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ADVANCES IN EARTHQUAKE MITIGATION IN MALAYSIA: A REVIEW OF GLOBAL CONTEXT AND LOCAL PROGRESS

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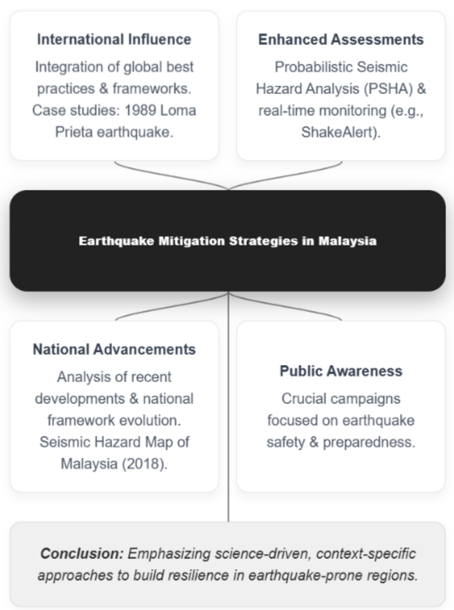
Graphical abstract



Abstract

This paper provides a critical review of earthquake mitigation strategies in Malaysia. It aims to synthesize global best practices and evaluate their local application, feasibility, and the systemic challenges that hinder effective implementation. A narrative review of academic literature, government policy documents, and technical reports was conducted. The collected sources were analyzed using a thematic synthesis framework to structure the review around global advancements, Malaysia's specific seismic context, and the critical gaps between policy and on-the-ground practice. The review finds that while Malaysia has developed a progressive policy framework, its effectiveness is challenged by several key issues. A significant "knowing-doing gap" exists, where the adoption of advanced standards like Eurocode 8 is undermined by inconsistent enforcement and a shortage of specialized expertise. The practical feasibility of adopting global technologies is often limited by local factors, including high costs and infrastructural prerequisites. Furthermore, governance is characterized by a reactive "policy-disaster cycle," and community-based programs face challenges in achieving long-term sustainability. The novelty of this review lies in its critical synthesis that moves beyond a descriptive compilation of strategies. By identifying and analyzing the systemic barriers to resilience—from governance gaps to the vast, unaddressed risk of pre-code buildings—this paper provides actionable insights for policymakers, engineers, and disaster managers. It offers a clear-eyed assessment of the steps required to bridge the persistent gap between policy ambition and practical reality in Malaysia's journey towards seismic resilience.

Keywords: Earthquake mitigation, Malaysia, seismic hazard, building codes, retrofitting

Abstrak

Kertas ini memberikan ulasan kritikal mengenai strategi mitigasi gempa bumi di Malaysia. Ia bertujuan untuk mensintesis amalan terbaik global dan menilai aplikasi tempatan, kebolehlaksanaan, serta cabaran sistemik yang menghalang pelaksanaan berkesan. Satu ulasan naratif terhadap literatur akademik, dokumen dasar kerajaan, dan laporan teknikal telah dijalankan. Sumber yang dikumpulkan dianalisis menggunakan kerangka sintesis tematik bagi menyusun ulasan ini sekitar kemajuan global, konteks seismik khusus Malaysia, serta jurang kritikal antara dasar dan amalan di lapangan. Kajian ini mendapati bahawa walaupun Malaysia telah membangunkan kerangka dasar yang progresif, keberkesanannya masih dicabar oleh beberapa isu utama. Wujud jurang ketara antara "pengetahuan dan pelaksanaan" di mana penerimaan piawaian maju seperti Eurocode 8 dilemahkan oleh penguatkuasaan yang tidak konsisten dan kekurangan cepacian khusus. Kebolehlaksanaan praktikal untuk mengadaptasi teknologi global sering terhad oleh faktor tempatan, termasuk kos yang tinggi dan prasyarat infrastruktur. Tambahan pula, tadbir urus dicirikan oleh kitaran "dasar-bencana" yang bersifat reaktif, manakala program berasaskan komuniti menghadapi cabaran dalam mencapai kelestarian jangka panjang. Keunikan ulasan ini terletak pada sintesis kritikalnya yang melangkaui kompilasi deskriptif strategi. Dengan mengenal pasti dan menganalisis halangan sistemik terhadap daya tahan—daripada jurang tadbir urus hinggalah kepada risiko besar bangunan pra-kod yang masih belum ditangani—kertas ini menyediakan pandangan yang boleh ditindak untuk pembuat dasar, jurutera, dan pengurus bencana. Ia menawarkan penilaian yang telus mengenai langkah-langkah yang diperlukan bagi merapatkan jurang berterusan antara aspirasi dasar dan realiti praktikal dalam perjalanan Malaysia menuju daya tahan seismik.*Kata kunci*: Tebatan gempa bumi, Malaysia, bahaya seismik, pemasangan semula, kod bangunan, kesiapsiagaan bencana.

Kata kunci: Mitigasi gempa bumi, Malaysia, bahaya seismik, kod bangunan, pengukuhan struktur

