CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2025; 35 (2): 0114-0131
DOI: 10.59440/ceer/202705
Original Research Article

PREVENTION THROUGH DESIGN APPROACH FOR GEOTECHNICAL DESIGN HAZARD RISK REDUCTION

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Abstract

Malaysian construction workers confront high accident rates and sustainability issues due to geotechnical risks. This study determines the significance of geotechnical hazards arising during conceptual design of construction projects and proposes Prevention through Design (PtD) strategies to mitigate the hazards. The mixed-method research uses a questionnaire survey for geotechnical hazards and Focus Group Discussions (FGD) for PtD solutions. The hazards are categorized into seven design aspects namely G1(Soil or ground Instability), G2(Presence of water table/ ground water level), G3(Sloppy area), G4(Soil classification), G5(Flood-prone area and proximity of area to water bodies), G6(Landfill Area) and G7(Area prone to earthquake). Ultimately, adopting PtD can significantly reduce geotechnical hazards, improve safety, and enhance project performance, fostering a safer and more resilient construction industry in Malaysia. The research findings aim to assist Malaysia's Department of Occupational Safety and Health (DOSH) in advancing the integration of PtD principles, as emphasized in the OSHCI(M) Guideline.

Keywords: prevention through design, design for safety, design hazards, risk assessment, construction industry

1. INTRODUCTION

Geotechnical engineering plays an integral role in the planning and execution of building construction projects, particularly in ensuring structural stability and safety. Critical activities within this field, such as foundation construction, excavation, and tunnelling, are often described as series systems, where the failure of one component can compromise the entire process. The sequencing of these activities is

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influenced by prior work processes, which in turn affect subsequent tasks [1]. Geotechnical design focuses on analyzing and designing foundations, earthworks, and underground structures based on the soil and rock properties at the construction site. Proper design minimizes risks associated with soil instability, groundwater issues, and seismic activity, which can lead to delays, increased costs, and even catastrophic failures [2]. Unaddressed hazards during the design phase may compromise structural integrity and pose significant safety risks to construction personnel [3].

In response to these challenges, this research aims to identify and analyze geotechnical hazards during the conceptual design phase and propose feasible Prevention through Design (PtD) solutions. By offering insights into effective PtD strategies, the study seeks to improve stakeholder communication and encourage proactive risk management practices. Ensuring safety in construction is a complex and ongoing process that requires collaboration and active participation from everyone involved [4]. Ultimately, it aims to promote a safety-oriented culture that prioritizes geotechnical considerations early in construction projects, thereby enhancing project outcomes while safeguarding the environment and workforce.

1.1 Geotechnical Design Aspect in Building Construction

Geotechnical design applies soil mechanics and rock mechanics principles to assess the suitability of subsurface conditions for proposed structures. The interaction between soil and structural loads is fundamental to ensuring stability, safety, and durability [5]. With the increasing complexity of modern structures and the rapid pace of urban development, robust geotechnical design practices are more critical than ever. Safe design and practice in geotechnical engineering require the identification of geotechnical hazards and the implementation of mitigation strategies across the decision-making, investigation, design, and construction phases [6].

An effective geotechnical design process relies on detailed site-specific data, including soil properties, groundwater conditions, and potential seismic risks. Comprehensive site investigations are indispensable to this process, employing techniques such as borehole drilling, soil sampling, in-situ testing, and geophysical surveys. These investigations provide critical insights into subsurface conditions, including soil characteristics, groundwater levels, and geological structures. The data collected from the site investigation informs essential design decisions, supports hazard identification, and contributes to the development of strategies to mitigate geotechnical risks.

1.2 Geotechnical Risk

Geotechnical risk factors refer to potential hazards arising from ground-related issues that can negatively impact construction projects. These risks include threats to human health and property due to emergencies, changes in environmental parameters, or site-specific geological, hydrogeological, and environmental conditions during construction [7]. Left unaddressed, these risks can result in project delays, increased costs, or serious accidents leading to injuries or fatalities [8]. However, timely responses, high-quality construction practices, and preventive measures can significantly mitigate or eliminate such risks [7].

Among geotechnical risks, slope instability has been identified as the most impactful in terms of cost and schedule, while soft compressible soils are the most frequently encountered [8].Soft clays, organic silts, and peat are particularly significant due to their combined frequency and impact. These challenges are worsened by faulty slope designs, insufficient drainage systems, and groundwater infiltration, which weaken foundations and contribute to soil erosion [6]. Groundwater intrusion poses risks to both existing infrastructure and new projects, necessitating thorough hydrogeological investigations to prevent water-related damage [9].

