predictive and computational frameworks.

Overall, the dense connectivity among clusters suggests that liquefaction research remains a cohesive domain in which experimental investigations, numerical modelling, and field observations are strongly interdependent rather than forming isolated research streams.

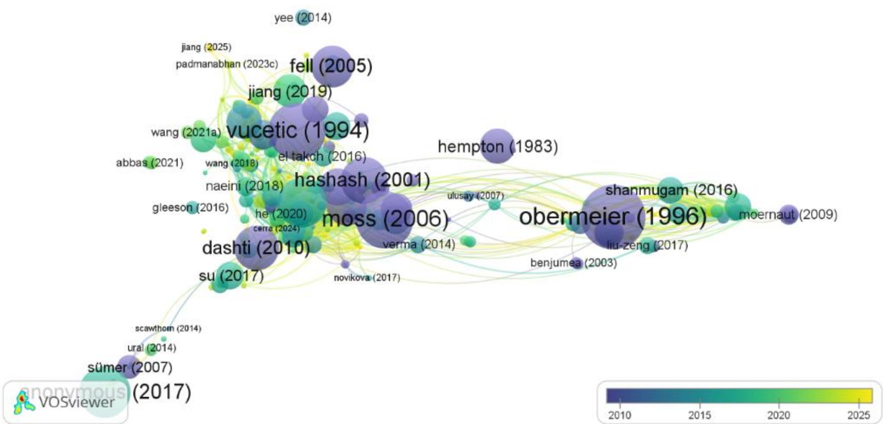

Figure 5: Bibliographic network of documents

3.5 Co-citation network of core references:

The co-citation network (Figure 6) highlights the intellectual structure governing knowledge development in liquefaction research by identifying references that are frequently cited together within the scientific literature.

A primary cluster includes Vucetic (1994), Hashash (2001), Dashti (2010), Naeini (2018), and Jiang (2019), representing studies focused on cyclic soil behaviour, pore-pressure generation mechanisms, and soil–structure interaction under dynamic loading. The strong co-citation relationships within this group indicate that laboratory testing and constitutive modelling remain central methodological approaches for interpreting liquefaction phenomena.

A second distinct cluster is dominated by the works of Obermeier (1996, 2005) and related USGS reports, which emphasize the interpretation of liquefaction-induced geological features such as sand blows and dikes for

Journal of Information Systems Engineering and Management
2026, 11(2s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/
Research Article

paleoseismic analysis [12], [14]. These references provide essential links between geotechnical engineering and geological earthquake reconstruction, particularly in regions lacking instrumental seismic records.

Bridging contributions, including Fell (2005), Scawthorn (2014), and Sumer (2007), connect these two major knowledge domains by integrating engineering risk assessment with observed field performance of infrastructure in liquefiable soils. The presence of these intermediary nodes demonstrates that liquefaction research increasingly combines theoretical modelling with applied hazard evaluation.

The co-citation structure therefore reveals two complementary intellectual pillars: (i) laboratory and constitutive modelling approaches aimed at quantifying cyclic resistance, and (ii) geological and paleoseismic investigations used to interpret earthquake history and ground-motion intensity [25]. The persistence of both pillars highlights the interdisciplinary character of the field.