1.0 INTRODUCTION

Earthquake mitigation research holds a pivotal role in the evolution of civil engineering, particularly as large-scale projects—ranging from high-rise buildings to critical infrastructure like dams and nuclear power plants—have grown in scale, scope, and complexity. The inherent vulnerability of these structures to seismic events poses significant financial, social, and operational risks. Over decades, research has focused on understanding seismic sources through fault studies [1] [2], developing hazard maps [3],[4],[5],[6], and advancing and advancing risk mitigation strategies [7],[8],[9],[10] to protect diverse infrastructure. While Malaysia's geographic location on the stable Sunda Plate generally places it at a relatively low seismic risk compared to tectonically active regions, events such as the 2015 Sabah earthquake have unequivocally demonstrated the nation's susceptibility to seismic hazards as highlighted by the seismic hazard map shown in Figure 2, including landslides triggered by ground motion [11],[12]. This event served as a stark reminder, underscoring the urgent need for targeted research and mitigation strategies to safeguard financial stability, public safety, and livelihoods across the country [13]. Prior to such events, there was a prevailing perception that Malaysia faced minimal seismic threats due to its geological stability. This is also challenged by presence of longstanding active faults in Pahang as shown in Figure 1. However, the 2015 Mount Kinabalu earthquake, which resulted in considerable damage and fatalities, directly challenged this long-held assumption [14]. While numerous studies have focused on specific aspects of Malaysia's seismic risk—such as local government preparedness, community awareness levels, and the development of fragility curves for specific structures —a comprehensive review that synthesizes these national advancements within the context of global technological and policy evolution is lacking. This paper aims to fill that research gap. It provides a critical review of international mitigation strategies, from advanced structural designs to AI-powered early warning systems, and evaluates their application, progress, and feasibility specifically for Malaysia. By bridging the gap between global best practices and local context, this review provides a synthesized roadmap for enhancing Malaysia's earthquake resilience.

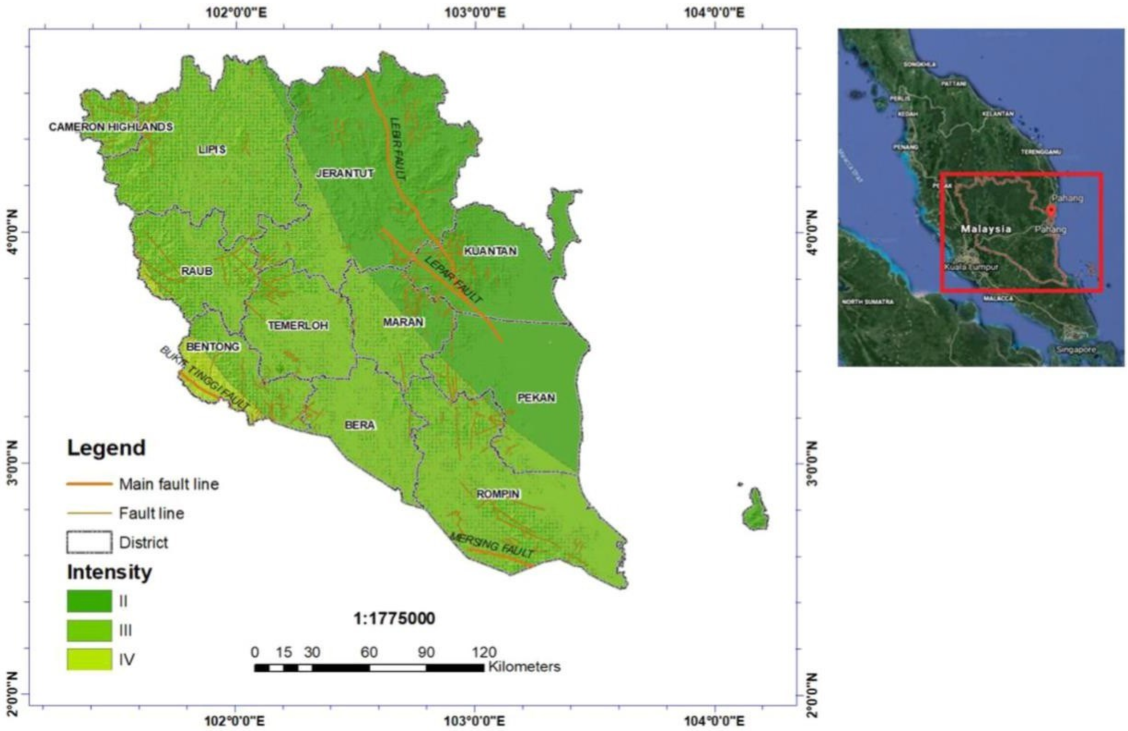


Figure 1 GIS-based seismic hazard map for Pahang, illustrating the proximity of major fault lines (e.g., Lepar Fault) to populated districts. This visualization underscores the importance of local-scale risk assessment even in regions of Peninsular Malaysia traditionally considered to have low seismicity [15]

