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Seismic Hazard Map of ASEAN Countries towards Risk Assessment and Sustainability of Structures and Infrastructures

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Abstract: This study contains the most recent seismic hazard map of Southeast Asia. This area is located to the south of the Eurasian plate. The Ring of Fire that surrounds the region makes it one of the most active in terms of earthquakes and volcanoes. Malaysia, Indonesia, Thailand, Singapore, the Philippines, Myanmar, Vietnam, Laos, Cambodia, and Brunei are among the countries being studied. The goals of this project are to provide Peak Ground Acceleration (PGA) values for all regions in ASEAN countries, and then to create seismic zoning maps for these countries so that zones with non-seismic regions can be identified and zones with no special steel reinforcement-detailing requirements can be specified. The final step is to create design response spectra. Based on each nation's most recent body of literature, the PGA hazard map is created. There are two maps that need to be created, one for 10% and one for 2% probability of exceeding. The PGA contours of all the compiled maps were then reconstructed, and the baseline colours were compared to an Indonesia seismic hazard map. The maximum PGA value for Southeast Asia is as high as 0.8g at 10% and 2.0g at 2% probability of exceedance, respectively, whereas the minimum PGA value is typically equal to 0.0g at both 10% and 2% probability of exceedance. The design response spectrum distribution of the stable with moderate earthquake region from 0 to 4 s (including West Malaysia, Sabah and Sarawak of East Malaysia) and the distribution of spectra for active earthquake regions including Indonesian cities (including Acheh, Padang and Palu) are plotted. Then, the design response spectra for the selected cities in regions of moderate seismicity and active earthquakes are integrated.

Keywords: Sustainable structure, Earthquake asian, Seismic hazard

Introduction

Southeast Asia is lying within the Pacific Ring of Fire, an area with frequent seismic and volcanic activity. It is flanked on the west by the seismically active Indonesian Volcanic Arc (200-300 km away), which marks the inter-plate boundary (subduction zone) between the Indo-Australian and Eurasian Plates, and on the east by the Eurasian and Philippines Plates. These plates interact in complex ways, resulting in a diverse set of geological characteristics and seismic hazards. Metcalfe (2017), Shah et al. (2018), Pilia et al. (2023), Holt et al. (2018), Lallemand (2016), Khin et al. (2017) on Cummins (2017), Triyoso et al. (2022), and others have investigated Southeast earthquake hazards. Large earthquakes originating in these volcanic arcs have been felt across Southeast Asia. The regular occurrence of tremors inside the country and its surrounding region appears to indicate that ASEAN countries such as Malaysia, Brunei, Indonesia, the Philippines, Singapore, Myanmar, Vietnam, Laos, Thailand, and Cambodia face seismic risk. The question now is whether seismic variables should be included in infrastructure planning and design, as well as the degree of risk and its regional variation. These questions have gone unanswered thus far due to a dearth of seismic knowledge and seismic data. As a result, the magnitude of seismic hazard is unknown. It is unknown whether such a risk should be included in the design of future structures and infrastructure. This is exacerbated by the fact that ASEAN nations are quickly developing and critical transportation systems are being built at a rapid pace. Long-term ground vibrations produced by distant earthquakes may also endanger these structures.

One of Southeast Asia's most notable tectonic features is the Sunda Trench, a deep oceanic trench that extends along the western shores of Sumatra and Java. The Eurasian and Indo-Australian continents are separated by this trench, which is a hotspot for earthquakes and volcanic activity. The subduction of the Indo-Australian plate beneath the Eurasian plate, in particular, is responsible for the formation of the Indonesian archipelago and many active volcanoes in the region (Lemenkova, 2020, 2021). Another notable tectonic feature of Southeast Asia is the Philippine Mobile Belt, a zone of dynamic deformation that comprises the Philippine Sea plate and numerous smaller microplates. This area is also known for frequent earthquakes, many of which are triggered by the subduction of the Philippine Sea plate beneath the Eurasian plate, as reported by Rangin (2016) and Suzuki et al (2017). The tectonic setting of Southeast Asia is complex and active, with multiple plates and microplates interacting in various ways (Li et. al., 2021; Hua et.al.,2022). This creates a high level of seismic and volcanic activity, putting people and infrastructure in the region at risk.