Meanwhile, slope instability remains a critical safety concern, potentially resulting in landslides that endanger construction sites and surrounding areas. The interaction of soil and rock on slopes presents unique challenges for engineering projects as urban construction continues to expand [10]. Additionally, soil erosion, especially in regions with high rainfall or inadequate drainage, can undermine foundations and exacerbate the risk of landslides [11].

Other notable geotechnical risks include foundation failures due to inadequate assessment of bearing capacity, which can lead to structural collapse [12]. Differential settlement, where uneven ground settling causes structural damage and misalignment, is also a significant concern [13]. Similarly, soil liquefaction in earthquake-prone areas weakens saturated soils, leading to ground failure and structural harm [2]. Another major hazard is seismic vulnerability that particularly in earthquake-prone regions, where ground shaking can cause substantial structural damage. Comprehensive seismic hazard assessments and appropriate design measures are essential to ensure the resilience of structures against such forces [2,14].

1.3 Geotechnical Design Risk Management

Geotechnical risk registers and risk management frameworks play a crucial role in managing geotechnical risks throughout the duration of civil and building engineering projects. Incorporating these tools into a project's overall risk management strategy has been shown to mitigate economic damage, enhance safety, and improve construction quality [15,16]. Geotechnical risks, if unaddressed, can significantly impact project outcomes, leading to financial losses and compromising the structural integrity of constructions.

A comprehensive geotechnical risk management process should encompass planning, risk identification and assessment, selection of solutions, implementation of response measures, and ongoing risk control [17]. Addressing these risks through detailed literature reviews and design evaluations enables project stakeholders to identify hazards, analyze risks, and implement appropriate measures. Findings by [18] shows that most accidents occurred at work during the construction of new buildings. Therefore, conducting thorough design reviews that integrate hazard identification and risk analysis is essential for preventing accidents, minimizing financial losses, and ensuring the safety and durability of construction projects.

2. HIERARCHY OF HAZARDS CONTROL

The Hierarchy of Hazard Controls (HHC) is a globally recognized framework for systematically managing workplace hazards, organized from the most to the least effective: elimination (physically removing the hazard), substitution (replacing the hazard), engineering controls (isolating people from the hazard), administrative controls (changing work practices), and personal protective equipment (PPE) [19]. This hierarchy prioritizes methods that eliminate or reduce hazards at their source, enhancing overall safety in construction and other industries. A recent study highlighted that most hazard mitigation measures implemented in construction projects fall under administrative controls (53.9%) and engineering controls (35%) [20].

2.1. Engineering Control Approached

Engineering controls represent one of the most effective layers in the HHC framework for mitigating construction hazards. These controls aim to isolate workers from risks by introducing physical modifications to the work environment or processes. This proactive approach to safety focuses on designing and implementing solutions such as barriers, ventilation systems, and automated equipment to reduce exposure to hazards. In construction, examples of engineering controls range from simple protective barriers to advanced automated systems. These measures align closely with the Prevention through Design (PtD) principle, emphasizing worker safety through thoughtful engineering design.

2.2. Prevention through Design in Geotechnical Hazard Mitigation

The Prevention through Design (PtD) principle is a critical framework in engineering, emphasizing the integration of safety measures during the design phase to mitigate risks throughout a project's lifecycle [21]. In geotechnical engineering, PtD involves enhancing site-specific investigations during the planning stage to identify and address potential hazards. Examples include incorporating preventive design measures such as slope reinforcement, soil stabilization, and effective drainage systems. Advanced technologies, such as ground monitoring systems, can track soil movement or changes in conditions, enabling early detection of potential risks [22]. In addition, [23] discovered that, chemical stabilization methods, such as lime and cement treatments, as well as mechanical approaches, including compaction and the use of geosynthetics can be adopted to enhance soil performance. Additionally, leveraging insights from studies like [24] ensures that geotechnical risks are mitigated during the design phase, reducing costly failures and enhancing resilience in construction projects.

2.3. Prevention through Design Implementation

In the empirical study by [25], the application of Prevention through Design (PtD) in the South African construction industry was explored as a proactive approach to improving construction safety. The study identified 14 key PtD practices as critical to ensuring site safety, including designing to eliminate confined spaces, overhead hazards, and specifying non-hazardous materials. Proactive integration of PtD at the design stage, supported by laws, guidelines, and digital innovations, can significantly improve construction safety and reduce occupational hazards [26]. In Malaysia, although designers are generally less willing to implement the Prevention through Design (PtD) concept, findings indicate that they demonstrate a strong commitment to achieving the concept. Moreover, they exhibit a positive attitude towards incorporating PtD into their design practices [27]. Therefore, having this dataset will provide valuable insights to designers in enhancing their understanding and assist in practicing PtD.