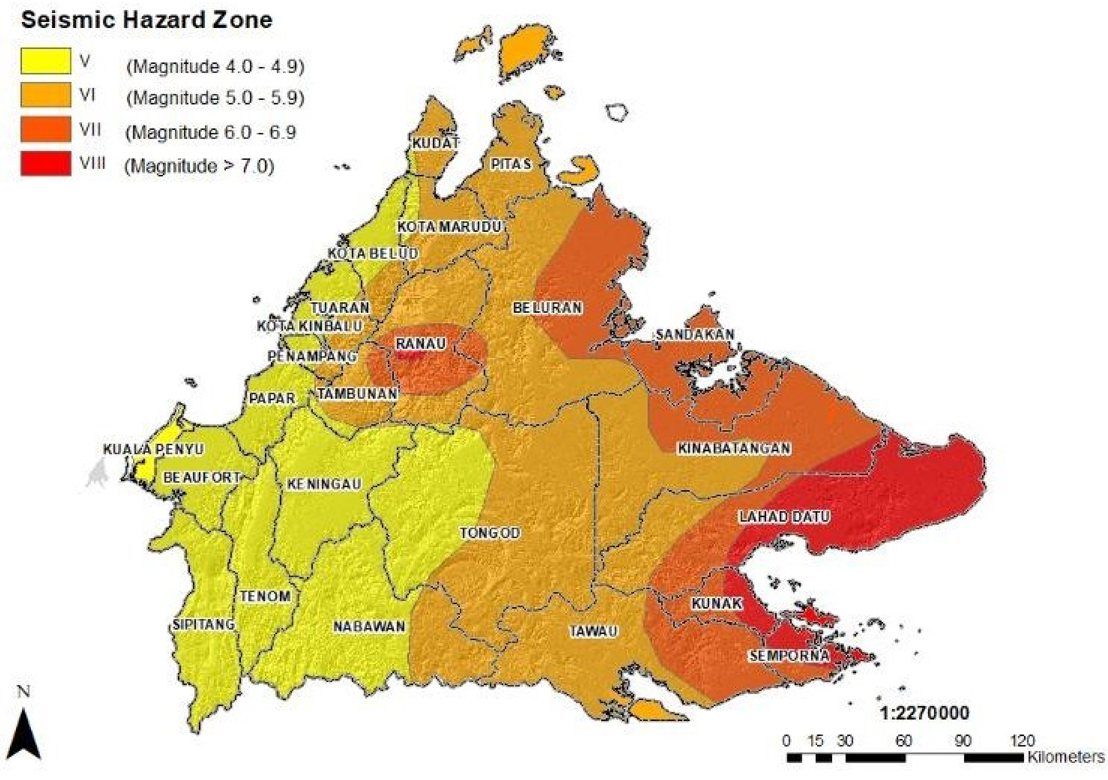


Figure 2 Seismic hazard zonation map of Sabah, which identifies the eastern regions, including Lahad Datu and Sandakan, as having the highest risk (Zone VIII, Magnitude >7.0). This data provides a clear rationale for prioritizing these areas for stricter building code enforcement and retrofitting initiatives [14]

2.0 METHODOLOGY

This paper reviews earthquake mitigation measures undertaken by authorities and researchers in Malaysia and compares them with international standards. The methodology involved a three-stage process. First, a comprehensive literature search was conducted across academic databases, primarily Scopus and Google Scholar. Second, the results were filtered to select studies specifically relevant to the Malaysian context and the field of earthquake mitigation. Finally, the selected literature was thematically analyzed and organized to compare the global state-of-the-art with local practices, allowing for an evaluation of Malaysia's strategies in the context of its specific seismic needs.

The initial step was to gather a broad and relevant body of literature. The search was not limited to a single set of keywords but was an iterative process designed to capture the complex nature of earthquake mitigation measures. The primary databases from which the studies were filtered were Scopus and Google Scholar owing to the comprehensive coverage of engineering and earth sciences journal databases. The keywords used were “earthquake mitigation”, “seismic risk” and “disaster risk reduction” first alone then in combination with “Malaysia”,’ “Sabah”, and “peninsular Malaysia” for finding literature specific to the national context. In addition to which searches were also carried out for “base isolation”, “Eurocode 8”,” Malaysian annex” and “fragility curve” to find technical details and earthquake mitigation measures advancements specific to Malaysia, in addition the Boolean statements used.

The search resulted in many sources, which were then filtered to create a more focused and relevant dataset for the review. The primary criteria were the source’s direct contribution to understanding the paper’s core theme: the mismatch between global mitigation efforts and Malaysian ones. Foundational papers on global mitigation strategies such as the shifts in policy after the Loma Prieta earthquake or the Mexico earthquake were included as guides for the global mitigation efforts, high priority was given to studies focused directly on Malaysia, these included research on the 2015 Sabah earthquake, the development of the national seismic hazard map, and the challenges in implementing the Malaysian Annex locally. To maintain focus, studies were generally excluded if they were purely geological without an engineering or policy application, or if they focused on mitigation for non-seismic hazards. The review also prioritized contemporary sources (largely post-2020) to ensure the analysis was current, especially given the significant shift in Malaysia's seismic policy after 2015.

After the final selection, the literature was synthesized thematically as it was organized to build the narrative an answer to the key research question, namely, to bridge the gap between global best practices and local context. This is done by synthesizing the literature that defines Malaysia’s evolving seismic risk i.e. combining sources on historical events and the geology of the Sunda Plate. After which the review then moves onto international literature too create a “toolbox” of available mitigation strategies. This theme connects policy frameworks with specific technologies like base isolation, energy dissipation, EEWS, and advanced assessment tools like GIS and AI. This all builds up to the core which is to analyze how the global ‘toolbox’ applies to Malaysia. This involved connecting international best practices to specific Malaysian research and policy actions, such as the adoption of Eurocode 8 and assessments of public preparedness.

Finally, the synthesis identifies the critical gaps that emerge from the whole analysis – such as the challenges in retrofitting older buildings, the need for greater public awareness, and the practical hurdles for implementing an EEWS.

3.0 GLOBAL ADVANCES IN EARTHQUAKE MITIGATION

Earthquake mitigation involves strategic measures to reduce seismic risks, protecting lives and infrastructure. Effective strategies rely on understanding hazards, exposure, and vulnerabilities to inform policies and engineering practices. Historically, mitigation was reactive, focusing on post-disaster recovery [16], [17]. A major shift occurred after the 1989 Loma Prieta earthquake in the US, which led to regulatory reforms emphasizing resilience over recovery [18], [19]. The evolution of mitigation highlights the interplay between data, technology, and policy. Disasters like Loma Prieta drive policy changes that fuel technological advancements such as Geographic Information Systems (GIS), Probabilistic Seismic Hazard Analysis (PSHA), machine learning, and Earthquake Early Warning Systems (EEWS). These technologies enable better risk assessment, prediction, and structural resilience, creating a feedback loop where policies and technology continually refine each other. Effective mitigation thus requires integrating engineering solutions, scientific data, and responsive policies. For countries like Malaysia, advancing mitigation capabilities demands investment in research, robust data collection, and adaptive policies. Globally, tools like fragility models and software such as R2R-EU have refined risk assessments, empowering better mitigation design [20]. GIS enables spatial modeling to assess seismic risk based on exposure and resilience, as applied in regions like Pahang, Malaysia. EEWS are crucial, providing real-time alerts seconds before shaking, allowing infrastructure shutdowns and protective actions [21]. Effective strategies rely on understanding hazards, exposure, and vulnerabilities to inform holistic policies and engineering practices [22]. Their use in sports highlights their importance for high-risk facilities. Decision-support systems also bridge seismic science and practical applications. Additionally, engineering solutions like tuned vertical isolation systems and retrofitting methods—

including base isolation and energy dissipators—enhance structural resilience. Innovative approaches, such as monitoring water quality as early warning indicators, further expand mitigation strategies. Overall, the field has shifted from passive approaches to proactive, science-based practices aimed at building sustainable, resilient communities capable of withstanding future earthquakes. Decision- support systems also bridge seismic science and practical application by providing frameworks for risk-informed warnings [23].

