

# Study on Sinkhole Formation: A Comparative Analysis of Natural Vs Human-Induced Factors

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## Abstract

This study investigates the formation of sinkholes through a comparative analysis of natural geological processes and anthropogenic factors, emphasizing their environmental impacts and implications for urban resilience. Geological contributors such as karst dissolution and subsurface erosion are assessed alongside human-induced triggers like over-extraction of groundwater, construction over unstable ground, and poor drainage management. A structured questionnaire survey was conducted with 14 selected experts from civil engineering, geology, and environmental science fields. Statistical analysis using SPSS and the Frequency Index method revealed that poor drainage systems (100% agreement) and construction without geotechnical assessments (64%) were the most critical human-induced contributors, especially in urban areas. While natural processes were still relevant, their effects were less prominent in developed regions. The findings highlight the necessity of mandatory site investigations, improved drainage planning, and strengthened regulatory frameworks. This study offers practical recommendations for policy makers and engineers to reduce sinkhole risks through sustainable development practices.

## 1. Introduction

Sinkholes are sudden ground collapses that pose serious threats to infrastructure, environmental stability, and public safety (Gutiérrez et al., 2008). They are particularly common in karst landscapes, where the dissolution of soluble rocks such as limestone, gypsum, or dolomite causes underground voids that eventually collapse the surface (Ford & Williams, 2007). These collapses can occur naturally or be triggered by human-induced disturbances, including groundwater withdrawal, construction loads, mining, and poorly managed drainage systems (Waltham et al., 2005; Milanovic, 2000).

Globally, sinkholes have caused significant damage and loss of life. In the United States, Florida has experienced recurring events due to intensive groundwater pumping (Wood, 2023). Italy's Apulia region and China's Guangxi Province have reported similar challenges as urban expansion encroaches on unstable terrain (Nisio et al., 2007; Pappas, 2022). While extensive research has been conducted in Europe, North America, and East Asia, there is relatively less localized research in Southeast Asia, including Malaysia.

In Malaysia, increasing urban development over karst bedrock and frequent rainfall patterns have intensified sinkhole risk. Several incidents, such as the 2024 Kuala Lumpur sinkhole (Ravindran, 2025), have drawn public attention to the urgency of addressing this geohazard. Ahmad Khairut Termizi (2018) documented several sinkhole-prone areas in the Kinta Valley, linking them to human activities and subsurface instability. Despite these events, current mitigation efforts remain fragmented, and geotechnical assessments are often limited to large-scale infrastructure, leaving small developments vulnerable. Recent studies have focused on

sinkhole mapping, hazard modeling, and geophysical methods (Galve et al., 2012; Gutiérrez et al., 2014). However, there is a lack of integrated frameworks that combine expert perspectives with risk-based prioritization of human and natural causes. Moreover, few studies offer comparative insights tailored to the Malaysian context or propose locally relevant mitigation strategies.

Therefore, this study addresses an important gap by assessing sinkhole formation from both natural and anthropogenic dimensions, using structured expert input. The objectives are to identify the environmental effects of sinkhole formation due to both natural and human activities, and to conduct a comparative analysis of these factors to propose effective, expert-informed mitigation strategies. This research contributes to the field by providing region-specific data, improving the understanding of sinkhole risks in Malaysia, and supporting evidence-based planning and prevention in urban development.

## 2. Methodology

This study employed a structured expert questionnaire to investigate the environmental impacts and causative factors of sinkhole formation. The instrument consisted of 15 items divided into four main sections: Part A covered general demographics and expert background (e.g., profession, years of experience); Part B focused on observations and knowledge of sinkhole occurrences and causes; Part C gathered expert judgments through comparative views on natural versus human-induced factors; and Part D explored mitigation strategies and recommendations. This structured format ensured standardized data collection while capturing the informed perspectives of professionals in engineering, geology, and environmental science.

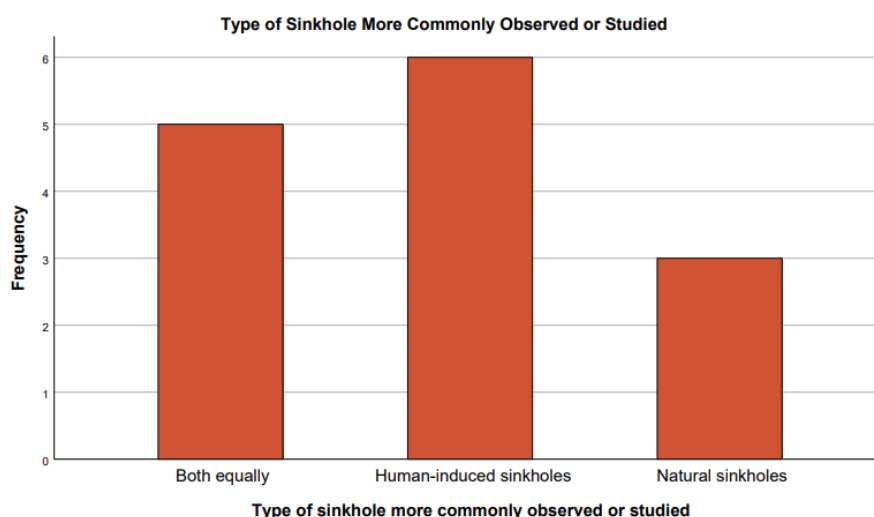
A purposive sampling method was used to select 14 experts with relevant qualifications and practical experience in geotechnical assessments or sinkhole-related issues. This sample size is supported by Banda (2018), who emphasized that expert-based studies typically reach reliable conclusions with a panel of around 12 to 15 respondents. Data were analyzed using SPSS, applying frequency and percentage distributions, alongside the Frequency Index method to rank key contributing and mitigating factors. All experts provided informed consent and were assured confidentiality and anonymity throughout the study.