2.4. Research Aim and Objectives

This study aims to identify and analyze geotechnical hazards and risks commonly encountered during the conceptual design phase of construction projects and propose feasible Prevention through Design (PtD) solutions. The objectives are to improve communication among stakeholders such as clients, geotechnical engineers, foundation designers, and contractors regarding the adoption of PtD approaches and to promote their broader application in managing geotechnical risks during the early stages of construction projects.

The geotechnical hazards analyze in this study are drawn from a comprehensive literature review [24] supplemented by expert feedback to provide a holistic perspective. These hazards are categorized into seven design aspects to ensure structured analysis and actionable insights. The findings are intended to support Malaysia's Department of Occupational Safety and Health (DOSH) in promoting the integration of Prevention through Design (PtD) principles, as outlined in the Occupational Safety and Health in Construction Industry (Management) Guideline known as OSHCI(M). By aligning with these guidelines, the research seeks to enhance safety, minimize risks, and improve construction project outcomes.

3. RESEARCH METHODOLOGY

This study comprises two distinct phases: a Questionnaire Survey and a Focus Group Discussion (FGD). The integration of quantitative and qualitative methodologies provides a comprehensive framework for identifying risk factors and devising mitigation strategies in construction projects [17]. By applying this mixed-methods approach, the study effectively addresses geotechnical hazards and their mitigation measures, thereby contributing to the enhancement of safety performance in the construction industry. This study was conducted on a voluntary basis without any obligation, and informed consent was implied, as participants were informed of the study's purpose, their rights, and data usage. Anonymity and confidentiality were ensured, with no sensitive data collected. As the study posed minimal risk and did not involve vulnerable groups..

3.1 Phase 1: Questionnaire Survey

This study employed an online survey to identify geotechnical hazards as perceived by construction practitioners in Malaysia. The questionnaire consisted of two sections which are the first section captured the demographic profile of respondents, while the second section focused on 33 potential geotechnical hazards which has been categorized into seven design aspects that significantly impact construction projects. The design aspects include soil or ground instability, presence of water table/groundwater level, sloppy areas, soil classification, flood-prone areas, landfill areas, and areas prone to seismic activities. Each design aspect encompasses specific hazards and respondents were asked to rate the hazards using a five-point Likert scale, where 1 indicated "Strongly Disagree", 2 indicated "Disagree," 3 indicated "Neither Disagree nor Agree," 4 indicated "Agree," and 5 indicated "Strongly Agree." The five-point Likert scale originally developed by Rensis Likert, remains the standard for effective attitude measurement [28]. Likert scales are widely used to assess respondents' attitudes by measuring their agreement or perception of given statements due to its clarity and ease of use. It provides respondents with well-defined response options, facilitating more accurate and reliable data collection. Additionally, research has shown that fully labelling scale points with descriptive terms, rather than numerical values alone, enhances response reliability, consistency, and the overall validity of attitude assessments [29]. To ensure methodological consistency, the questionnaire underwent expert validation and a pilot test before distribution. These steps enhanced its reliability and clarity, ensuring that the survey instrument effectively captured meaningful quantitative data for analysis.

3.2 Phase 2: Focus Group Discussion

The Focus Group Discussion (FGD) method, as emphasized by [30], facilitates the collection of in-depth insights through interactive dialogue among diverse stakeholders. This method has been effectively used in prior studies, such as [31], which utilized FGDs to enhance the Design for Safety (DfS) evaluation process in regulated industries. Similarly, [32] conducted focus group interviews with the United Kingdom (UK) construction professionals to explore their perspectives on Prevention through Design (PtD). In this study, FGDs were critical for developing a robust dataset on engineering control approaches within the PtD framework during the construction design phase. Significant geotechnical hazards identified through statistical mean analysis were presented during the FGD sessions, enabling a deeper exploration of challenges and mitigation strategies.

To ensure the reliability of the discussions, purposive sampling was adopted to recruit expert participants [33]. The panel comprised industry professionals and members of professional groups with expertise relevant to the study. All participants had attended at least one PtD workshop organized by Malaysia's Department of Occupational Safety and Health (DOSH) and were listed in DOSH's database.

Additionally, the invited expert participants possessed at least ten years of experience in the construction industry and a thorough understanding of occupational safety and health issues. This sampling approach, widely recommended for FGDs [34], ensures the selection of participants capable of providing meaningful and relevant insights.