The Southeast Asia seismic hazard map, created previously by Petersen et al., (2007), is a vital tool for understanding the potential of earthquakes occurring in the region. Peak Ground Acceleration (PGA) hazard maps of 10% and 2% in 50 years were released by Petersen et al. (2007). The most recent hazard map is also available from Pagani et al. (2018, 2020) and published geographic distribution of the PGA with a 10% likelihood of being surpassed in 50 years, estimated under reference rock conditions (shear wave velocity, V, of 760-800 m/s). Despite being published in Pagani et al. (2018, 2020), the data map initially shows different values in contrast to MS EN1998:2015 (2017) for the Malaysia region. The most recent hazard map is also available from Pagani et al. (2018, 2020) and published geographic distribution of the PGA with a 10% likelihood of being surpassed in 50 years, estimated under reference rock conditions. Despite being published in Pagani et al. (2018, 2020), the data map initially shows different values in contrast to MS EN1998:2015 (2017) for the Malaysia region. This could be linked to an updated Malaysian database that includes local seismic sources, as discovered by Shoushtari et al. (2018) and Harith et al. (2023).

The seismic hazard map depicts the likelihood and intensity of earthquakes in different parts of Southeast Asia. Based on the information supplied by the map, governments and emergency responders may prioritise resources and prepare for possible disasters. The seismic danger map was constructed by using a variety of data sources, including prior seismic activity, geological surveys, and satellite photography (Morell et al., 2020; Xu et al., 2022). Statistics are used to assess which areas are most vulnerable to earthquakes and to estimate the potential damage caused by an earthquake in each area. On the map, a color-coded system is utilised to illustrate the level of seismic danger posed by each region. The bright colour represents the probability of an earthquake occurring in a location, while the low colour represents the probability of a small earthquake occurring in a region. The map also includes information on the probable repercussions of earthquakes, such as the possibility that buildings and infrastructure would be destroyed. The seismic hazard map for Southeast Asia is a vital resource for regional decision-makers and first responders. It contributes to the process of making decisions on infrastructure development, emergency planning, and disaster response. For example, the image might be used to evaluate whether areas require additional strengthening of building norms and standards to ensure that buildings can resist the effects of earthquake. This study aims to create the most recent seismic hazard map by incorporating all Southeast Asian nations (Malaysia, Brunei, Indonesia, the Philippines, Singapore, Myanmar, Vietnam, Laos, Thailand, and Cambodia).

Active Earthquake Region (Indonesia, Philippines, and Myanmar)

A region characterised by frequent earthquakes and ongoing tectonic activity is referred to as an active earthquake region. Consisting of the earth's surface, tectonic plates are constantly shifting and interacting with one another. The Earth's crust may experience pressures and strains where these plates converge, which may result in earthquakes. In comparison to other Southeast Asian nations, Indonesia, the Philippines, and Burma have the highest earthquake activity. Indonesia is prone to a high level of seismic and volcanic activity, with earthquakes and volcanic eruptions happening on a regular basis across the archipelago. The Indonesian archipelago and the region's many active volcanoes are the result of the subduction of the Indo-Australian plate beneath the Eurasian plate (Hutchings & Mooney, 2021). Indonesia is situated in the Ring of Fire, a seismically active region that encircles the Pacific Ocean. On December 26, 2004, a magnitude 9.1 earthquake off the coast of Sumatra caused one of the most devastating earthquakes to strike Indonesia. The earthquake triggered a series of tsunamis that affected several countries in the region, including Indonesia, Sri Lanka, India, and Thailand. The earthquake and resulting tsunamis killed more than hundreds of thousand people, making it one of the deadliest natural disasters in history. On September 28, 2018, a magnitude 7.5 earthquake struck off the coast of Sulawesi, an Indonesian island. The earthquake triggered a massive tsunami, wreaking havoc and killing thousands of people. Movement along the Palu-Koro Fault, a strike-slip fault that runs through the island of Sulawesi, caused the earthquake.