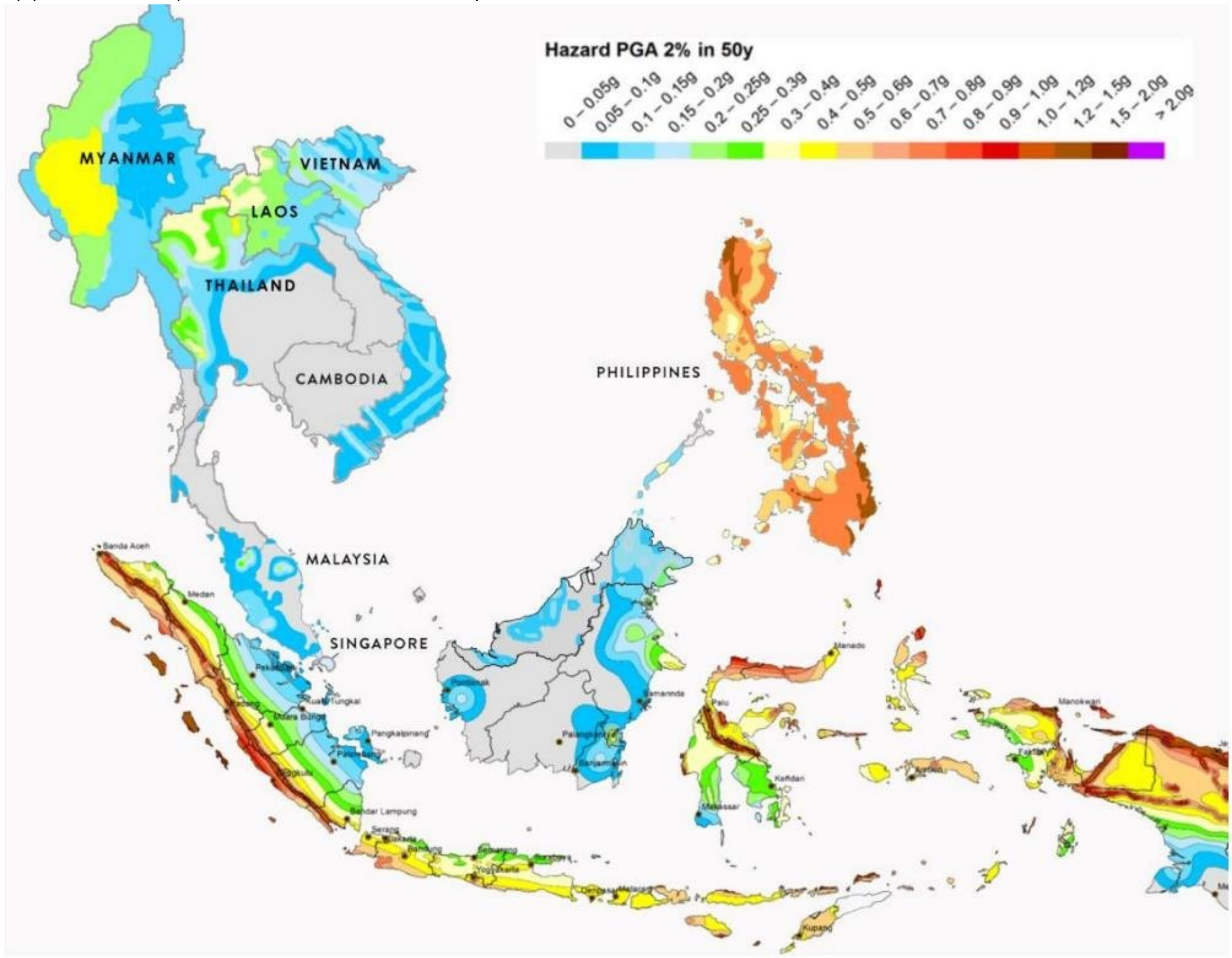


Figure 3 Regional seismic hazard map of Southeast Asia, illustrating Malaysia's position in a comparatively lower hazard zone than neighboring Indonesia and the Philippines. This map visually contextualizes Malaysia's unique challenge of mitigating risk in a region often perceived as safe, which contributes to its 'low seismicity, high vulnerability' paradox [24]

4.0 MALAYSIA'S SEISMIC CONTEXT AND VULNERABILITIES

Malaysia is generally considered a low-seismicity region due to its position on the stable Sunda Plate as can be seen in Figure 3 and 4. However, its proximity to the Pacific Ring of Fire and the Sumatran Fault System makes it vulnerable, particularly in Sabah and Sarawak. The 2015 Mount Kinabalu earthquake highlighted this risk, causing significant damage and fatalities in East Malaysia. Local geological conditions, such as those in Miri, Sarawak, can also amplify seismic effects, increasing vulnerability. Additionally, earthquake-induced debris flows threaten cultural heritage sites, including UNESCO World Heritage areas. Although Peninsular Malaysia has been seen as aseismic, recent evidence indicates rising intraplate seismicity over the past century, challenging assumptions of tectonic stability. The Great Sumatran Fault (GSF), with its strain-accumulating segments, remains a major seismic source affecting Malaysia [4],[15],[14],[25], [26]. Local faults like Kimanis and Sulu in Sabah also pose significant risks, as shown by the 2015 Sabah earthquake [27]. Malaysia faces the paradox of “low seismicity” but “high vulnerability.” Moderate earthquakes can have severe impacts due to underestimating risks and underinvestment in preparedness. Proximity to active faults, amplifying local geology, and vulnerable infrastructure combine to create substantial seismic risk. Therefore, comprehensive risk assessments focusing on vulnerability and exposure are essential. Robust building codes, public awareness, and resilient infrastructure remain critical to prevent devastating consequences, requiring proactive policymaking that avoids complacency