4. RESULTS AND DISCUSSION

This section presents the results of the data analysis and discusses the findings, integrating insights from the questionnaire survey and focus group discussions (FGD). The analysis identifies critical geotechnical hazards, evaluates their significance, and explores mitigation strategies to address these risks. Quantitative data from the survey provide a statistical understanding of hazard prevalence and significance, while qualitative insights from the FGDs delve into practical challenges and opportunities for implementing mitigation measures. The findings emphasize the importance of adopting the Prevention through Design (PtD) framework to enhance safety and sustainability in construction projects. By bridging theory and practice, this study offers actionable recommendations for improving geotechnical risk management and promoting safer, more efficient construction practices.

4.1 Questionnaire Survey Data Analysis

The questionnaire survey serves as the initial phase of this study, aiming to collect quantitative data on geotechnical hazards as perceived by construction practitioners in Malaysia. The demographic characteristics of the respondents including their roles within the construction sector and years of experience were highlighted. This is important for contextualizing their perceptions and ensuring the relevance and reliability of the findings. Next, the mean values of geotechnical hazards categorized under seven design aspects were discovered. The data reveal the perceived significance of hazards, with higher mean values indicating greater concern among respondents. This quantitative analysis lays the groundwork for assessing geotechnical hazards and guiding PtD mitigation strategies.

4.1.1 Participant’s Demographic of Questionnaire Survey

The demographic profile of the respondents involved in this study shows in Table 1. Gender distribution indicates that 60% of the participants are male, while 40% are female. This indicates a relatively balanced participation; however, the study remains male-dominated, which is a common trend in construction-related research due to the historically male-oriented nature of the industry which is consistent with previous construction-related studies [35]. This can be attributed to the traditionally male-oriented workforce composition in the construction industry, where technical, managerial, and on-site roles are predominantly occupied by men. In terms of employment, participants are categorized into public/government (53.3%), private (36.67%), and self-employed professionals (10%). The dominance of public/government employees aligns with broader industry trends where public sector projects form a significant portion of construction activities. Furthermore, participant experience levels show notable variation: 43.3% have 5–10 years of experience, 26.67% possess 11–15 years, 20% bring 16–20 years, while a smaller segment (10%) exceeds 20 years of professional experience. This diversity ensures a well-rounded understanding of design hazards, stakeholder perspectives, and construction practices. Additionally, participants are classified based on their major disciplines, where 76.67% specialize in civil engineering, a logical outcome given the study's focus on construction projects. Smaller groups include those from electrical engineering, architectural, and surveying disciplines, each constituting 3.33%, showcasing interdisciplinary contributions essential for holistic construction safety solutions.

Finally, the study explores participants' familiarity with various construction methods. 56.67% report using both conventional and prefabricated methods, whereas 40% rely solely on conventional methods, and a minimal percentage (3.33%) specialize in prefabricated construction. These findings highlight the ongoing reliance on conventional approaches despite increasing interest in prefabrication techniques for risk mitigation and efficiency. In conclusion, the demographic distribution of this study effectively captures the diverse expertise and experiences required to address design hazards in construction projects.

Table 1. Demographic of Survey's Respondents

		Frequency	Percentage (%)
Gender	Male	18	60
	Female	12	40
Employment	Public/Government	18	60
	Private	11	36.67
	Self Employed	1	3.33
Experience	5 - 10 years	13	43.33
	11 - 15 years	8	26.67
	16 - 20 years	6	20
	More than 20 years	3	10
Major Discipline	Civil Engineering	23	76.67
	Others	3	10
	Electrical Engineering	2	6.67
	Architectural	1	3.33
	Surveying	1	3.33
Construction Method	Conventional& Prefabricated	17	56.67
	Conventional	12	40
	Prefabricated	1	3.33

4.1.2 Mean Analysis of Geotechnical Hazard

The data collected from the questionnaire survey were analyzed using the Statistical Package for the Social Sciences (SPSS) version 22. This software was employed to organize and analyze all the data obtained from the survey. A mean analysis was conducted to determine the average response for each potential geotechnical hazard that may arise during the design phase of building construction projects. Table 2 shows the results of mean analysis of 33 potential geotechnical hazards, categorized under seven design aspects, with mean values reflecting their perceived significance. Overall, the average mean value for all geotechnical hazards were 3.82.

Among these hazards, slope failure (mean = 4.13) and landslides (mean = 4.07), both under the "Soil or Ground Instability (G1)" category, were identified as the most critical risks. These findings highlight the severe impact of ground instability on construction safety and project performance. Additionally, hazards associated with sloppy areas (G3), such as slope instability (mean = 4.00) and earthflows (mean = 3.80), further emphasize the challenges posed by unstable slopes and terrains, particularly in projects located in hilly regions.