The Philippines is situated on the boundary between the Philippine Sea Plate and the Eurasian Plate and is prone to a high degree of seismic and volcanic activity. Active fault systems in the country, such as the Philippine Fault System and the Marikina Valley Fault System, pose significant earthquake hazards to the region. The Philippines is also located on the Ring of Fire and is highly prone to earthquakes due to its location on the intersection of several tectonic plates. Every year, thousands of earthquakes strike the country, with many of them being minor tremors that go unnoticed. However, there have been several devastating earthquakes in the country's history. On July 16, 1990, a magnitude 7.8 earthquake struck the island of Luzon, resulting in one of the deadliest earthquakes to strike the Philippines. The earthquake caused widespread devastation and the deaths of thousands of people. More recently, on October 15, 2013, a magnitude 7.2 earthquake struck the island of Bohol, causing extensive damage and killing hundreds of people. Volcanic activity also causes earthquakes in the Philippines. For example, Mount Pinatubo's eruption in 1991 caused a magnitude 7.8 earthquake, resulting in several deaths and widespread damage.

Myanmar is located on the boundary of the Indian Plate and the Eurasian Plate, which makes it an active earthquake region. The Sagaing fault, which runs north-south through the country, in particular, is a major source of seismic activity. The collision of these two plates is responsible for the tectonic activity in Myanmar, which has resulted in the formation of the Himalayan Mountain range and other mountain ranges in the region. Myanmar is vulnerable to earthquakes due to the region's tectonic activity, and the country has previously experienced several significant earthquakes. One of the most devastating earthquakes in Myanmar's recent history occurred on August 24, 2016. The 6.8 magnitude earthquake occurred in central Myanmar, near the town of Chauk. The earthquake was felt throughout the country as well as in neighbouring Thailand and Bangladesh. The earthquake caused widespread damage to buildings, roads, and other infrastructure, and at least three people were killed.

Stable Continental Region (Malaysia, Singapore, Thailand, Vietnam, Laos, Cambodia and Brunei)

A stable continental region is a tectonically stable area of the Earth's crust that does not experience significant geological activity such as earthquakes or volcanic eruptions. These regions are typically found deep within tectonic plates, far from the boundaries where plates collide or move apart. Malaysia, Singapore, Thailand, Vietnam, Laos, Cambodia, and Brunei are examples of stable continental regions. A moderate earthquake is one with a Richter magnitude of 5.0 to 5.9 on the Richter scale. This magnitude earthquake can cause noticeable shaking and minor damage to buildings and other structures. Malaysia is located on the Sunda Plate, which is prone to earthquakes caused by the Indian Plate subduction beneath the Eurasian Plate. The region is also impacted by active far-fault systems, such as the Sumatran fault, which poses a significant earthquake risk. On June 5, 2015, Malaysia was struck by a powerful earthquake with a magnitude of 6.0. The earthquake struck in the country's east, near the borders with Brunei and Kalimantan, and was felt throughout the region. The earthquake damaged buildings and infrastructure, particularly in the Sabah town of Ranau. The earthquake in Sabah, Malaysia, was caused by movement along the Ranau Fault, which runs through the country's northern region. Malaysia is also close to the Sunda Megathrust, which is a subduction zone where the Indo-Australian Plate is being pushed beneath the Sunda Plate. The Sumatran Fault is a major fault system located off the western coast of Sumatra, Indonesia, and about 300 kilometres from Malaysia. The fault is a transform fault that divides the Indian-Australian Plate to the west from the Sunda Plate to the east. The fault system stretches for about 1,800 kilometres and is known to be a source of significant seismic activity in the area. On December 26, 2004, the Sumatran Fault caused one of the most notable earthquakes in Malaysia. This 9.1 magnitude earthquake was one of the largest ever recorded and triggered a devastating tsunami that caused significant damage and loss of life throughout Southeast Asia. While Malaysia did not feel the full force of the 2004 earthquake and tsunami, there was significant seismic activity because of the event.

