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A Thematic Review of Seismic-Induced Slope Instability and Road Robustness Research in the Philippines

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Abstract: *This study presents a bibliometric analysis of global and local research related to seismic-induced slope failures and the robustness of road networks, with a focus on the Philippines. Using the Scopus database, 548 relevant publications from 2000 to 2025 were analyzed through VOS viewer and Bibliometric to identify thematic trends, research clusters, and geographic representation. Results reveal that while geotechnical modeling and rainfall-triggered landslides are well-studied, integration with infrastructure resilience remains limited. Additionally, Philippine-specific research is significantly underrepresented, comprising only 1.3% of the dataset. Key concepts such as robustness and transportation functionality are often treated in isolation from slope stability studies. This thematic and methodological gap highlights the need for interdisciplinary frameworks that combine geotechnical reliability with performance-based infrastructure assessments tailored to hazard-prone environments like the Philippines.*

Keywords: Seismic-induced landslides, Slope stability, Road network robustness

1. INTRODUCTION

The Philippines is among the most seismically active regions in the world because of its proximity within the Pacific Ring of Fire. Its mountainous terrain and frequent seismic activity, makes the road networks within the region particularly vulnerable to seismic-induced landslides [1]. Historically, disasters such as the 1990 Luzon earthquake have highlighted the need for slope stability in maintaining the functionality of a road during seismic events. However, despite the existing vulnerabilities, there is still fragmentation on the understanding of how seismic events affect the robustness of road slopes, especially within a Philippine context. It necessitates a systematic exploration of the existing knowledge base through bibliometric analysis to identify critical gaps and guide future engineering research in terms of geotechnical and transportation engineering.

Seismic-induced slope failures along road networks not only disrupt the flow of transportation but also delay emergency response and recovery efforts during times of crisis [2,3]. Traditional geotechnical studies have focused extensively on local slope stability analysis, utilizing models such as Newmark's sliding block method to predict potential displacements on various forms of surfaces. The concept of robustness in geotechnical engineering, revolves around the ability of embankments and natural slopes to maintain stability despite the effect of seismic loading [4]. Robustness is an aspect of resilience, which focuses primarily on damage mitigation rather than post-failure recovery. In the context of Philippine Road slopes, assessing robustness involves the integration of seismic displacement models, site-specific geotechnical data, and transportation network analysis. Meanwhile, literature regarding transportation engineering has separately assessed network vulnerability in terms of traffic flow disruptions and critical node failures [5]. A gap persists between the corridors of both fields as researchers from each field would understandably focus on aspects that are related to their discipline. The lack of integration underlines the need for a multidisciplinary approach to evaluate and improve the seismic resilience of road infrastructures in the Philippines.

A review of previous works using bibliometric methods reveals that most studies prioritize rainfall-induced landslides over seismic causes. Furthermore, international literature heavily dominates the field, with limited studies contextualized for the Philippines. However, there are studies such as Paringit et al. (2020) have made notable contributions to landslide susceptibility mapping in Baguio City but emphasized rainfall as the primary trigger [6]. Research on the specific intersection of seismic impacts, slope stability, and road robustness within the country remains sparse, suggesting a significant opportunity for targeted geotechnical exploration tailored to the local seismic and geological conditions [7-9]. There have been few comprehensive bibliometric analyses regarding the topic that systematically maps the current body of knowledge, trends, and research gaps in the field within the Philippine setting. Given the prevalence of gaps on the field of topic, this paper seeks to bridge that gap.

The bibliometric analysis is conducted to map the evolution of research concerning seismic impacts on slope stability and the robustness of road networks, particularly within the context of the Philippines. By identifying trends, thematic clusters, and underrepresented areas in the literature, the study offers a structured understanding of where the current body of knowledge stands and where critical gaps persist. The bibliometric analysis aims to support the development of a research framework that reflects both innovative global practices and a multidisciplinary approach that applies

both transportation and geotechnical realities in the Philippines. The use of a targeted review of international and local sources and the utilization of bibliometric programs such as VOSviewer and Bibliometric allows the research to determine which gaps could be filled between the integration between geotechnical and transportation resilience studies in the Philippine setting. This systematic approach would allow for more unified and data-driven approaches in future geohazard-focused infrastructure research.