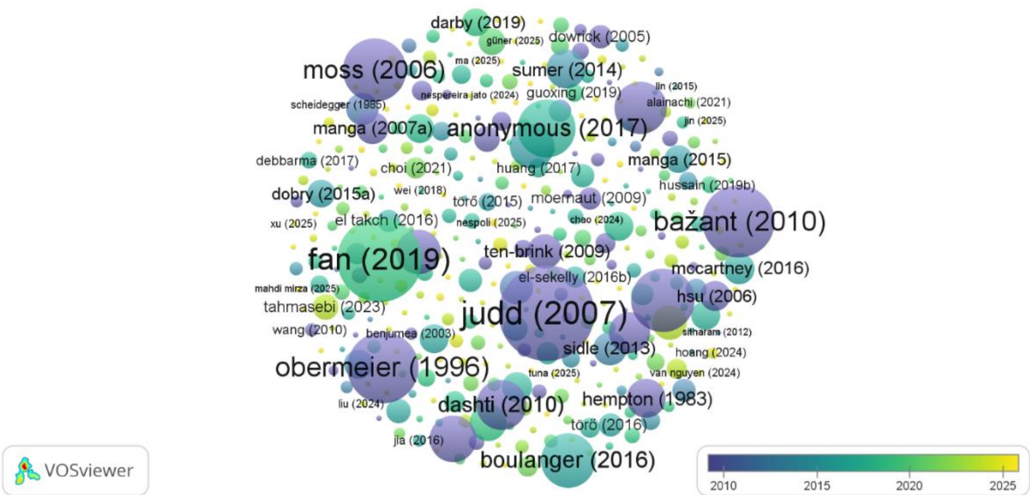

Figure 6: Co-citation network

The persistence of these interconnected reference clusters suggests that liquefaction research has evolved through cumulative knowledge integration rather than disciplinary fragmentation, indicating a mature scientific field supported by stable theoretical foundations.

3.6 International collaboration network:

The international collaboration network (Figure 7) illustrates the global distribution of scientific cooperation through co-authorship relationships among countries involved in liquefaction research.

The United States appears as the dominant central node, maintaining strong collaborative links with China, Canada, Japan, India, Turkey, and several European countries. This central position reflects both the historical leadership of U.S. institutions in developing liquefaction assessment methodologies and their continued involvement in international research programs and guideline development.

China, India, and Italy form large nodes with relatively recent average publication years, indicating rapid expansion of research activity driven by urban development in seismically active regions and increasing investment in experimental and computational geotechnics. These countries contribute significantly to recent advances in constitutive modelling and energy-based liquefaction assessment approaches.

European countries—including the United Kingdom, Germany, the Netherlands, Denmark, France, and Poland—form a dense regional cluster characterized by strong intra-European collaboration. Such connectivity likely reflects coordinated research initiatives and shared interest in seismic risk mitigation strategies.

Emerging nodes such as Iran, New Zealand, South Korea, Hong Kong, Chile, Egypt, and Greece demonstrate the growing diversification of research contributions. In several cases, increased publication activity appears linked to

Journal of Information Systems Engineering and Management
2026, 11(2s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/
Research Article

regions that have experienced significant earthquake-induced liquefaction events, suggesting that major seismic disasters act as catalysts for international collaboration and scientific development.

The temporal colour distribution (2016–2022) further indicates an intensification of global collaboration during the last decade, consistent with the broader globalization of earthquake engineering research and increased data sharing across scientific communities.

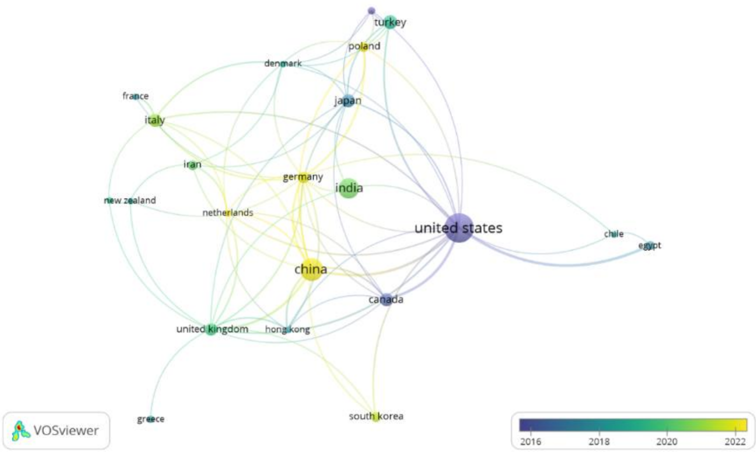

Figure 7: International collaboration network

3.7 Experimental results: pore-pressure evolution:

Figure 8 presents the evolution of excess pore pressure ratio Ru as a function of the number of loading cycles under regular cyclic loading conditions (CSR = 0.69, σc′=100 kPa).