Hazards related to groundwater and water table presence (G2), such as drainage basin and saturated ground (mean = 3.70 each), also emerged as significant concerns, pointing to the importance of managing water infiltration and related consolidation issues. The category "Soil Classification (G4)" revealed that saturated soils (mean = 3.87) and soft soil deposition (mean = 3.83) are prominent risks, reflecting challenges in soil strength and composition. Meanwhile, hazards within flood-prone areas (G5), including sedimentation (mean = 3.93) and saturated ground (mean = 3.77), underscore the critical need for flood control measures to prevent ground saturation and foundation instability in areas near water bodies.

In the context of landfill areas (G6), hazards such as soil contamination due to leachate seepage (mean = 3.77) and groundwater contamination (mean = 3.67) highlight environmental risks that require proper site investigations and mitigation strategies. Finally, hazards within areas prone to earthquake activities (G7) were also significant, with ground movement (mean = 4.00), underground faults (mean = 3.83), and ground shaking (mean = 3.67) indicating the importance of seismic assessments and earthquake-resistant designs in ensuring structural resilience. Overall, the findings demonstrate that hazards related to soil instability, slope risks, groundwater issues, and seismic activity are perceived as the most significant threats to construction projects.

Table 2. Geotechnical Potential Hazard [24] and Mean Value Results

ID	Design Aspect	ID	Potential Hazard	Mean Value
G1	Soil or ground Instability [36][22] [37]	G11	Settlement	3.90
		G12	Landslide	4.07
		G13	Subsidence	3.67
		G14	Erosion	3.93
G2	Presence of water table/ ground water level [2] [3]	G21	Liquefaction	3.33
		G22	Drainage basin	3.70
		G23	Saturated ground	3.70
		G24	Consolidation	3.60
		G25	Dampness	3.67
G3	Sloppy area [38]	G31	Slope instability	4.00
		G32	Slope failure	4.13
		G33	Earthflows	3.80
		G34	Rock slope fault zones	3.73
G4	Soil classification [39]	G41	Saturated soils	3.87
		G42	Soft soil deposition	3.83
		G43	Delineating weak zones	3.60
		G44	Soil cavity	3.40
		G45	Soil voids	3.40
G5	Flood-prone area and proximity of area to water bodies [40]	G51	Saturated Ground	3.77
		G52	Sedimentation	3.93
		G53	Settlement	3.67
		G54	Uneven foundation	3.50
		G55	Corrosion	3.67

G6	Landfill Area [41] [42]	G61	Ground water contaminated due to leachate leaking	3.67
		G62	Soil contamination due to leachate seepage	3.77
		G63	Underground fire due to existence of methane gas	3.37
		G64	Emissions of toxic /greenhouse gases	3.40
G7	Area is prone to earthquake (seismic) activities [43]	G71	Ground movement	4.00
		G72	Underground faults cause damage to underground structures or utilities	3.83
		G73	Lateral spreading on the ground surface due to liquefaction	3.67
		G74	Surface fault rupture	3.80
		G75	Ground deformation	3.80
		G76	Ground shaking	3.67

The mean values were sorted in descending order to prioritize geotechnical hazards based on their perceived significance as reported by the respondents, as shown in Table 4.1. In this study, a mean value of 3.5 was considered the threshold for significance. This threshold was selected because it closely approaches a value of 4, which represents agreement on the Likert scale. As a result, any mean value above 3.5 was interpreted as a tendency towards agreement among respondents, indicating that those hazards are significant and require attention. By applying this threshold, the analysis effectively highlighted the collective opinions and attitudes of respondents regarding the geotechnical hazards encountered during construction projects. Majority of the hazards (28 hazards) were perceived as significant, suggesting general agreement among respondents about their importance.

Amongst the significant hazards, G32 (Slope collapse) indicate the highest mean value (4.13) compared to other. This is followed by G12 (landslide, mean = 4.07) and G31 (Slope instability, mean = 4.00). Meanwhile, the mean value of G3 (Sloppy area) is 3.92 indicate that this design aspects required more attention during design phase as this aspect comprised of high risk of potential geotechnical hazards existences that can create harm to humans and surroundings. This followed by design aspect, G1 (Soil or ground Instability with mean value of 3.89.

However, five hazards which are G21 (Liquefaction, mean = 3.33), G44 (Soil cavity, mean = 3.40), G45 (Soil voids, mean = 3.40), G63 (Underground fire due to methane gas, mean = 3.37) and G64 (Emissions of toxic/greenhouse gases, mean = 3.40) had mean values less than or equal to 3.5, which categories below the significance threshold (≤ 3.5). This suggesting that mentioned hazards are perceived as less critical by the respondents. Consequently, these five hazards were excluded from further analysis and discussion in the Focus Group Discussion (FGD) session. This focused identification ensures that the study prioritizes the most significant hazards, aligning with the objectives of effective geotechnical risk management.