2. METHODS

This study adopted a structured process to properly conduct the bibliometric analysis in exploring trends and research directions on seismic-induced slope failures and the robustness of road networks. Data acquisition was conducted using one primary database—Scopus, which was selected for their broad coverage of peer-reviewed literature in geotechnical and infrastructure engineering in terms of abstracts and citation databases. An advance search was carried out using combinations of keywords including *"seismic" OR "landslide" OR "Philippines"* and *"road network" OR "slope stability" OR "robustness"*, applied specifically to article titles. Specific Boolean operators "AND" and "OR" were strategically used to refine results and focus the dataset on studies relevant to the topic. The publication range was also set to be limited from 2000 to 2025 to capture the recent advancements in seismic slope stability and transportation resilience within a realistic time frame.

Following the search, a manual screening process was applied to refine the results. Selection criteria for literature inclusion were carefully established to maintain objectivity and technical rigor. Articles were only included if they involved seismic slope analysis, road network impacts, or methodologies transferable to Philippine terrain. Abstracts and titles were reviewed to confirm its relevance to the topic before downloading full texts for detailed analysis. Bibliographic metadata—such as authorship, publication year, keywords, source title, and geographic focus—were also considered as these data were extracted and organized to facilitate further processing.

The extracted data were processed using VOSviewer, a tool designed for bibliometric visualization and analysis. The software was used to develop keyword co-occurrence maps, author collaboration networks, and thematic clusters to visualize the relationships between research topics. Keyword frequency and link strength were analyzed to identify core research areas and emerging themes. Overlay, network, and density visualizations were also produced to observe the temporal evolution and relative concentration of research activity across different topics. Thematic groupings helped clarify which areas were well-established versus those that were underexplored.

In addition to co-occurrence and clustering analysis, the same dataset will be subjected to a thematic analysis using the Bibliometric package via RStudio. Bibliometric enables advanced statistical evaluation of bibliographic metadata, offering tools such as thematic evolution, conceptual structure mapping, and strategic diagrams. This analysis will help identify the development, centrality, and maturity of specific research themes over time. Unlike VOSviewer, which emphasizes network visualization, Bibliometric provides structured outputs that quantify the significance and interrelationships of emerging and established topics. These two tools will be used in conjunction to ensure both visual and statistical robustness in identifying trends within the field of seismic slope stability and road infrastructure resilience.

The following flowchart illustrates the phases that were utilized in conducting the bibliographic analysis of the topic. It includes the data collection, parsing, analysis, and interpretation. The flowchart was primarily derived using existing bibliographic analysis methodologies such as Fernandez et al. (2024) [10].

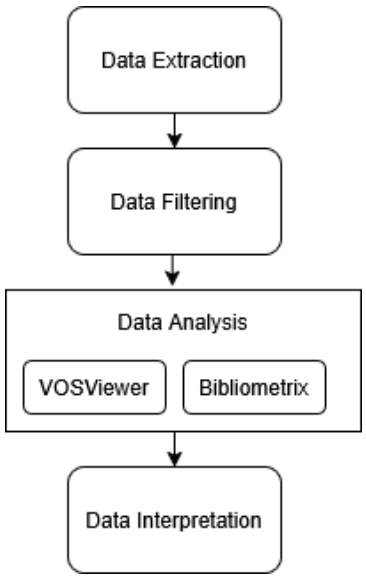

Fig. 1 Methodology of the Research

The cleaned and curated dataset served as the foundation of the bibliometric analysis. Initial preparation involved standardizing metadata formats and ensuring completeness of the records, particularly for author names, keywords, and publication years. The filtration of data was done in the data filtering phase, which allowed consistent input across the two software tools used for analysis: VOSviewer and Bibliometric. Both tools were applied concurrently to maximize the analytical depth of the study. The objective was to identify not only keyword patterns but also broader research structures and thematic progressions relevant to seismic slope stability and road infrastructure resilience.