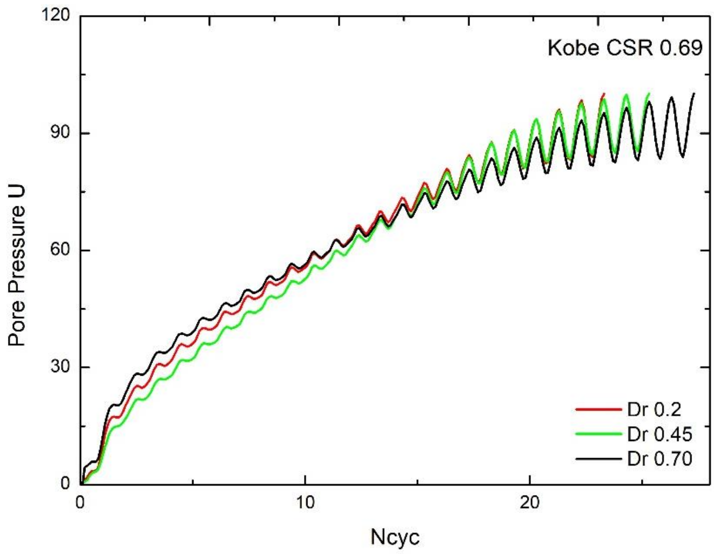

Figure 8: Evolution of pore pressure during loading (Kobe csr 0.69) versus Ncyc for a confining pressure of 100 kpa.

All specimens exhibit progressive pore-pressure accumulation characteristic of contractive sand behaviour under cyclic loading [5], [15], [19]. The loose specimen (Dr = 20%) shows rapid pore-pressure generation, reaching the liquefaction criterion (Ru ≈ 1) after approximately 23 cycles. Increasing relative density results in pore-pressure build-up, with liquefaction occurring after 25 and 27 cycles for Dr = 45% and 70%, respectively (**table 1**).

Table 1. Summary of the response of specimens subjected to regular cyclic loading.

N°	Nom	CSR	f (Hz)	DR (%)	B (%)	σ'c (Kpa)	Nc
1	Kb-0.20-reg	0.69	1.44	20	98	100	23
2	Kb-0.45-reg	0.69	1.44	45	96	100	25
3	Kb-0.70-reg	0.69	1.44	70	98	100	27

Although the increase in cycles to liquefaction remains moderate, the observed trend indicates enhanced cyclic resistance with increasing density. The limited variation in Nc may be attributed to the high applied cyclic stress ratio (CSR = 0.69), which induces severe loading conditions that reduce the influence of density differences on liquefaction resistance [1], [2].

The agreement between experimentally observed pore-pressure evolution and the dominant laboratory-testing cluster identified in the bibliometric analysis demonstrates how bibliometric mapping can effectively guide targeted experimental investigations, linking global research trends with site-specific soil behaviour .

4. DISCUSSION:

4.1 Evolution of liquefaction research paradigms :

The temporal growth identified in this study reflects more than a simple increase in publication output; it indicates a structural transformation in the scientific approach to liquefaction assessment. Early research phases were largely dominated by post-earthquake observations and empirical triggering correlations, as reflected by the limited publication activity prior to the late 1990s. The progressive increase observed after 2000 corresponds to the consolidation of semi-empirical procedures supported by expanding case-history databases.

The rapid acceleration after 2015 suggests a transition toward predictive and performance-based frameworks integrating numerical modelling [28], probabilistic assessment, and data-driven methodologies. This evolution demonstrates a paradigm shift from reactive analysis of past seismic events toward proactive risk evaluation and forecasting approaches. The interdisciplinary distribution of subject areas further confirms that liquefaction research has evolved into a hybrid domain linking geotechnical engineering, seismology, and computational sciences.

4.2 Global collaboration and seismic-driven research dynamics :

The international collaboration patterns reveal that scientific production in liquefaction research is strongly influenced by seismic exposure and technological capacity. The central role of the United States reflects its historical leadership in developing liquefaction triggering methodologies and large experimental research programs. Meanwhile, the rapid growth of China and India indicates an ongoing geographical redistribution of research activity associated with urban expansion in seismically active regions.

The emergence of countries such as Chile, New Zealand, and Turkey highlights the role of major earthquake events as catalysts for scientific collaboration and knowledge exchange. These findings suggest that liquefaction research evolves through cycles of seismic events followed by intensified investigation phases, reinforcing the applied and hazard-driven nature of the discipline.