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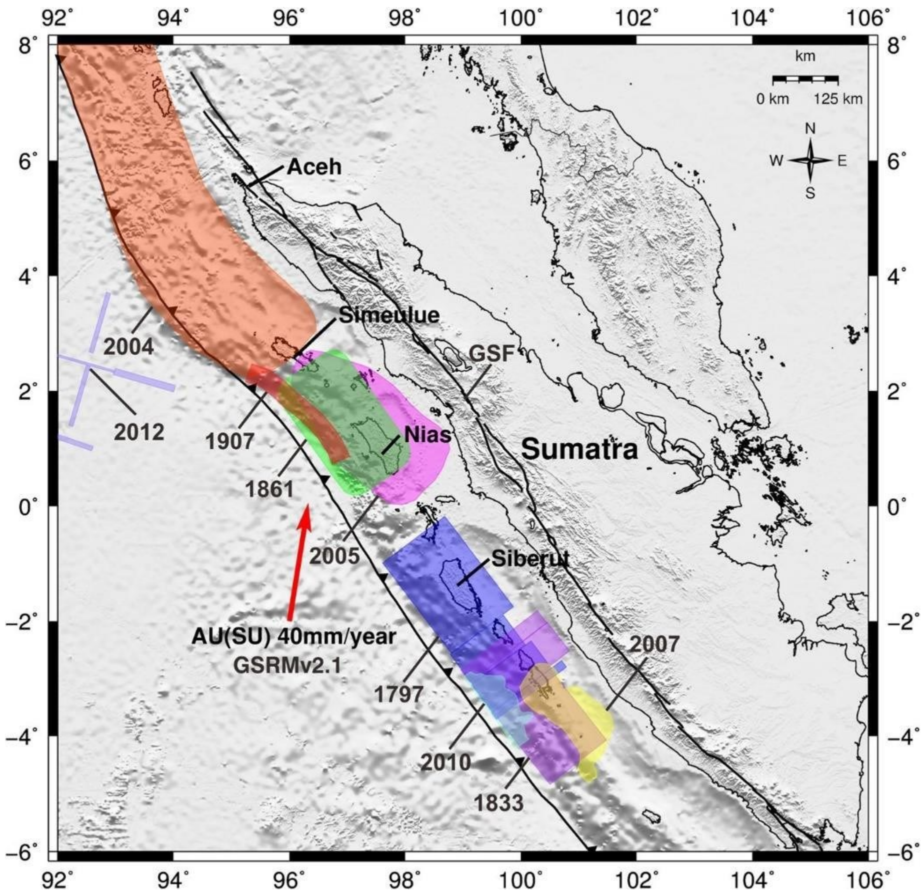

Figure 4 Historical rupture zones along the Great Sumatran Fault, the primary far-field seismic source affecting Malaysia. The map highlights the scale and frequency of major earthquakes in the region, underscoring the constant seismic threat that necessitates preparedness in western Peninsular Malaysia [28]

5.0 MITIGATION STRATEGIES IN MALAYSIA: STRUCTURAL AND NON-STRUCTURAL APPROACHES

Malaysia has undertaken significant efforts to mitigate earthquake risks, implementing both structural and non-structural approaches to enhance the country's resilience.

5.1 Structural Resilience and Design Codes

The evolution of seismic design codes in Malaysia has greatly improved structural safety. Following events like the 2015 Mw 6.0 Sabah earthquake and rising intraplate seismicity in Peninsular Malaysia, Malaysia adopted Eurocode 8 (EC8) as its benchmark for earthquake-resistant design [11], [29], [30], aligning national standards with international practices. The Malaysian National Annex tailors EC8 to local conditions, focusing on low-to-mid-rise buildings. While compliance slightly increases material use, it significantly enhances resilience. However, implementation faces challenges, especially for older buildings built before seismic codes existed. Failures in beam-column joints post-earthquake reveal these vulnerabilities [31], [55], highlighting the gap between policy and practice. Thus, strong enforcement, funding, and long-term strategies are needed to upgrade existing infrastructure.

To address these risks, fragility curves provide probabilistic insights into structural performance, guiding retrofitting and risk assessments. Microzonation studies using GIS, such as in Sarawak, localize earthquake risks for better land-use planning. Additionally, AI is emerging as a powerful tool for improving prediction models and performance-based designs, crucial for high-risk areas like Sabah.

5.2 Innovative Structural Designs (Base Isolation and Energy Dissipation)

Malaysia is increasingly adopting innovative structural designs, such as base isolation systems, to mitigate seismic risks. Base isolation decouples a building's foundation from its superstructure, allowing it to remain relatively stationary during earthquakes, thereby reducing forces transmitted to the structure. This is especially important for critical infrastructure like hospitals, emergency centers, and high-rises. Studies confirm base isolation's effectiveness in controlling structural deformations, including research on two-storey RC frames [32],[33],[34]. Its hysteresis behavior under cyclic loading has been well studied. Sustainable options, like scrap tyre-based isolators, offer eco-friendly and cost-effective solutions [35]. Numerical models also support the use of base isolation in high-performance precast concrete systems. Advanced techniques include tuned vertical isolation for critical structures and inter-story isolation for high-rises, which isolates specific floors to reduce dynamic responses. Intermediate isolation systems (IIS) and optimized layouts for mid-rise RC buildings are being explored to enhance efficiency. It is recommended that base isolation and energy damping systems be integrated during the architectural design phase, with isolator parameters carefully selected for optimal performance. Overall, seismic assessments show significant improvements in safety and resilience with base isolation.