VOSviewer was utilized for its capabilities in visually mapping bibliometric relationships and presenting them in an intuitive network format. The co-occurrence analysis function also generated keyword maps based on term frequency and co-appearance across records. Clustering features helped group related research terms into thematic categories. Next, overlay visualization was used to track the chronological emergence of these topics from 2000 to 2025. These visualizations in essence helped uncover the relationships topics within the engineering fields such as from foundational research topics to rapidly developing subtopics. The insights

developed were used to identify core and peripheral themes within the literature.

Simultaneously, the same dataset was subjected to thematic analysis using the Bibliometric package in RStudio. Bibliometric enabled the construction of strategic diagrams, conceptual structure maps, and thematic evolution plots to statistically evaluate research maturity and centrality. Thematic quadrants were interpreted using density and centrality values to classify topics into motor, niche, basic, or emerging themes. Moreover, thematic evolution analysis segmented the timeline to show how research priorities shifted over multiple year intervals. The analysis provided by Bibliometric gives supplementary support in setting a more structured and quantitative understanding of research development patterns as it complements the network-oriented visuals produced by VOSviewer.

To ensure reliability, the outputs of both programs were systematically cross validated. Keyword frequency trends, thematic clusters, and evolution trajectories from VOSviewer were compared against those generated in Bibliometric. The discrepancies between the outputs are reported and manually reviewed of relevant metadata and full-text articles/ These validation checks ensure consistency in the interpretation of the literature landscape to provide a clear and accurate summary of the entire research workflow.

3. RESULTS

3.1 VOS Viewer Results

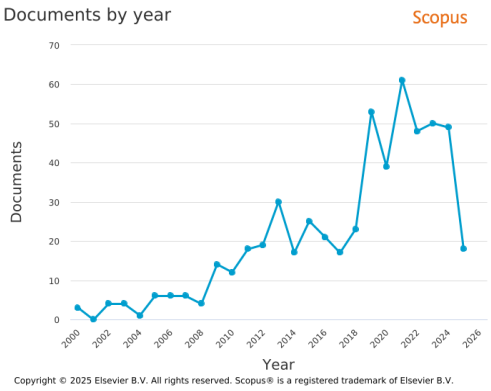

Fig. 2 Total Documents from 2000 to 2025

Using the analysis function of Scopus, initial bibliometric analysis was conducted, where it was found that a total of 548 publications were produced from 2000 to 2026. These articles addressed topics related to seismic hazards, landslides, slope stability, and road networks. From Figure 2, it is seen that there is a clear upward trend in the frequency of publication of articles over the past decade with the peaks being reported in 2019 and 2021 as it recorded 53 and 61 publications respectively. The trend indicates that there is growing global interest in geohazard-related infrastructure resilience. However, Philippine-specific studies comprised only 1.3% (7 journal articles) of the entire dataset, reflecting a potential gap in locally contextualized research. This imbalance emphasizes the need for scholarly pursuits on slope hazards and infrastructure vulnerabilities specific to the Philippines as there is a potential disconnect between national geotechnical risks and the current direction of international research output. Addressing this disparity between local and global research could improve the applicability and impact of geohazard mitigation strategies for developing countries.