4.3 Intellectual structure and knowledge integration :

The co-citation analysis demonstrates that liquefaction research is structured around two complementary intellectual pillars. The first pillar focuses on laboratory characterization and triggering procedures [2], [3],[20], represented by the works of Idriss, Boulanger, and Moss, which provide the methodological foundation for engineering practice. The

Journal of Information Systems Engineering and Management
2026, 11(2s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/ **Research Article**

second pillar, associated with Obermeier's contributions, emphasizes geological evidence and paleoseismic interpretation [24].

The persistence of these interconnected clusters indicates cumulative knowledge development rather than disciplinary fragmentation. Modern research integrates constitutive soil behaviour, field observations, and seismic hazard analysis into unified assessment frameworks. Bridging studies linking infrastructure performance and hazard evaluation further illustrate the increasing convergence between theoretical and applied research domains.

4.4 Linking bibliometric trends with experimental observations :

A key contribution of this study lies in connecting global research trends identified through bibliometric analysis with experimentally observed soil behaviour. The keyword co-occurrence analysis identified laboratory cyclic testing as one of the dominant thematic clusters within liquefaction research. The cyclic triaxial experiments performed on the Algerian coastal sand provide a physical illustration of this central research focus.

The experimental results demonstrate progressive pore-pressure accumulation and density-dependent liquefaction resistance, consistent with mechanisms widely reported in cyclic soil mechanics studies [5], [6], [15], [21]. The relatively limited variation in cycles to liquefaction observed under high CSR conditions suggests that severe cyclic loading reduces the influence of density differences, emphasizing the dominant role of stress amplitude under strong seismic demand.

By aligning experimental findings with bibliometric thematic structures, the study illustrates how science mapping can guide targeted laboratory investigations and help contextualize local soil behaviour within global research trends. This integrated approach highlights the potential of combining bibliometric analysis with experimental validation as a methodological framework for future geotechnical research.

5. CONCLUSION:

This study presented an integrated bibliometric and experimental investigation of soil liquefaction research under cyclic loading in high-seismicity regions over the period 1980–2025. By combining quantitative science mapping with laboratory testing, the research provides both a global perspective on the evolution of scientific knowledge and a physical illustration of liquefaction behaviour using a natural Mediterranean coastal sand.

The bibliometric analysis reveals a sustained expansion of liquefaction research over the last four decades, with a pronounced acceleration after 2015 marking a transition toward predictive, performance-based, and data-driven approaches. The disciplinary distribution confirms the inherently interdisciplinary nature of the field, positioned at the intersection of geotechnical engineering, seismology, and geological sciences. Collaboration networks highlight the central influence of historically leading countries while also demonstrating an ongoing geographical diversification driven by seismic exposure and technological development.

Science mapping results indicate that contemporary liquefaction research is structured around interconnected intellectual pillars combining semi-empirical triggering procedures, laboratory cyclic testing, and geological evidence derived from paleoseismic investigations. The persistence of these complementary approaches suggests that advances in liquefaction assessment emerge through cumulative knowledge integration rather than methodological replacement.

The experimental investigation conducted on an Algerian coastal sand provides a site-specific illustration of the dominant laboratory-testing theme identified bibliometrically. Cyclic triaxial results demonstrate progressive pore-pressure generation and density-dependent liquefaction resistance, while highlighting the reduced influence of density under high cyclic stress ratios representative of strong seismic loading. These findings confirm the consistency between global research trends and locally observed soil behaviour.

Beyond individual findings, the study proposes a methodological perspective in which bibliometric analysis can be used to identify research gaps and guide targeted experimental investigations. This combined framework offers a pathway for linking global scientific evolution with regional geotechnical characterization, particularly for underrepresented geological contexts such as Mediterranean coastal environments.

Journal of Information Systems Engineering and Management
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Future research should focus on expanding experimental databases in geographically underrepresented regions, integrating site-specific observations with probabilistic and data-driven models [8], [16], and strengthening the coupling between laboratory experimentation, field evidence, and large-scale bibliometric insights. Such integration is essential for improving predictive capability and enhancing resilience against earthquake-induced soil liquefaction.

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