4.2 Focus Group Discussion Data Analysis

Out of the 33 potential geotechnical hazards identified through the questionnaire survey, only 28 hazards with mean scores above the threshold of 3.5 were selected for further analysis and discussion in the Focus Group Discussion (FGD) sessions. These hazards perceived significant by respondents due to its potential to impact the stability, safety, and performance of construction projects. The aim of the FGD sessions was to explore Prevention through Design (PtD) solutions to mitigate effectively these critical hazards during the design phase of construction projects.

4.2.1 Participant's Demographic of Focus Group Discussion

Table 3 provides a demographic of the participants involved in The Focus Group Discussion (FGD) participants. The gender distribution indicates a higher representation of male participants (60%) compared to female participants (40%),. In terms of age, the largest proportion of participants falls within the 36-45 years age group (42.86%), followed by those aged 46-55 years (25.71%), and 26-35 years (22.86%). A smaller percentage of participants are over 55 years old (8.57%), indicating that most respondents are in the mid-career stages, contributing relevant experience and perspectives to the study. Regarding academic qualifications, participants with a master's degree form the largest group (48.57%), followed by those with a bachelor's degree (28.57%). Participants holding PhDs account for 22.86%, showcasing a well-educated pool of respondents capable of offering high-level insights into the study's objectives. The participants' roles in the construction industry are diverse, with Contractors comprising 28.57% of the total, followed by consultants (20.00%) and representatives from Regulatory Bodies (17.14%). Meanwhile, Academicians make up 20.00%, and Academician with Practice roles contribute an additional 14.29%, highlighting a mix of practical and academic expertise. This diversity of professional backgrounds offers valuable insights from multiple perspectives, helping to uncover assumptions and processes that might otherwise remain overlooked [44].

Table 3. Demographic of FGD's Participants

Category	Subcategory	Frequency	Percentage (%)
Gender	Male	21	60
	Female	14	40
Age	26-35	8	22.86
	36-45	15	42.86
	46-55	9	25.71
	>55	3	8.57
Academic Qualification	Master's Degree	17	48.57
	Bachelor's Degree	10	28.57
	PhD	8	22.86
Designation/ Roles in the construction industry	Contractor	10	28.57
	Consultant	7	20
	Regulatory body	6	17.14
	Academician and Practice	5	14.29
	Academician	7	20.00
Experience	<10	6	17.14
	11-20	11	31.43
	21-30	14	40
	>30	4	11.43

In terms of years of experience, most participants fall within the 21-30 years range (40%), indicating a highly experienced group of professionals. This is followed by participants with 11-20 years of experience (31.43%) and those with less than 10 years (17.14%). A smaller group of participants has more than 30 years of experience (11.43%), contributing seasoned expertise to the study. The inclusion of both senior experts and experienced professionals ensures a balanced and less biased analysis, as their varied viewpoints contribute to a more comprehensive understanding of geotechnical hazard mitigation strategies[45].Furthermore, the diverse expertise amongst FGD participants enables detailed discussions on practical solutions to identify risks, allowing the study to explore innovative and context-specific approaches. This diversity enhances the validity of the findings and supports the applicability of the proposed Prevention through Design (PtD) strategies in real-world construction projects. By including professionals from various disciplines, the study captures a comprehensive view of geotechnical challenges and facilitates the development of effective mitigation measures.

4.2.3 Qualitative Analysis for Prevention through Design Solution

In this study, data from the Focus Group Discussion (FGD) sessions were analyze using qualitative content framework analysis, a method that interprets and examines written, spoken, or visual content to uncover meanings and messages [46]. The recorded data from the FGD sessions were systematically compiled and organized in table form, following the recommendations of [39], to ensure clarity and ease of presentation. This structured approach allowed for a more convenient and comprehensive interpretation of the findings.

To enhance the accuracy and relevance of the data, the recommended Prevention through Design (PtD) solutions were categorized according to the corresponding geotechnical hazards, following the method outlined by [47]. This categorization eliminated redundancies and ensured consistency in terms and meanings. Additionally, ambiguous terms that required further clarification were revised and elaborated to improve understanding. Necessary adjustments to wording and explanations were incorporated to enhance the clarity of the proposed solutions. The final dataset was validated through an expert review conducted at the conclusion of the FGD sessions. This validation process ensured that the recommended PtD solutions were practical and aligned with industry best practices. Importantly, this study focused solely on PtD solutions related to engineering control measures, as these represent proactive strategies to mitigate geotechnical risks effectively.