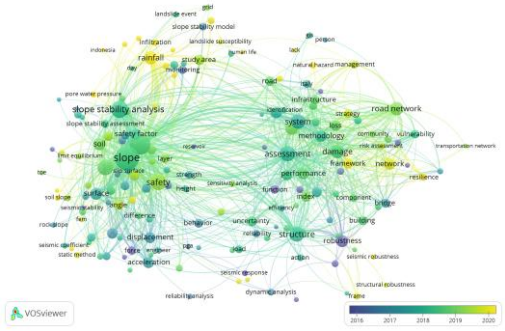

Fig. 3 Overlay Visualization

The overlay visualization map indicates the temporal distribution of research themes by illustrating when specific keywords gained prominence over the periods of 2016 to 2025. The transition of colors from blue to yellow indicates newer terms that have been emphasized in recent studies while earlier studies are indicated by dark shades of blue and green. It was found to cluster around the foundational keywords such as "slope," "rainfall," and "failure". It suggests an initial focus on general hazard characterization and rainfall-induced landslide mechanisms. On the other hand, keywords that are shaded in yellow represent newer areas of interest that have been gaining attention in recent years, these include "resilience," "infrastructure," and "transportation". However, as these terms are relatively new, it appears sparsely and based on the periphery of the network; the integration of both fields have been underdeveloped. The visualization reinforces the earlier observation that while slope stability and rainfall hazards have been well-explored, the explicit linkage to road networks and resilience frameworks remains limited and relatively recent. This supports the argument that research on infrastructure robustness and multidisciplinary hazard modeling is still in its emergent stage, especially in contexts relevant to the Philippines.

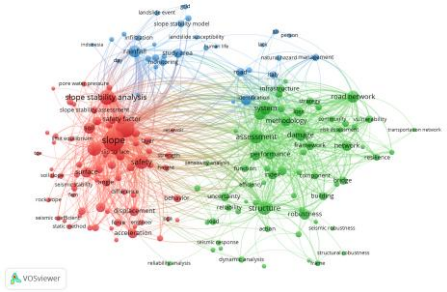

Fig. 4 Network Visualization

In terms of the network visualization, a notable pattern emerged in the relationship between road network analysis and other key topics. The terms such as “infrastructure," "road network," and "transportation" appeared most frequently in the methodology cluster, often linked to simulation or network performance

metrics. However, these road-related terms demonstrated limited co-occurrence with geotechnical or slope-specific keywords, such as “displacement” or “stability.” It suggests that existing studies on infrastructure resilience operate independently of detailed geotechnical analysis, resulting in siloed research domains. This gap is a concern for countries such as the Philippines because of its geographical features where mountainous roads are directly affected by seismic and landslide hazards. The results imply that future research must deliberately integrate both slope mechanics and transportation systems modeling. The integration of both fields would enable development of predictive tools capable of evaluating both the physical and functional impacts of seismic slope failures.

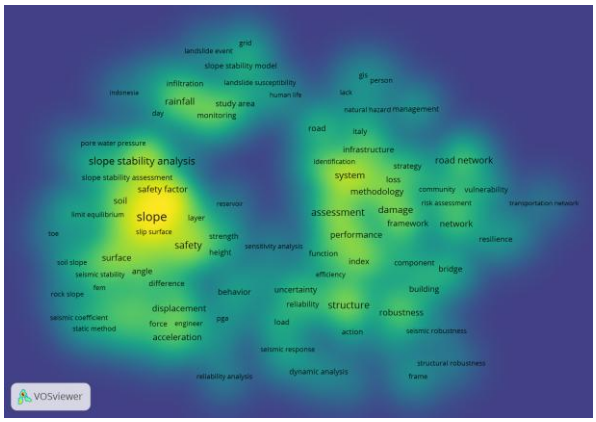

Fig. 5 Density Visualization

Another notable observation from the VOSviewer output was in terms of its density visualization. The mapping indicated the limited use of resilience-oriented terminology across the dataset. Words like “resilience,” “robustness,” and “adaptability” were not as bright compared to foundational keywords, which means that topics involving these concepts were largely confined to papers discussing broader urban systems or general infrastructure frameworks. Moreover, there were few instances where these terms were directly linked to slope-specific studies or quantitative geotechnical analyses. It indicates that resilience, as a measurable attribute of slope performance under seismic loading, remains underexplored. The lack of integration suggests that current research stops at the level of hazard characterization without progressing toward performance-based assessment or post-event functionality evaluation. The absence of robustness indicators represents a missed opportunity for advancing infrastructure design in seismic zones. Future researchers could implement the use of resilience metrics—such as performance degradation curves, residual capacity models, or system-level robustness indices—to significantly enhance the relevance and applicability of slope stability studies, especially in guiding long-term infrastructure investments and disaster risk reduction strategies.