Singapore is in Malaysia's southern region, which is generally considered to be earthquake-free. Singapore is located on the stable Sunda Shelf, which is less prone to earthquakes than the rest of Southeast Asia. While Singapore has had earthquakes in the past, most of them were minor and did not cause significant damage. With a magnitude of 6.1, one of the most notable earthquakes to have struck Singapore occurred on February 4, 2018. The earthquake struck off the coast of Java, Indonesia, and was felt in several parts of Singapore.

Thailand is situated on the Indochina block, which is bordered by the Eurasian Plate to the north, the Indian Plate to the west, and the Australian Plate to the south. Thailand has experienced a number of significant earthquakes in the past, the most recent occurring on May 5, 2014. The quake had a magnitude of 6.0 and occurred in the northern region of the country near the Myanmar border. The earthquake was felt throughout the region and caused significant damage to buildings and infrastructure. The quake in Thailand was caused by movement along the Mae Tha Fault, which runs through the country's northern region. The Mae Tha Fault is a major source of seismic activity in Thailand and can produce magnitude 7 or greater earthquakes. Thailand is situated near the Mae Tha Fault and the subduction zone where the Indian Plate is being pushed beneath the Eurasian Plate, resulting in the formation of the Himalayas and the associated seismic activity in the region.

Vietnam is situated on the eastern margin of the Eurasian Plate and is surrounded by the South China Sea. The principal cause of tectonic activity in Vietnam is the collision between the Eurasian Plate and the Philippine Sea Plate, which generates a complex system of fault zones and volcanic activity in the region. Vietnam is also located close to the subduction zone where the Philippine Sea Plate is being pushed beneath the Eurasian Plate, resulting in the formation of the Ryukyu Islands and the associated seismic and volcanism. Vietnam has experienced several significant earthquakes in the past, with the most recent one occurring on July 6, 2021. The earthquake had a magnitude of 6.2 and occurred in the province of Son La in the country's northwest. Several regions of the country, including Hanoi, felt the earthquake, which caused damage to buildings and roads.

Laos is located on the Southeast Asian Tectonic Plate, which is surrounded by several active plate boundaries. Numerous significant earthquakes have occurred in the country, including a magnitude 6.8 quake in 2011 that caused widespread destruction and fatalities. Laos is situated on the Indochina block, which is bordered by the Eurasian Plate to the north, the Indian Plate to the west, and the Australian Plate to the south. On November 21, 2019, Laos experienced a significant earthquake with a magnitude of 6.1. The earthquake occurred in the northern portion of the nation near the Thai border and was felt throughout the region. The earthquake resulted in several fatalities and extensive damage to buildings and infrastructure, particularly in Muang Nan. The Laos earthquake was caused by movement along the Xayaburi Fault, which runs through the country's northern region. The Xayaburi Fault is a major source of seismic activity in Laos and can produce magnitude 7 or greater earthquakes.

Cambodia is bordered by several active plate boundaries. Several significant earthquakes have occurred in Cambodia, including a magnitude 5.5 earthquake that caused damage and fatalities in 2021. Cambodia is situated on the Indochina block, which is bordered by the Eurasian Plate to the north, the Indian Plate to the west, and the Australian Plate to the south. On December 13, 2019, an earthquake with a magnitude of 6.1 occurred in Cambodia. Particularly in Kampot, the earthquake caused damage to buildings and infrastructure. The quake in Cambodia was caused by movement along the Prek Kampi Fault, which runs through the country's southern region. The Prek Kampi Fault is a major source of seismic activity in Cambodia and can produce magnitude 7.0 or greater earthquakes.