4.2.4 Prevention through Design Solution

The findings presented in Table 4 highlight the Prevention through Design (PtD) solutions proposed for the significant geotechnical hazard, categorized under different design aspects. These recommendations are derived from the qualitative analysis of the data gathered from the FGD session. Primarily, the focus of PtD solution is on engineering control measures, emphasizing the integration of proactive strategies during the design phase to mitigate geotechnical risks and enhance construction safety**.** The recommended PtD solutions offering actionable insights for improving safety performance during the design phase of construction projects.

Table 4. Geotechnical Significant Hazards and Recommended PtD Solutions

Design Aspect	ID	Potential Hazard	Mean Value	Recommended PtD Solutions (Engineering Control)
G1	G12 G14 G11 G13	Landslide Erosion Settlement Subsidence	4.07 3.93 3.90 3.67	• Design a stable platform or foundation • Design for soil replacement • Design for soil improvement • Conduct detail geotechnical investigation and testing • Design and implement an effective stormwater management system, such as concrete drainage channels
G2	G22 G23 G25 G24	Drainage basin Saturated ground Dampness Consolidation	3.70 3.70 3.67 3.60	• Design for basin based on the existing stream at the site area • Design for basin to store runoff temporarily during heavy rains, • Design for basin to reduce peak discharge and prevent downstream flooding • Design of settlement control system • Increase the level of structural platform element in design • Design for soil improvement • Design suitable infrastructure to discharge or divert any excess water or pounding water • Design all elements based on the design standards and requirements • Accurate calculation and design to receive negative water pressure • Design and implement effective drainage system • Design for extra Factor of Safety in structural elements • Design for installing prefabricated U or V shaped drains • Integrate the usage of water-resistant sealants and coatings on building surfaces (e.g., plastic and geotextile) to create an impermeable barrier against moisture
G3	G32 G31 G33	Slope collapse Slope instability Earthflows	4.13 4.00 3.80	• Design the structural elements based on input provided in the Environment Impact Assessment (EIA) and Traffic Impact Assessment (TIA) project report • Design for soil protection system • Design for soil reinforcement system

	G34	Rock slope fault zones	3.73	• Design for temporary or permanent support structures • Design slopes with appropriate gradients and incorporate retaining structures such as retaining walls, gabions, and geotextiles • Design efficient surface and subsurface drainage systems like in-situ V shape drain to control water infiltration and reduce pore water pressure • Develop maps to identify and monitor high-risk areas
G4	G41	Saturated soils	3.87	• Conduct comprehensive Soil Investigation (SI) • Design for suitable temporary or permanent support structures • Adjust the design of the building to avoid the identified vulnerable zones whenever possible • Implement proper soil preparation and compaction techniques to improve soil strength and reduce susceptibility to saturation and soil deposition
	G42	Soft soil deposition	3.83	
	G43	Delineating weak zones	3.60	
G5	G52	Sedimentation	3.93	• Design for water isolated area • Design for suitable structural platform • Create retention or detention ponds to reduce sediment transport • Design adequate drain to control runoff • Specify in design for corrosion-resistant materials for geotechnical structures, considering factors such as soil aggressiveness, moisture levels, and potential chemical exposure • Construct sediment basins or ponds to capture and settle out sediment from runoff before it enters waterways
	G51	Saturated Ground	3.77	
	G53	Settlement	3.67	
	G55	Corrosion	3.67	
	G54	Uneven foundation	3.50	
G6	G62	Leachate seepage causes soil contamination	3.77	• Design for method statement of using suitable Authorized Gas Test (AGT) devices during excavation works • Conduct soil treatment • Design for temporary or permanent support structures • Use landscape plants to absorb and break down contaminants in the soil thus improving soil quality over time • Design for leachate collection systems, including drainage layers, pipes, and sumps, to capture leachate before it can seep into the ground • Design for buffer zone implementation
	G61	Leachate leakage causes ground water pollution.	3.67	

G7	G71	Ground movement	4.00	• Conduct detailed geological surveys to identify fault lines and avoid placing critical structures directly overactive faults • Design site layouts to ensure that essential buildings and infrastructure are located away from high-risk areas • Consider all potential earthquake/seismic load in the structural design • Integrate a suitable anti-vibration system in the structural design
	G72	Underground faults cause damage to underground structures or utilities	3.83	
	G74	Surface fault rupture	3.80	
	G75	Ground deformation	3.80	
	G73	The ground surface undergoes lateral spreading due to liquefaction.	3.67	
	G76	Ground shaking	3.67	

Mainly for soil or ground instability (G1) design aspects, the recommended PtD solutions ensure the structural integrity and stability of construction sites in unstable ground conditions. For, groundwater (G2)-related hazards, the recommended PtD solutions ensure effective water management and mitigate risks of infiltration, dampness, and soil consolidation, safeguarding the structural stability of buildings and infrastructure. For, G3(Sloppy Area), the recommended PtD solutions focus on slope stabilization and erosion control, ensuring safety and stability in construction projects located in steep or unstable terrains.