3.2 Bibliometric Results

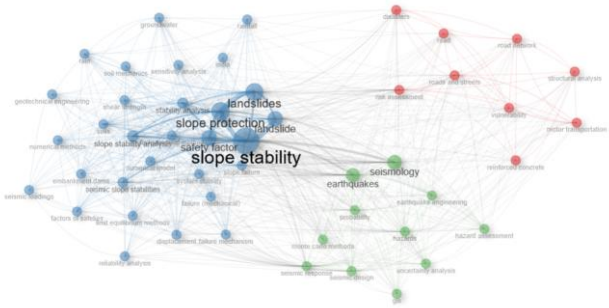

Fig. 6 Co-occurrence Network

The results largely reinforce the findings observed in the VOSviewer co-occurrence maps. The conceptual structure map revealed a similar thematic clustering pattern, wherein topics naturally divided into three main subfields: geotechnical slope analysis, methodological development, and rainfall-induced landslide studies. These clusters echo the same fragmentation noted in earlier analysis as methodological and analytical advancements were separated from applied infrastructure or slope performance research. The keywords the keywords "slope stability," "landslide," and "rainfall" dominated one cluster, while terms like "modeling," "risk assessment," and "approach" formed another. The third thematic group, though smaller, was composed of resilience-adjacent terms such as “infrastructure” and “transportation,” often distantly located in the conceptual map. The spread in keyword positioning suggests that integration between slope mechanics and road network robustness remains conceptually inefficient within the current literature.

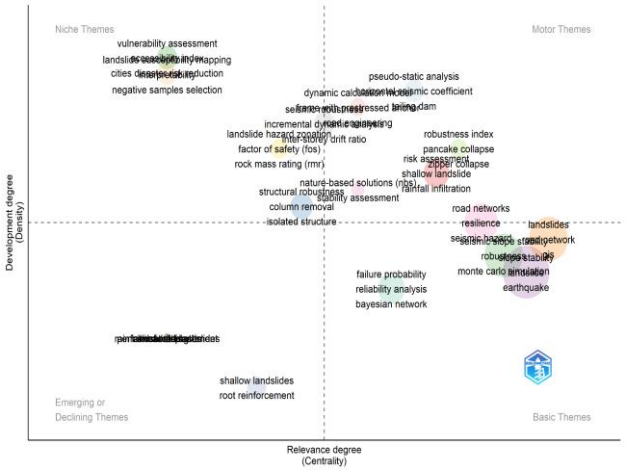

Fig. 7 Thematic Map

On the other hand, the thematic map generated through Bibliometric categorized research themes in the field of slope stability according to their relevance and development. The upper-right quadrant, known as the motor themes quadrant, contains topics that are both well-developed and highly connected to other areas of study. The core research themes were found to be “landslides,” “slope stability,” “rainfall infiltration,” and “risk assessment”, which are prominently positioned in the map. These topics are placed in the section of the map because these have consistently drawn academic

attention and are embedded within multiple research streams, indicating their significance to geotechnical engineering and hazard analysis. The strong presence suggests that these areas benefit from a robust methodological foundation, frequent citation, and interdisciplinary relevance. In particular, the inclusion of rainfall-induced landslides reflects growing concern over climate-related triggers in slope failures. Therefore, this quadrant represents the intellectual backbone of current landslide-related research.

In contrast, topics related to resilience such as “robustness,” “resilience,” “transportation network,” and “robustness index” are placed in a different position within the thematic map as it is positioned away from the motor themes quadrant, which falls into the niche or emerging/declining areas. Niche themes like “vulnerability assessment” and “landslide susceptibility mapping” are internally developed, but they lack strong connections to other themes, which implies limited cross-disciplinary integration. Another location of interest is the placement of resilience-centric topics near the lower quadrants, which are indicative of either underdeveloped or declining interest. It reveals that although resilience is conceptually important, it has not yet achieved broad recognition or application within the core geotechnical literature. The theme of “robustness,” for example, appears isolated and peripheral, indicating that it is still seeking theoretical coherence within the field of geotechnical engineering. These findings highlight an imbalance in existing literature, where structural and probabilistic analyses dominate, while resilience concepts remain marginal.