Brunei is in Southeast Asia share its boundaries with Sarawak, Malaysia and situated on the northern edge of the island of Borneo. While there have not been any major earthquakes reported in Brunei in recent years, the potential for seismic activity exists due to its location near the plate boundary. Earthquakes in this region can range in magnitude and can be felt over a wide area, depending on their depth, location, and the type of rock and soil in the area. To prepare for earthquakes, it is important for Brunei to have measures in place to mitigate their impact. This includes developing building codes that are designed to withstand seismic activity, as well as emergency response plans and public education campaigns to promote earthquake safety. Nevertheless, the region has experienced several moderate earthquakes in the past, including a magnitude 6.0 quake in 2015 that was felt across the nation. Brunei is located on the northern coast of Borneo, which is near several active faults from Sabah and Sarawak. Despite this, earthquakes in Brunei are uncommon and typically of low magnitude.

Methodology

Several procedures and methodologies using geological, seismological, and geotechnical data go into creating a seismic hazard map. Seismic hazard mapping is a complex process that calls for precise knowledge of the local geology and tectonics, in addition to sophisticated modeling and analysis tools. Using these methods to create a thorough seismic hazard map can help reduce the damage caused by earthquakes and keep residents and vital infrastructure safe. The seismic hazard map developed by each Southeast Asian country was the starting point for this research. The map includes two different levels of potential overshoot: 10% and 2%. The most up-to-date map data was collected to create a composite hazard map for all Southeast Asian nations.

Figure 1 illustrates the step-by-step process that must be followed to carry out the current project activities. The seismic hazard maps for Southeast Asian countries (including Malaysia, Indonesia, Thailand, Singapore, the Philippines, Myanmar, Vietnam, Laos, Cambodia, and Brunei) were collected at the beginning of the activity. These maps were created based on the most recent results that were published. After that, every map will be compiled so that the values of Peak ground Acceleration (PGA) can be observed. There will also be a comparison made between these PGA values and other previously published seismic hazard maps for the Southeast Asian region. After obtaining the parameters of the PGA, the next step is to combine all the seismic hazard maps into a single map. This will be done as part of the activity. The map is going to be made into two different types, including one with a 10% probability of exceedance and another with a 2% probability. Finally, the design response spectra will be generated using the data findings based on the latest literature.

