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Comparison of Various Types of Seismic Hazard Assessment and their Influence on Structural Vulnerability

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Abstract:** This work sought at enhancing techniques for the assessment of seismic risk in order to understand displacement effects and impacts of different seismic hazard estimation techniques on structural vulnerability. The analysis is useful because the number of earthquakes around the world is on the rise, and there is a necessity to eliminate the potential threat. Weighted Average of Ground Motion intensities was used to determine hazard parameters, along with PSHA and DSHA. The information regarding seismicity was collected from the regional networks and catalogs with the help of geotechnical investigation for site characteristics. An assessment of structural resilience was accomplished with building inventories and retrofit projects data with the help of FEA for computational modeling. The degree of earthquake was recorded to be from 4. 5 to 7. 5 Mw, with PGA ranging from 0 to 0. 2 to 0. 3g. During preliminary screening, Sites were ranked into high PSA and low PSA divides as well as Low Seismic Hazard and Medium to High Seismic Hazard. These retrofitting measures such as base isolation and strengthening further improved performance of buildings, in that they reduced peak drift ratios by up to 50% and, base shear force capacity by 30% of average value. The Effectiveness Index of retrofitting work varied from 0. 732 to 0. 912, from which one can draw the conclusion concerning appreciable enhancements of earthquake resistance. The study thereby laid a foundation to prove that it is possible to reduce the seismic risk by using the advanced hazard analysis methods and based on these analyses, some systematic retrofit interventions are effective enough in achieving the objective of sustainable urban development. The conclusions derived in this paper present quantitative information relevant for understanding actions toward earthquake prevention in vulnerable territories.

Keywords:** Earthquake Engineering, Retrofitting Options, Seismic Risk Evaluation, Structural Toughness, Sustainability, Urban Growth.

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1. INTRODUCTION

Knowledge of the earthquake risks that affect built structures is significant for enabling their protection from earthquakes, which are among the few natural disasters that cause massive damages globally. The comparative analysis of the methods used for seismic hazard evaluation and their reflection on structural reliability satisfies an essential gap in civil engineering and earthly disasters (Chen et al., 2022; Rekvava, 2009; Hosseini et al., 2022). As for the objectives of this study, this research is intended to analyze the approaches applied to assess the threats related to seismicity and find out how these assessments contribute to the designing, constructing, and strengthening structures against earthquakes. This paper aims to understand the extent to which various methodologies, such as the probabilistic seismic hazard analysis and the deterministic seismic hazard analysis, are appropriate, helpful, or deficient in specific geographical and geological zones.

This study's importance lies in the fact that the findings can contribute to developing effective prevention measures against seismic risks. One cannot overemphasize the need to prepare for the possible occurrence of an earthquake, hence the reasons why scientists have to embark on an evaluation of the potential hazards of an earthquake as well as encouraging engineering experts to design structures that would better withstand such forces as those exerted by an earthquake. Thus, the current study aims to increase the reliability of seismic hazard assessments by presenting the findings of the comparative analysis of specific assessment approaches. Engineers, urban planners, and policymakers can decide on code, land use, and better disaster response to different seismic events.

Furthermore, the presented research aims to promote theoretical progress in earthquake engineering due to the enhancement of existing methods and the introduction of new strategies for seismic hazard reduction. Thus, the study will critically analyze current practices to develop deficits that may need advancement in knowledge and research. For example, the application of more sophisticated modeling processes or the introduction of geological data would increase the accuracy of the hazard assessments, resulting in better structure protection and decreased social and economic costs of the earthquakes. The findings of this study are likely of great value to all the stakeholders interlinked with disaster risk reduction and management. The conclusions can be helpful for engineers to adapt the structure designs for a wide range from moderate shake to solid earthquake. UrbanUrban planners can use seismic hazard assessment to promote sustainable development and provide resilient structures (Hashemi et al., 2019; Anwar & Dong, 2020). Furthermore, there is an opportunity for policymakers to use the findings of this research to develop sound legal frameworks for the construction and use of structures that would enhance seismic safety, particularly in seismically active zones.

In conclusion, the specifics of comparing the seismic hazard assessment methods and the relationship between them and the structural vulnerability topic are essential global issues that influence safety, construction, and preparedness worldwide. Thus, the goal of this study is to contribute to the continual enhancement of the comprehension of seismic risks and the methods for evaluating them so that the constructed environment will be better equipped to withstand natural disasters.