The absence of resilience-related topics from the motor themes quadrant reinforces the observation that infrastructure resilience within geotechnical contexts is still in its formative stages. Despite the increasing frequency of extreme weather events and the clear need for adaptive infrastructure systems, academic research has not yet fully aligned with these practical demands. It suggests an opportunity for further exploration, specifically in linking traditional slope stability models with resilience frameworks that address system adaptability, redundancy, and robustness.

4. DISCUSSION

The results of the bibliometric and visual analyses highlight evidence of clear imbalance in current slope stability research. Most studies concentrate heavily on core geotechnical issues such as landslide mechanisms, rainfall infiltration, and hazard assessment. These themes, situated in the motor quadrant of the thematic map, indicate well-established and actively evolving areas. However, the limited representation of resilience-related keywords, especially in geotechnical applications, suggests that the existing literature has yet to prioritize infrastructure robustness and long-term performance. While slope failures and hazard assessments are extensively documented, their integration with infrastructure serviceability and recovery potential remains insufficient. This points to a narrow focus in current research, largely centered on hazard characterization rather than system adaptation and recovery.

A deeper issue revealed by the results of the VOS Viewer is the thematic fragmentation across the literature. The keyword clusters and network maps show that road network analysis, geotechnical modeling, and rainfall-induced landslides are often studied in isolation. This siloed approach restricts the development of comprehensive models that can assess how slope failures directly impact critical infrastructure like road systems. In particular, the low co-occurrence of transportation-related terms with slope-specific metrics such as "displacement" or "stability" highlights a disconnect between geotechnical modeling and infrastructure functionality. As mentioned in the previous chapters for countries like the Philippines—where transportation systems traverse mountainous, hazard-prone terrain—this disjointed research landscape may hinder the development of integrated risk mitigation strategies. Bridging this gap would allow for more effective disaster preparedness and design interventions.

Another finding that was evident was the minimal representation of Philippine-specific research within the dataset, reflecting a geographic disparity in scholarly output. Although the country is highly vulnerable to seismic and rainfall-induced slope hazards, only a small fraction of the 548 articles retrieved addressed this context. The term "Philippines" rarely appeared alongside technical modeling terms, indicating that advanced geotechnical methods have not been widely applied to local case studies. This lack of contextual application hampers the relevance of international findings to the Philippine setting. Increasing domestic research efforts—particularly those that incorporate modern modeling approaches and resilience metrics—would not only localize global methodologies but also inform targeted policy and infrastructure planning.

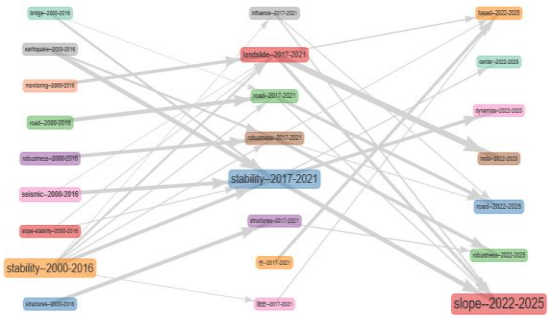

Fig. 8 Thematic Evolution Map

The thematic evolution map shows how important research themes in the areas of slope stability, seismic hazards, and infrastructure resilience have developed and are related between 2000 and 2025. Most of the literature during the first phase concentrated on fundamental subjects like “stability,” “earthquake,” “monitoring,” “bridge,” and “slope stability.” These terms represent traditional engineering concerns that prioritize hazard identification and structural integrity, with little regard for wider system-level effects. It is evident that the main idea of "stability" acted as a significant anchor, linking to several technical terms that influenced the field's early development. One interesting thing to note is that "road" and "robustness" had already surfaced at this point,

despite having weak links to other subjects. This suggests that infrastructure performance was of limited interest at first.

A change in scholarly priorities was indicated by the thematic structure's diversification between 2017 and 2021. With strong connections to "landslide," "road," "robustness," and "structures," the keyword "stability" emerged as the new central hub, indicating a growing interest in combining traditional geotechnical analysis with infrastructure-related factors, like the performance of road networks during slope failures. The advent of "robustness" indicates that during this time, researchers started taking performance-based metrics into account when assessing structural systems that were subject to geohazards. Likewise, the closer relationship between "road" and "landslide" points to a more application-focused focus in the literature. However, while these links represent progress toward integration, the thematic structure still shows clustering rather than full conceptual blending, indicating that geotechnical and infrastructure themes were still often explored in parallel rather than in unison.