Additionally, energy-dissipating systems, such as viscous, friction, and tuned mass dampers (TMDs), absorb seismic energy, reducing force transmission. TMDs are particularly effective for high-rises, as seen in Taipei 101 [36], and are also used in retrofitting to enhance existing buildings' performance. Combining base isolation with energy-dissipating systems creates hybrid solutions offering superior seismic protection by both isolating structures and absorbing earthquake energy. These technologies have informed resilient building codes in countries like Japan, New Zealand, and the US, where they are integrated into national standards. Such innovations in earthquake risk reduction include advanced retrofitting techniques for vulnerable structures, such as using Buckling-Restrained Braces (BRBs) in concrete frames [37], contributing to a growing portfolio of resilience strategies [38].

5.3 Non-Structural Preparedness and Early Warning Systems

Early warning systems are not new, they have been in place in many of the worlds most earthquake prone areas for decades, and they hinge greatly on where to focus first in such, one such framework of focus has been proposed by [39], shown in Figure 5, represents a strategic shift towards a more holistic assessment model for Malaysia. In practical application, a municipal authority could use this framework to overlay a specific hazard model, such as seismic risk, with layers of vulnerability data—for instance, identifying areas with a high concentration of older buildings (physical vulnerability) and a large elderly population (social vulnerability). This integrated analysis allows for the creation of nuanced risk maps that can guide targeted policy interventions, such as prioritizing specific neighborhoods for retrofitting programs or enhanced emergency response plans. However, the framework's primary limitation is its intensive data dependency. Its effectiveness is contingent on the availability and continuous updating of accurate, multi-sectoral data at various scales (from household to state), which presents a significant challenge for institutional capacity.

Non-structural mitigation measures are crucial for enhancing Malaysia's seismic resilience by providing early warnings, enabling real-time monitoring, and promoting public awareness. Early warning systems detect initial P-waves before the arrival of destructive S-waves, giving seconds to minutes for protective actions like evacuation, halting transport, and shutting down critical infrastructure. Recent studies integrate machine learning (ML) with seismic data to improve these systems' accuracy. ML algorithms can predict damage to RC buildings and estimate casualties or economic losses in real time, aiding faster emergency response and decision-making [40],[41]. Real-time monitoring continuously collects and analyzes seismic data to assess earthquake progression, aftershocks, and areas at risk. Systems like ShakeAlert [42] in the US provide critical information for first responders. Frequency-based surrogate models have also been developed to predict the seismic response of irregular structures, enhancing damage assessments. However, the effectiveness of early warning systems and real-time monitoring relies heavily on public preparedness. Advanced technologies like EEWS, AI, and IoT are only effective when people understand and respond appropriately to warnings. Public education, community drills, and the development of clear communication protocols, including effective post-alert messaging, are therefore essential to translating technological alerts into lifesaving actions [43]. Overall, effective earthquake mitigation requires a balanced approach: investing in advanced technologies while equally strengthening public awareness and preparedness to ensure timely and effective responses during seismic events.

Table 1 and 2, adapted from a study by [32] on earthquake prediction in Terengganu, is presented. The table compares the performance of several supervised learning algorithms, including regression models like Support Vector Machine and MARS Spline, alongside ensemble methods such as Boosted Decision Trees and Random Forests, which improve predictive power by combining multiple models. The original study trained these models using localized data from a single state, not on a comprehensive national dataset. Therefore, the performance metrics shown—such as the correlation coefficient (R) and Root Mean Square Error (RMSE) serve as a conceptual demonstration rather than a benchmark for a nationwide system. The primary relevance of this table to the current review is to highlight the potential of these technologies while underscoring that for AI to be effectively leveraged for seismic mitigation across Malaysia, a significant effort in collecting robust, standardized national seismic data for training and validation is an essential prerequisite.

Table 1 *ML models with different correlation coefficients corresponding to Time Interval and Depth* [44]

Model algorithms	**Time interval**	**Acceleration**				**Depth**			
		R	R^2	RMSE	MAE	R	R^2	RMSE	MAE
Support vector machine regression: Type 1	10	0.2298	0.0528	0.3415	0.2688	0.0916	0.3027	0.3026	0.2038
	15	0.3365	0.1133	0.2969	0.1847	0.3602	0.1297	0.2771	0.1764
	20	0.4551	0.2071	0.3241	0.1773	0.3222	0.1038	0.2650	0.1391
Support vector machine regression: Type 2	10	0.2285	0.0522	0.3411	0.2687	0.3121	0.0974	0.2993	0.2064
	15	0.3358	0.1127	0.2861	0.1876	0.3587	0.1286	0.1677	158.16
	20	0.5105	0.2607	0.3145	0.1681	0.3222	0.1038	0.2634	0.1364
Boosted decision tree regression	10	0.6264	0.3924	0.2606	0.1867	0.2610	0.0681	0.3023	0.2185
	15	0.5237	0.2743	0.2592	0.1660	0.5911	0.3495	0.2332	0.1421
	20	0.5508	0.3033	0.3059	0.1622	0.3623	0.1313	0.2624	0.1390
Random forest: regression	10	0.2399	0.0576	0.3319	0.2452	0.2887	0.0833	0.2998	0.2049
	15	0.3268	0.1068	0.2867	0.1716	0.4475	0.2003	0.2702	0.1593
	20	0.2065	0.0427	0.3648	0.2003	0.2368	0.0561	0.2717	0.1368
MAR spline	10	0.2217	0.0492	0.3229	0.2384	0.2887	0.0833	0.2998	0.2049
	15	0.4708	0.2217	0.2862	0.1581	0.0710	0.0050	0.2862	0.1689
	20	0.0431	0.0019	0.2420	0.1986	0.3199	0.1023	0.2420	0.1411

Table 2 *Summary of Key Earthquake Mitigation Strategies and Their Application in Malaysia* [44]