The recommended PtD solutions for G4 (Soil Classification) address soil strength and stability issues through soil investigations, compaction techniques, and support structures, ensuring reliable foundation performance. Meanwhile, the recommended PtD solutions for G5 (Flood-Prone Area and Proximity to Water Bodies) aim to control runoff, sedimentation, and water-related hazards, protecting construction sites from flood risks and ensuring structural resilience. For design aspect, G6 (Landfill Area), the recommended PtD solutions focus on leachate management and soil contamination control, ensuring environmental safety and structural stability in areas affected by landfill activities. Lastly for G7(Areas Prone to Earthquake-Seismic Activities), the recommended PtD solutions incorporate seismic assessments and earthquake-resistant designs, ensuring the resilience and safety of structures in earthquake-prone areas.

In summary, the recommended Prevention through Design (PtD) solutions for all geotechnical design aspects (G1 to G7) emphasize proactive measures to address critical hazards, ensuring the stability, safety, and resilience of construction projects. From managing soil instability, groundwater infiltration, and slope-related risks to mitigating challenges in flood-prone, landfill, and seismic areas, the solutions focus on integrating engineering controls, advanced site investigations, and targeted mitigation strategies during the design phase. By prioritizing these solutions, construction projects can effectively reduce risks, enhance structural integrity, and promote sustainable and safer practices in the built environment. Holistically, these recommendations aim to minimize geotechnical risks during the design phase, ensuring safer and more sustainable construction practices. In addition, slope-related hazards, groundwater management, and seismic risks were identified as the most significant challenges requiring immediate attention during design phase.

5. CONCLUSIONS

Effective management of geotechnical hazards is a foundation of the construction industry, requiring comprehensive strategies that include thorough site investigations, detailed risk assessments, and strategic mitigation measures. By prioritizing these aspects, the industry can significantly enhance project safety, structural reliability, and overall performance. The Prevention through Design (PtD) principle is closely aligned with geotechnical risk management, as it emphasizes identifying and mitigating potential hazards during the design phase of construction projects. Incorporating geotechnical risk assessments into the design process enables designers to select appropriate materials and structural solutions that enhance safety and stability. This proactive approach not only prevents accidents and failures linked to geotechnical issues but also fosters safer construction environments. In summary, the integration of geotechnical considerations and PtD principles is essential for advancing safety performance in the construction industry. By prioritizing these elements and offering targeted recommendations for addressing specific hazards, the industry can achieve sustainable safety improvements that protect workers while enhancing the quality and resilience of construction projects. The proactive measures outlined in this study underscore the importance of embedding safety into all stages of construction practices, paving the way for a safer, more innovative, and resilient industry.

6. LIMITATIONS AND FUTURE DIRECTIONS

This study examined the Prevention through Design (PtD) approach for mitigating geotechnical design hazard risks. However, the scope of the study is limited to specific construction hazards within the geotechnical aspect, which may not fully represent the diversity of challenges encountered across various construction activities. Additionally, the study does not account for regional variations in geological conditions, which could influence the effectiveness of PtD interventions. Moreover, the identified hazards are generalized and not specific to project types or scales, potentially limiting their applicability in different construction contexts. Furthermore, the study primarily relied on expert opinions gathered through Focus Group Discussions (FGDs) to identify PtD strategies. While these discussions provide conceptual recommendations for assessing design hazards and risk mitigation measures, the reliance on expert judgment may limit the generalizability of the proposed solutions. To address these limitations, this study expands the hazard dataset to encompass a broader range of construction design aspects as outlined in the Occupational Safety and Health Construction Industry 2017 Guidelines known as OSHCI(M), published by the Department of Occupational Safety and Health of Malaysia. Additionally, to enhance the validity and practical relevance of the findings, this study aims on empirical validation through real-world case studies, experimental studies, or field implementations to assess the feasibility and impact of proposed PtD solutions. These advancements will help strengthen the applicability and practicality of PtD strategies, ultimately contributing to a safer construction industry.

ACKNOWLEDGEMENTS

The acknowledgement goes to the Malaysian Ministry of Higher Education and Universiti Teknologi Malaysia through the Fundamental Research Grant Scheme from vote of R.J130000.7822.5F671, and to the UTM Fundamental Research Grant via vote Q. J130000.3822.22H54. The acknowledgement goes to the Ministry of Higher Education under Fundamental Research Grant Scheme, UTM, FRGS/1/2023/TK01/UTM/02/3 and to the UTM Fundamental Research Grant via vote Q. J130000.3822.22H54.

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