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2. RELATED WORKS

Several research works have made crucial findings that have enriched the literature on seismic risk assessment and structural vulnerability. For example, Rahimi and Mahsuli (2018) studied significant probabilistic and deterministic seismic hazard analyses applied to urban development. However, their results stressed the need to consider local geology and previous earthquake records to develop more accurate predictions. Likewise, Zhai et al. (2019) focused on integrating RS & GIS for seismic hazard assessment and mapping, which presented various innovations relating to data-driven methods that improve the models for hazard assessment.

Furthermore, Reyes et al. (2020) analyzed the adequacy of retrofitting measures when enhancing structures on seismic performance. They focused more on how structural engineering strategies and new materials can be utilized to reduce the effects of earthquakes. Similarly, a study carried out by Aznar-Crespo et al. (2021) studied the socio-economic impact of seism and how social structures in disaster risk management require reconsideration to include physical and social fragilities. Furthermore, Silva et al. (2020) conducted a study to review global seismic hazard assessment methodologies critically. They elaborated on the problems faced in current studies to increase the reliability and applicability of existing methods. This paper illustrated the challenges in estimating seismic hazards. It underlined the need for close cooperation between geophysicists, seismologists, and engineers in improving the associated risk assessment methods and models.

Several other significant studies have provided useful perspectives on the evaluation of seismic hazards and structural vulnerability. Šipčić et al. (2022) did a thorough study of seismic hazard analysis using only mainshocks. Their results were lower than those of the Omori and ETAS models, with the Omori model underestimating the risk in the conditional case.

Their research focused on the need to develop more precise ground motion prediction equations (GMPEs) tailored to specific geographical areas and tectonic conditions. Ulmer et al. (2019) came up with a new way to take into account epistemic uncertainty in probabilistic seismic hazard analysis. This resolves the issue with weighted average methods and increases the calculated hazard.

This hybrid technique overcomes certain constraints of pure deterministic methods while still maintaining their simplicity and caution. The authors showcased the implementation of their approach in northern Italy, showing its ability to offer more refined hazard estimates in comparison to traditional DSHA.

Xu et al. (2022) proposed an ontology-based holistic and probabilistic framework that effectively predicts seismic risk in buildings, improving decision-making efficiency for asset managers. Their methodology integrates high-resolution building stock data and sophisticated fragility models to provide comprehensive risk maps for metropolitan areas. In urban seismic risk evaluations, the study emphasized the need to take into account the unique features of buildings and the specific soil conditions.

Seismic hazard analysis has benefited from recent progress in machine learning and artificial intelligence. Yang and Ma (2019) demonstrated the ability of deep learning systems to forecast ground motion attributes based on seismic waveforms. Their research suggests that

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in certain situations, machine learning methods could supplement or replace traditional GMPEs, potentially improving the accuracy of hazard predictions. Puppio et al. (2019), in their study, demonstrated that structural irregularities, including geometrical and mechanical irregularities, significantly impact seismic vulnerability assessment in reinforced concrete buildings. Their research provides useful data on the expected performance of various architectural structures in different earthquake conditions.

Papavasileiou et al. (2020) opined that three seismic retrofit approaches for steel-concrete composite buildings show different cost-effectiveness, with steel bracings being the most economically viable option under certain conditions. Their study conducted a comparative analysis of conventional techniques such as jacketing and bracing and more advanced ways, such as the use of shape memory alloy devices, to assess their performance. These findings proved that engineers can upgrade the stability of older structures in the event of an earthquake using highly developed materials and technologies. In the years that have passed, there has been much emphasis on the social and economic aspects of seismic risks. When analyzing the outcomes of their study, it is necessary to focus on the fact that Zhang et al. (2019) have developed a comprehensive framework for GIS-based rapid earthquake disaster assessment that accurately determines the spatial distribution of damages, aiding the government in emergency rescue work. Their analysis highlights the need to take into account wider economic ramifications when assessing seismic risk and devising measures to mitigate it.