## 3. Results and Discussion

This section presents the findings from expert responses and literature review, focusing on commonly observed sinkhole types, their contributing factors, and sectoral impacts. A comparative analysis between natural and human-induced causes is discussed, followed by expert-recommended mitigation strategies and insights from open-ended responses.

### 3.1 Observed Factors

Expert responses indicated that human-induced sinkholes were more commonly observed than naturally occurring ones, with 43% of experts selecting this category compared to 21% for natural causes. The remaining 36% believed both occurred equally. This distribution, as illustrated in Figure 1, highlights the dominant role of anthropogenic activities in recent sinkhole incidents. These findings support Galve et al. (2012), who emphasized the sudden and destructive nature of cover-collapse sinkholes in karst environments. The experts' responses reflect conditions commonly found in Malaysian development areas, such as unstable soils, shallow subsurface voids, and unregulated drainage.



**Fig. 1** Bar Chart of Sinkhole More Commonly Observed

### 3.2 Comparative Causative Factors

The analysis revealed that poor drainage systems or water mismanagement was unanimously acknowledged by all 14 experts (100%) as a major human-induced factor in sinkhole formation. Other significant contributors were construction without proper geotechnical investigation (64%) and over-extraction of groundwater (43%). These results align with the work of Waltham et al. (2005), who identified poor drainage and development practices as key drivers of sinkhole formation in urbanized settings. While natural geological processes, such as subsurface erosion and karst dissolution, were also cited, they were generally considered secondary compared to human actions.

### 3.3 Environmental and Sectoral Impacts

Experts highlighted the damage to road infrastructure, underground pipelines, and building foundations as the most visible impacts of sinkhole formation. These risks pose safety concerns and increase long-term maintenance costs for public and private infrastructure. Environmental consequences include soil instability, sediment loss, and changes in groundwater quality. These findings echo those of Gutiérrez et al. (2008), who reported that sinkholes can cause widespread environmental disruption in karst landscapes if not properly mitigated.

### 3.4 Mitigation Strategies

Experts recommended improved geological surveys before construction (93%) and engineering controls such as grouting or soil stabilization (86%) as the most effective methods for minimizing sinkhole risks. These preferences are reflected in Table 1, which summarizes the expert opinions on various mitigation strategies suitable for urban settings. This supports Galve et al. (2012), who emphasized the role of technical interventions and regulatory oversight in reducing collapse potential in susceptible areas. Moderate support was also given to land-use planning and groundwater extraction regulations (both 57%), with public awareness and early warning systems receiving less emphasis (29%).

**Table 1** The Type of Mitigation Strategy Most Effective in Reducing Sinkhole Risks in Urban Areas

Items	Frequency	Percent (%)
Improved Geological Surveys Before Construction	13	93
Regulations on Groundwater Extraction	8	57
Public Awareness and Early Warning Systems	4	29
Engineering Solutions (e.g. grouting, soil stabilization)	12	86
Integrated Land Use and Environmental Planning	8	57

### 3.5 Insights from Open-Ended Responses

Several respondents emphasized the importance of integrated land-use planning and continuous subsurface monitoring. One expert referenced the Kuala Lumpur sinkhole case (2024), linking poor maintenance of underground utilities to the incident. Another recommended referencing international case studies (e.g., Italy, Florida) to build local predictive models.

## 4. Conclusion

This study explored the causes and consequences of sinkhole formation through expert analysis, highlighting the critical roles of both natural geological processes and human-induced activities. The findings confirm that while natural factors such as karst dissolution contribute to sinkhole formation, human activities, particularly poor drainage systems (100% agreement), unregulated development, and construction without geotechnical assessments (64%), were identified as the primary accelerators of sinkhole occurrence and impact, especially in urban areas. The study's key contribution lies in prioritizing sinkhole risk factors and mitigation strategies based on expert consensus, providing a practical reference for engineers, planners, and policymakers. These insights can guide improvements in urban planning, construction regulations, and early warning systems in sinkhole-

prone regions. However, this study is limited to expert opinion and does not include field-based validation or spatial modeling. Future research could incorporate geospatial analysis or on-site investigations to enhance predictive capabilities and validate the identified risk hierarchy.

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## Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

## Author Contribution

The authors confirm contribution to the paper as follows: study conception and design: Ghaayeshthree A/P M. Subramaniam, Mohd Arif Rosli; data collection: Ghaayeshthree A/P M. Subramaniam; analysis and interpretation of results: Ghaayeshthree A/P M. Subramaniam, Mohd Arif Rosli; draft manuscript preparation: Ghaayeshthree A/P M. Subramaniam. All authors reviewed the results and approved the final version of the manuscript.

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