Strategy Type	Specific Measure/Approach	Key Benefit	Status/Application in Malaysia	Key Challenge/Gap (Malaysia)
Structural - Design Codes	Eurocode 8 Adoption	Enhanced structural safety, standardized design	Adopted with National Annex; ongoing refinement	Retrofitting older structures; funding for upgrades; enforcement compliance
Structural - Innovative Design	Base Isolation Systems	Reduced seismic forces, decoupled building response	Increasing prominence; active research (e.g., scrap tyre tech)	Technical expertise; cost for widespread adoption; integration into existing structures
Structural - Innovative Design	Energy Dissipation Systems	Absorbed seismic energy, reduced structural damage	Applied in high-rise buildings; research on hybrid systems	Widespread implementation; cost-effectiveness for diverse building types
Non-Structural - Early Warning	ShakeAlert Integration (concept)	Timely alerts, critical lead time for protective actions	Focus on integration of ML/AI; real-time monitoring enhancement	Data integration accuracy; public understanding of alerts; system reliability
Non-Structural - Preparedness	Public Awareness Campaigns	Improved community response, reduced casualties	Ongoing initiatives (e.g., school programs, safety drills)	Varying readiness levels; sustained engagement; reaching diverse communities

5.4 Governance, Institutional Capacity, and Community Participation

A critical review of Malaysia's earthquake mitigation strategies reveals significant shortcomings that exist beneath a surface of progressive policymaking. While the nation has modernized its disaster management architecture, a core weakness lies in its crisis-driven policy evolution. The country's history is marked by a "policy-disaster cycle," where major reforms are consistently a reaction to catastrophic failures rather than the result of proactive foresight [32]. The very formation of the National Disaster Management Agency (NADMA), for example, was not a preemptive measure but a direct response to the systemic inadequacies exposed during the 2014 floods and the 2015 Ranau earthquake. This historical pattern of reactive governance creates a deep-seated vulnerability; the political will and resources needed for structural change are typically mobilized only after a tragedy has occurred, suggesting that momentum for Disaster Risk Reduction (DRR) could easily wane during periods of calm, leaving the nation chronically underprepared [45]. Another contributing factor to Malaysia's mitigation efforts comes from the research community amongst which is the work of [32] who in their 2021 study, developed a local Integrated Disaster Risk Assessment Framework (IDRAF) to provide a more holistic tool for Malaysian decision-makers. Arguing that previous national approaches focused too heavily on post-disaster damage assessment, the authors proposed a framework built upon two core components: multi-hazard and multi-dimensional vulnerability. In their model, the multi-hazard component quantifies risk not only by the frequency of eight major hazards affecting Malaysia but also by their spatial interaction, or the potential for one hazard to trigger another. Their multi-vulnerability component, adapted from the European MOVE framework, assesses six key dimensions of society: social, economic, physical, institutional, environmental, and cultural. Through a rigorous five-phase process involving expert questionnaires and statistical analysis (PCA), Ramli *et al*. selected and weighed 54 critical indicators to measure these vulnerabilities. The authors acknowledge that their framework's practical application is challenged by significant limitations in data availability—especially for cultural indicators and at highly localized scales—and requires a high degree of inter-agency cooperation to be effective. Despite these hurdles, the study presents the IDRAF as a crucial, integrated approach for identifying high-risk areas and enhancing Malaysia's disaster mitigation and preparedness strategies.

This reactive approach at the policy level is mirrored by a significant "knowing-doing gap" at the institutional level, creating a persistent disconnect between well-formulated strategies and their on-the-ground implementation. This is starkly evident in the enforcement of the modern Eurocode 8 seismic building standard. Despite its adoption in 2017, its application has been hampered by inconsistent enforcement and a critical shortage of engineers with the specialized expertise needed to apply its complex provisions correctly, fostering a false sense of security in new construction [46]. This gap is exacerbated by an inflexible, top-down command structure that has been criticized for its rigidity and potential for creating communication bottlenecks during rapidly evolving disasters [47]. The 2015 Ranau earthquake response highlighted this flaw, as the centralized system was initially less effective than informal, local actors whose knowledge was essential for success [48]. Furthermore, current policies largely ignore the immense legacy risk posed by the vast stock of older, pre-code buildings. This represents the single largest unmitigated seismic vulnerability in the country, yet there is no comprehensive national framework to mandate or financially support the crucial task of retrofitting these high-risk structures [49].

Beyond these top-down institutional flaws, critical challenges also persist at the grassroots level. Despite the promotion of a "whole-of-society" approach, community-based programs face a fundamental struggle to achieve long-term sustainability. Initiatives like Community-Based Disaster Risk Management (CBDRM) often show initial success but see participation and impact "gradually diminish as the years passed" once external project support is withdrawn [50]. This lack of staying power often stems from a failure to instill a deep sense of local ownership, with programs sometimes being perceived as externally imposed rather than co-developed. This points to a deeper policy weakness: a focus on periodic "program implementation," such as annual drills, instead of the more complex task of continuously "cultivating a culture of resilience." Without a strategic shift toward empowering local leaders and permanently embedding preparedness into the social fabric, community resilience remains a short-term achievement rather than a sustainable, self-perpetuating characteristic of Malaysian society [50].