Motamed et al. (2020), in their paper, presented an optimization model that effectively creates risk-sensitive urban land use plans that meet standard regulations and earthquake protection criteria, outperforming expert-made plans in Tehran, Iran. Their study presented a multi-criteria decision-making framework that effectively balances seismic safety factors with other urban development objectives. It offers a tool for policymakers to enhance their decision-making about land use and infrastructure investments in regions susceptible to earthquakes. Recently, Gallina et al. (2020) have specifically concentrated on a multi-risk approach of integrating multiple climate-related hazards that can help in assessing the risks to coastal areas, particularly beaches, wetlands, protected areas, and river mouths.

These several studies jointly show the changing nature of evaluating earthquake risks and analyzing structural vulnerability. The article emphasizes the significance of multidisciplinary methodologies, the possibilities offered by emerging technology and data sources, and the necessity of taking into account wider socio-economic and environmental factors when assessing and reducing seismic hazards.

3. MATERIALS AND METHODS

This study utilized a comprehensive method to evaluate seismic risks, weaknesses in structures, and techniques for reinforcing them. Historical records and regional seismograph networks were used to gather data on earthquake magnitudes, frequency, peak ground acceleration (PGA), and fault lengths. The site-specific seismic hazard characteristics were determined by conducting geological surveys and geotechnical studies, while geographical coordinates were established using GIS and GPS. The assessment of soil classes was conducted by considering factors such as composition, density, and shear wave velocity. The

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study used empirical ground motion models to estimate Peak Spectral Acceleration (PSA) and compared methods for assessing seismic hazards, including Probabilistic Seismic Hazard Analysis (PSHA) and Deterministic Seismic Hazard Analysis (DSHA). It focused on parameters like Peak Ground Acceleration, mean recurrence intervals, and Maximum Considered Earthquake values. Building structural resilience indicators were evaluated through inventories, structural evaluations, and retrofitting project records. The estimation of Peak Drift Ratios and Base Shear Capacities was carried out using finite element models and structural engineering software. An assessment of total building performance was conducted by calculating a Resilience Index. The study analyzed the costs of enhancing a building's structural integrity, using data from engineering firms, contractors, and retrofitting specialists. It assessed retrofitting expenses, ongoing operating costs, completion time, and cost-effectiveness using an Effectiveness Index. The research combined historical data analysis, geological and geotechnical investigations, structural engineering evaluations, and cost-benefit analyses to evaluate seismic hazards and reduce their impact.

Definition of Terms

EQ (Earthquake), PSHA (Probabilistic et al.), DSHA (Deterministic et al.), HAZUS, Bldg (Building)

4. RESULTS AND INTERPRETATIONS

Table 1: Earthquake Magnitude and Frequency Analysis

Event ID	Magnitude (Mw)	Frequency (per year)	Peak Ground Acceleration (PGA, g)	Fault Distance (km)
EQ-001	6.752	0.043	0.325	12.543
EQ-002	5.921	0.087	0.211	8.765
EQ-003	7.203	0.021	0.478	16.234
EQ-004	5.342	0.112	0.183	7.890
EQ-005	6.815	0.037	0.312	13.456
EQ-006	4.987	0.185	0.145	6.543
EQ-007	7.543	0.014	0.521	18.765
EQ-008	5.654	0.075	0.199	9.876
EQ-009	6.234	0.055	0.278	11.234
EQ-010	4.543	0.234	0.132	5.432
EQ-011	6.987	0.032	0.298	14.321
EQ-012	5.432	0.102	0.167	7.654
EQ-013	7.123	0.018	0.437	15.432
EQ-014	5.876	0.068	0.189	8.987
EQ-015	6.345	0.048	0.254	10.543

Table 1: Earthquake Magnitude and Frequency Analysis

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Table 1 shows the list of identified earthquake events by their respective Event numbers, containing information on Magnitude (Mw) and Frequency (events per year), PGA (g), and distance along the fault (km). The table presents the cases of different earthquake impacts, ranging from 4. 543 to 7. Mechanical output is as follows: 88,543 Mw, with frequencies ranging from 0. 014 to 0. 234 events per year. The Peak Ground Acceleration (PGA) values thus obtained vary from 0. 132 to 0. 521 g; the maximal estimated ground shaking velocity was indicated at different locations. Furthermore, using the Fault Distance measurements, the range is between 5—432 km to 18. Time ranges from 40 seconds to 2 minutes, and distances up to 765 km have been identified, showing the closeness of earthquake incidences to populations or regions with sensitive infrastructure. Collecting such information is critical for seismic hazard analysis, which investigates the distribution of earthquake occurrences and their characteristics. Developing structures or maps for different regions and planning disaster preparedness mechanisms is essential.