The last section of the thematic map is the most recent period (2022–2025), which demonstrates a continued evolution toward more specialized and interdisciplinary topics. The keyword “slope” emerged as a dominant theme, now connected with terms like “based,” “center,” “dynamics,” and “India.” This suggests a deeper exploration of localized case studies, dynamic modeling techniques, and computational tools to better understand slope behavior under various loading conditions. Notably, the increased frequency of “robustness” and “road” alongside “slope” reflects an encouraging trend toward holistic modeling—linking physical slope behavior with infrastructure resilience and post-event functionality. The links to “dynamics” and “center” may indicate a methodological shift, with more emphasis on centralized simulation models and dynamic systems analysis. These developments reveal that the existing research landscape of the topic has been maturing because slope stability is no longer treated as an isolated problem, but instead as part of a broader resilience-oriented engineering problem.

The evolution of topics reveals some fragmentation, particularly in connecting geotechnical robustness with transportation functionality. While “robustness” has gained thematic traction in recent years, its limited overlap with earlier periods suggests that it has yet to be deeply embedded in long-standing research traditions. Likewise, while “road” appears in all three periods, the connections remain largely confined to infrastructure-centric clusters rather than geotechnical modeling clusters. This pattern implies that although interdisciplinary language is emerging, true conceptual integration is still developing. For instance, robustness models are often explored independently from dynamic slope analysis, rather than being embedded within it. As such, future research must focus on creating unified frameworks that bring together slope mechanics, infrastructure systems, and resilience modeling under a cohesive methodology.

5. CONCLUSION

The results of the analysis indicate that there is a clear thematic imbalance and fragmentation in the body of research on seismic-induced slope failures and road network robustness, according to the bibliometric analysis done for this study. Most studies continue to concentrate on conventional geotechnical concerns like slope stability, landslides, and rainfall infiltration, despite recent trends suggesting that the global literature shows an increasing focus on geohazard-related infrastructure issues. Because of their importance to hazard research, these areas are well-developed and frequently show up in the motor themes quadrant. However, because it is rarely combined with in-depth geotechnical modeling, infrastructure robustness and resilience continue to be peripheral subjects.

The limited co-occurrence of pertinent keywords such as “stability,” “displacement,” and “road network” further demonstrates the disconnect between the geotechnical and transportation domains. Many studies examine the mechanisms of slope failure without evaluating how these failures affect vital transportation routes, particularly in mountainous areas. This lack of integration is especially troublesome in nations like the Philippines were roads cross dangerous terrain. It hinders the creation of comprehensive predictive models that could guide emergency preparation, infrastructure design, and recovery plans after a disaster.

Although the Philippines faces frequent seismic and rainfall-induced slope hazards, only a small fraction of the analyzed literature directly addresses this context using advanced modeling techniques. Most Philippine-based studies focus on hazard mapping or rainfall-induced landslides, with little incorporation of seismic displacement modeling or infrastructure impact analysis. Bridging the gap is essential to adapt global methodologies to local conditions and to create more context-sensitive approaches for national disaster risk reduction and transportation planning.

Regardless of these gaps, the results also suggest that the field is still in a developmental phase, and opportunities for future advancement remain promising. The peripheral status of infrastructure resilience and robustness in current literature indicates that these are relatively new areas of inquiry, rather than neglected ones. As research priorities evolve and the need for multidisciplinary solutions becomes more apparent, it is likely that future studies will begin to close the gap between geotechnical hazard analysis and infrastructure systems modeling. The emerging appearance of keywords such as “resilience” and “transportation” in more recent publications supports this potential shift. Therefore, the findings of this study should be viewed not only as an assessment of current limitations but also as a roadmap for the future direction of research in seismic slope stability and infrastructure robustness.

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