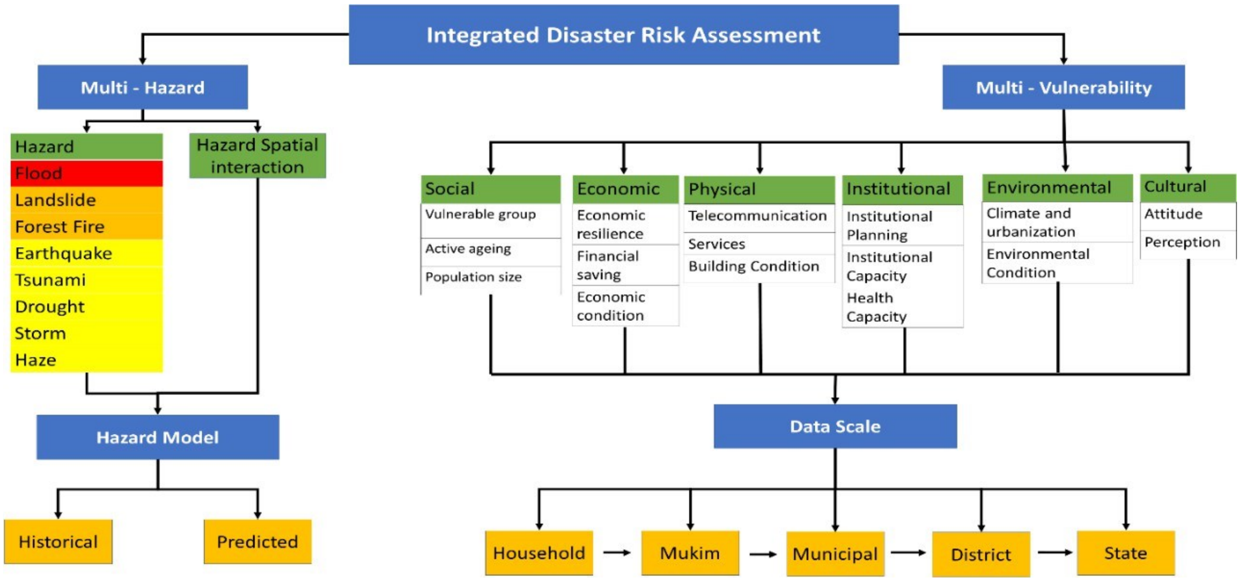

Figure 5 An Integrated Disaster Risk Assessment Framework proposed for Malaysia, which moves beyond single-hazard analysis to incorporate multiple hazards and vulnerabilities (social, economic, physical). This framework represents a strategic shift towards a more holistic and proactive model for building national resilience [32]

6.0 VULNERABILITY AND FRAGILITY ASSESSMENTS IN MALAYSIA

Vulnerability and fragility studies are gaining importance in Malaysia due to its exposure to seismic risks, especially in Sabah. While Malaysia is less seismically active than countries like Japan or Indonesia, its eastern regions remain vulnerable. Vulnerability studies assess the capacity of buildings, infrastructure, and populations to withstand earthquakes, while fragility studies quantify the likelihood of structural failure underground shaking. For example, [51] assessed local government preparedness in Bentong and Selayang, finding improved disaster response capabilities but identifying the need for better infrastructure resilience and community awareness. Similarly, [51] found community earthquake preparedness in Peninsular Malaysia remains generally low. Critical infrastructure, such as dams and bridges, also faces seismic risks. [52] highlighted the need for retrofitting dams, while [53] identified structural failures in beam-column joints after Malaysia's first major earthquake, underscoring the need for enhanced design standards. Fragility curves developed by [46] for tall concrete wall buildings provide data for designing more resilient structures. Web-based rapid screening tools, like that proposed by [54], facilitate vulnerability assessments, aligning with international practices [55], [56], which offer probabilistic models to identify weak structural components, including pile foundations [57]. Environmental impacts such as earthquake-induced landslides, studied by [11] after the 2015 Sabah earthquake, highlight the need to integrate seismic assessments with geohazard planning. Hospitals are also a concern, with [51] emphasizing the need for specialized preparedness plans. [32] proposed an integrated disaster risk assessment framework for Malaysia, incorporating fragility data into national strategies as is illustrated in Figure 5. Policy efforts include seismic disaster zone mapping by [13], essential for guiding vulnerability assessments and preparedness plans. Overall, while Malaysia's seismic risk is lower than its neighbors, vulnerability and fragility studies are crucial to enhance infrastructure resilience, reduce risks to the population, and ensure preparedness for potential seismic events.

7.0 CONCLUSION

This study concludes that Malaysia is in the midst of a significant and commendable transformation in its approach to seismic risk, successfully shifting from a historically reactive posture to a proactive, risk-informed framework. The establishment of the National Disaster Management Agency (NADMA) and the alignment of national policy with the Sendai Framework demonstrate a clear, high-level commitment to building resilience. This national architecture is supported by a strong scientific base and a vibrant civil society, creating a "whole-of-society" ecosystem capable of addressing complex hazards. However, the analysis reveals that this progress is tempered by deep-seated, systemic challenges that create a gap between progressive policy and on-the-ground reality. A critical "knowing-doing gap" persists in the enforcement of modern building codes like Eurocode 8, hampered by inconsistent application and a shortage of specialized expertise. The nation's single largest vulnerability—the vast stock of older, pre-code buildings—remains a largely unaddressed legacy risk due to formidable legal and financial barriers to retrofitting. Furthermore, the 2015 Ranau earthquake exposed a "decentralization paradox" where the formal, top-down disaster management structure was less effective than the indispensable knowledge of local actors. At the community level, while preparedness programs show promise, their long-term sustainability is a key concern, with a need to shift from temporary projects to the continuous cultivation of a national culture of resilience. To bridge these gaps, the study's findings point to several strategic pathways. For governance, the focus must be on formally integrating local leadership into official disaster management structures and establishing sustainable funding for community-based initiatives. For institutional capacity, priorities include launching a national certification program for Eurocode 8 to close the skills gap and developing a comprehensive legal and financial framework to address the retrofitting imperative. Finally, for community participation, the strategy must evolve from implementing periodic drills to a continuous model of "resilience cultivation" that is embedded in school curricula and local life. Ultimately, charting Malaysia's course towards a seismically resilient future requires sustained political will and an unwavering commitment to closing the gap between policy and practice. By addressing the implementation challenges with foresight and strategic investment, Malaysia can build upon its strong policy foundation to ensure a safer and more secure future for all its communities.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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