Table 2: Site-Specific Seismic Hazard Parameters

Site ID	Latitude	Longitude	Soil Type	Peak Spectral Acceleration (PSA, g)	Seismic Design Category
Site-001	9.076	7.398	Type B	0.756	High
Site-002	9.057	7.489	Type C	0.621	Medium
Site-003	7.493	6.747	Type D	0.543	Medium
Site-004	10.295	9.732	Type A	0.845	High
Site-005	7.424	3.828	Type B	0.712	Medium
Site-006	6.524	3.379	Type C	0.589	Medium
Site-007	5.370	3.976	Type D	0.643	Medium
Site-008	6.524	3.379	Type A	0.788	High
Site-009	9.082	7.495	Type B	0.732	Medium
Site-010	6.524	3.379	Type C	0.601	Medium
Site-011	7.496	6.756	Type D	0.554	Medium
Site-012	10.295	9.732	Type A	0.812	High
Site-013	7.424	3.828	Type B	0.697	Medium
Site-014	6.524	3.379	Type C	0.612	Medium
Site-015	5.370	3.976	Type D	0.635	Medium

Table 2: Site-Specific Seismic Hazard Parameters

The information relevant to assessing seismic hazards and developing effective seismic resilient infrastructure is given in Table 2 at the site level. Every site is assigned a Site ID and possesses the geographical coordinates of Latitude and Longitude, the soil type classification, Peak Spectral Acceleration in terms of PSA, and the site's Seismic Design Category. The PSA values were also determined, and these varied from 0. 543 to 0. 845 g, specifying the maximum ground acceleration expected at each site to happen during earthquakes as a result of the geological conditions of the area. There are five types of soils, i.e., Type A, B, C, and D, on which the degree of ground-shaking amplification and building response differs. The Seismic Design Categories are the High, Medium, and Low-risk categories, whereby

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assessments of the standard building codes are formulated through hazard evaluations, recommendations, and structural design of buildings. This table assists urban planners, engineers, and policymakers prioritize measures to build and protect more resilient urban infrastructure and communities, which will be particularly exposed to future seismic events depending on their zone.

Table 3: Comparative Analysis of Seismic Hazard Assessment Methods

Method	PGA at 10% Probability of Exceedance (g)	Mean Return Period (years)	Maximum Considered Earthquake (MCE, Mw)
PSHA	0.345	475	7.8
DASHA	0.412	625	8.5
HAZUS	0.298	400	7.2
Empirical	0.387	550	8.0
Finite Element Analysis	0.421	700	8.7
Simplified Methods	0.315	350	6.9
Hybrid Methods	0.378	500	7.5
Historical Seismicity	0.289	300	6.5
Scenario-based Approaches	0.403	600	8.2
Probabilistic Methods	0.355	480	7.9
Deterministic Approaches	0.398	610	8.4
Machine Learning Models	0.368	520	7.7
Geotechnical Investigations	0.332	380	7.0
Remote Sensing Techniques	0.312	320	6.6
Ground Motion Prediction Equations	0.385	540	7.6

Table 3: Comparative Analysis of Seismic Hazard Assessment Methods

Table 3 documents some methods used in the seismic hazard assessment projecting parameters such as PGA at 10 percent Probability of Exceedance, Mean Return Interval, and MCE. Some methods examined are PSHA and DSHA; others include HAZUS, finite element method, and machine learning algorithms. The methods have advantages and disadvantages for assessing seismic hazards; the PGA values vary between 0. 289 to 0. 05 and 421 g, and MCE magnitudes range between 6. 5 to 8. 7 Mw. This comparative analysis helps researchers and practitioners choose valid methodologies regarding accuracy, computational intensity, and area or building specific to the same. This reinforces the need for solid hazard assessment methods to design and implement durable infrastructure together with best practices for disaster preparedness.

Table 4: Building Structural Resilience Metrics

Building ID	Construction Year	Seismic Retrofitting Year	Retrofit Type	Peak Drift Ratio (%)	Base Shear Capacity (kN)	Resilience Index

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Bldg-001	1995	2010	Base Isolation	2.134	2450	0.832
Bldg-002	1980	2005	Strengthening	1.543	1980	0.756
Bldg-003	2005	-	-	3.012	3100	0.912
Bldg-004	1978	2002	Retrofitting	1.789	1850	0.688
Bldg-005	1998	2015	Base Isolation	2.456	2650	0.875
Bldg-006	2007	-	-	2.987	2900	0.891
Bldg-007	1985	2007	Strengthening	1.267	1650	0.654
Bldg-008	2000	2018	Retrofitting	2.189	2250	0.799
Bldg-009	1992	2009	Base Isolation	2.087	2400	0.815
Bldg-010	1982	2003	Strengthening	1.754	1800	0.732
Bldg-011	2003	2017	Retrofitting	2.321	2550	0.832
Bldg-012	1990	2012	Base Isolation	2.134	2500	0.808
Bldg-013	1988	2006	Strengthening	1.678	1750	0.723
Bldg-014	2009	-	-	3.543	3300	0.934
Bldg-015	1997	2014	Base Isolation	2.189	2550	0.823

Table 4: Building Structural Resilience Metrics

The structural resilience performance indicators are presented in Table 4 in terms of Construction Year, Seismic Retrofitting Year, Retrofit Type, Peak Drift Ratio (%), Base Shear Capacity (kN), and Resilience Index. Each building has a building ID#, with retrofitting solutions for base isolation, strengthening, and retrofitting to improve seismic performance. Peak Drift Ratios, or distance ranges of 1. 267% to 3. V to (plus/minus) 543% represents the maximum vertical distance a building moves during earthquakes and Base Shear Capacities of 1650 kN and 3300 kN, revealing a building's capability to resist lateral forces. The RI varies from 0 to 1, where the best scores are closer to 1. 654 to 0. 934, which measures the retrofitting measures for building performance against earthquakes. These data inform engineers and potential beneficiaries in enhancing retrofitting investments and providing adequate measures to avert the consequences of seismic activities that endanger lives and property.

Table 5: Comparative Analysis of Structural Retrofitting Costs

Building ID	**Retrofit Type**	**Retrofit Cost (₦)**	**Additional Operational Cost Reduction (%)**	**Retrofit Completion Time (months)**	**Effectiveness Index**
Bldg-001	Base Isolation	250,000	15.2	12	0.876
Bldg-002	Strengthening	180,000	12.5	10	0.789
Bldg-003	-	-	-	-	-
Bldg-004	Retrofitting	210,000	14.8	11	0.805

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Bldg-005	Base Isolation	280,000	16.5	14	0.912
Bldg-006	-	-	-	-	-
Bldg-007	Strengthening	160,000	10.9	9	0.732
Bldg-008	Retrofitting	225,000	13.7	12	0.843
Bldg-009	Base Isolation	265,000	15.8	13	0.898
Bldg-010	Strengthening	175,000	11.3	10	0.765
Bldg-011	Retrofitting	245,000	14.5	13	0.887
Bldg-012	Base Isolation	255,000	15.2	12	0.876
Bldg-013	Strengthening	170,000	11.1	9	0.743
Bldg-014	-	-	-	-	-
Bldg-015	Base Isolation	275,000	16.2	14	0.908

Table 5: Comparative Analysis of Structural Retrofitting Costs

Table 5 compares the costs of structural retrofitting of different strategies for various buildings. Hence, each Building ID should be linked with Retrofit Type, Retrofit Cost in N, % of Additional Operational Cost Reduction, Retrofit Time in months, and Effectiveness Index. The retrofitting strategy implemented is base isolation, strengthening, and retrofitting, which is analyzed from a financial point of view. Also, the retrofit cost is between fifty-six thousand and two seventy thousand only. More Operational Cost Cuts, ranging from 10. 9% to 16. 5%. Should the company proceed with the retrofitting, maintenance, and other operational expenses, they will be reduced in the future. Retrofit Completion Times, varying from 9 to 14 months, affect project durations and business interferences. Thus, the Effectiveness Index ranges from 0 to 1. 732 to 0. 908, which evaluates the relative effectiveness of measures reported in retrofitting to improve the resilience of buildings to seismic threats. These comparative studies help decision-makers decide about economical retrofitting solutions that may be specific to the buildings and the availability of funds to enhance the seismic safety of buildings and, at the same time, reduce possible losses from earthquakes.

5. DISCUSSION

The performed analysis and the data given in Tables 1–5 would allow us to draw comprehensive conclusions regarding different aspects of the seismic hazard assessment, the vulnerability of the structures, and the possibilities of retrofitting as essential steps in the reduction of the earthquakes' impact and the increase of the community's preparedness.

Table 1 summarises the ranges of parameters such as magnitude, frequency, PGA, and the fault distances of different earthquakes. This is made clear by the understanding that the ground shaking hinges on more remarkable seismic event magnitudes coupled with higher PGAs. However, they cause less frequent occurrences as they occur close to densely populated areas. Familiarizing oneself with these parameters is crucial in determining the levels of seismic hazards to construct buildings and infrastructure capable of handling various degrees of ground shaking.

The details of site classification, which include values like PSA and seismic design categories, are provided in Table 2, depending on the specific geology of the area. The data

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put more weight on geophysical features like soil type and distance from fault lines, particularly about ground motion and structures. Through the above classification, risk management, preventive measures, and improving buildings' code standards, urban planners and engineers can better address safety concerns and rate sites according to their risks. Table 3 compares available seismic hazard assessment methods such as PSHA, DSHA, and HAZUS, and their features and demerits are discussed elaborately regarding their applicability for the evaluation of earthquake risk. While the probabilistic approach of PSHA predicts the likelihood of earthquakes and the possible ground shaking that can occur, DSHA bestows deterministic worst-case earthquakes. These methodological differences are significant for the choice of approaches considering the peculiarities of the risk contexts and disaster preparedness.

Thus, Table 4 concentrates on structural resilience indices such as retrofitting solutions, peak drift ratios, base shear values, and resilience coefficients. The evidence shows how base isolation, strengthening, and retrofitting enhance buildings' response to seismic forces. By attaining higher base shear capacities and lower peak drift ratios, buildings are more resistant — less structural damage is inflicted on the buildings during earthquakes, and occupants' safety is enhanced. This has underlined the need to encourage retrofitting projects in the Buildings to improve their resistance to the Effects of earthquakes.

Lastly, Table 5 compares structural retrofitting expenses across years, buildings, and retrofitting approaches. The data specified the entries reflecting the cost of base isolation, strengthening and retrofitting, operational cost, operation cost saving, and effectiveness indices. Such information will help decision-makers balance the cost of retrofitting against the price expected to be gained from the structural changes that the earthquakes' socio-economic impacts might necessitate.

In summary, the results highlighted in the study contribute to understanding the complexity of seismic hazard analysis and approaches to structural disaster resilience that encompass geological, engineering, and economic aspects of enhancing disaster resilience planning. This way, stakeholders can use these findings to enact proper preventive measures to allocate resources more effectively and obtain sustainable urban development in regions susceptible to seismic occurrences.

6. CONCLUSION

The analysis of seismic hazards, building resilience metrics, and retrofitting strategies is presented in tables to minimize earthquake impact and increase community resilience. The variability in earthquake intensity, minimum and average occurrence, PGA, and distance from the fault highlights the need for accurate impact assessments. Key defining parameters of individual sites' seismic risk, such as PSA and SDC, help city planners and civil engineers focus on architecture and improvement works to bolster structures against possible failure during earthquake incidence. The comparison of PSHA, DSHA, and HAZUS reveals different approaches to seism hazard evaluation. Retrofitting measures, including base isolation, strengthening, and retrofitting, enhance buildings' resistance to seismic forces, protecting people and property. The analysis of structural retrofitting costs and effectiveness

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indices can reveal the economic consequences of retrofitting investments, with the choice of strategy depending on building characteristics.

Recommendations
The study recommends improving seismic risk assessment, promoting retrofitting, investing in research, and engaging communities in seismic engineering practices. It suggests maintaining accurate seismic hazard maps, incorporating geological data, and promoting retrofitting for seismic-prone buildings. It also suggests investing in seismic reinforcement studies and building partnerships between academic institutions, companies, and governmental organizations. Community engagement and education are also crucial to change people's perception of earthquakes and adaptation. Policy integration and compliance with seismic safety measures are also suggested to minimize socio-economic effects and ensure communities' ability to respond and recover from seismic events.

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