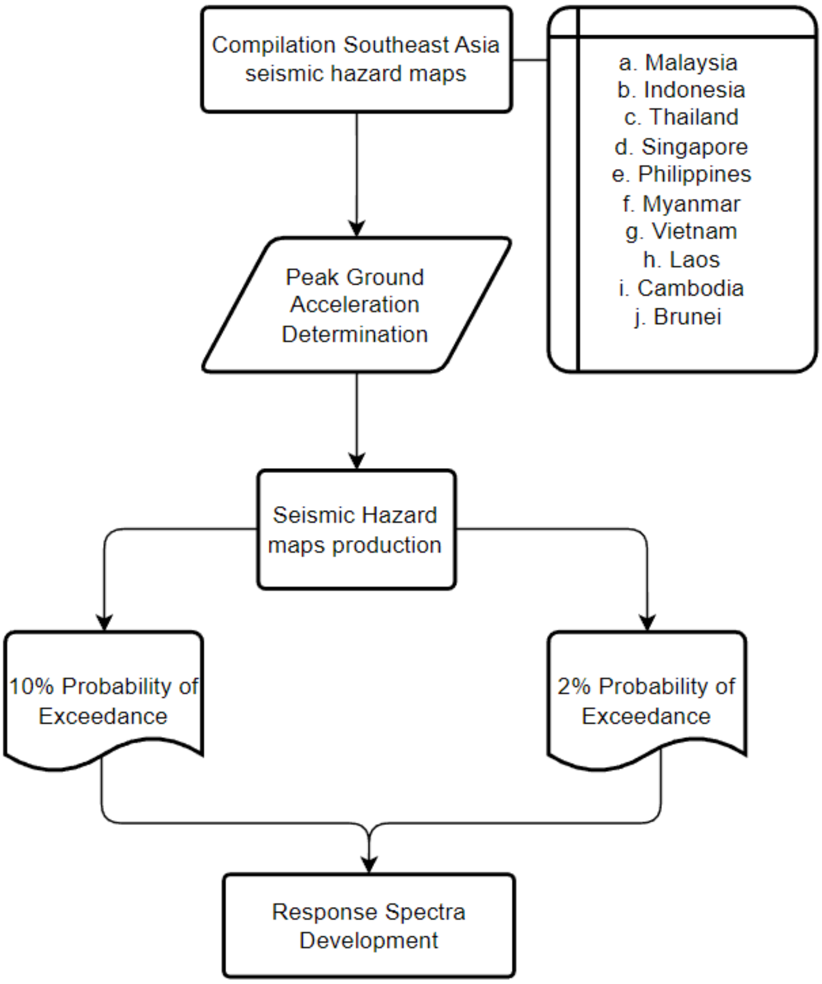


Figure 1. The flow of track development of the study

Review of Seismic Hazard Map in Asian Countries

Petersen et al. (2007) and Pagani et al. (2018) initially compiled seismic hazard maps for Southeast Asia. Pagani et al. (2018) presents the latest version of the hazard component for the Global Earthquake Model (GEM). The most recent research and data on seismicity, fault sources, and ground motion have been incorporated into this model to provide an up-to-date assessment of the risk of earthquakes occurring all over the world. This article discusses the hazard maps that were generated because of using the GEM model and presents the methodology that was used to generate them along with any associated uncertainties. The earliest documentation for the Southeast Asia Seismic Hazard Maps can be found in Petersen et al. (2007)'s publication. These maps, which provide estimates of the likelihood and intensity of earthquakes in Southeast Asia, were developed by the United States Geological Survey (USGS).

Pagani et al. (2018)'s GEM model incorporates the most up-to-date research and data to provide a global assessment of earthquake hazard. Southeast Asia Seismic Hazard Maps, on the other hand, were developed by

Petersen et al. (2007) and are more than a decade older than the GEM model. While the Southeast Asia Seismic Hazard Maps developed by Petersen et al. (2007) use simpler ground motion prediction equations based on older research, the GEM model presented by Pagani et al. (2018) uses a more sophisticated methodology that incorporates ground motion prediction equations based on the latest research. Pagani et al. (2018) maps of seismic risk. Most of the highest PGA values in Southeast Asia are found within the Ring of Fire, which includes Myanmar, Indonesia, and the Philippines. Some regions of Thailand, Cambodia, Vietnam, and Borneo have the world's lowest PGA values.

Guidelines for designing buildings to withstand earthquakes can be found in Eurocode 8, and their development is described in the MS EN1998:2015 (2017) is Malaysia National Annex. This report examines Malaysia's general regulations, seismic actions, and rules for buildings with the overarching goal of ensuring that all structures in the country are adequately prepared to withstand seismic activity. Two additional maps of East Malaysia complement the Malay Peninsula or West Malaysia map (Sabah and Sarawak). The 10% probability of West Malaysia and East Malaysia exceeding is depicted in Figure 4. The range of PGA values in Malaysia is 0.00 g to 0.16 g. Sabah, in East Malaysia, has the highest PGA contributions compared to West Malaysia and Sarawak, also in East Malaysia. The concentrated contours on these three maps indicate areas where local fault influence has been detected. The results for the 2% probability of exceeding are shown in Figure 5. Sabah, East Malaysia has the highest PGA values, ranging from 0.02 to 0.25g. The 2% probability of exceeding PGA values in the Malaysia region falls between 0.00 and 0.25g.

Irsyam et al. (2017) create a map showing earthquake hotspots and fault lines across Indonesia. The map can be used to inform earthquake preparedness and response strategies by revealing the expected frequency and intensity of earthquakes in various regions of Indonesia. There is only a tiny fraction on both maps where the PGA value is 0.00 - 0.05g. The PGA value for most of Indonesia falls between 0.05 and 0.8g with a 10% chance of exceeding, and between 0.05 and 2.0g with a 2% chance of exceeding. A probabilistic seismic hazard analysis model for the Philippines is described in Penarubia et al. (2020). The model incorporates several variables, including seismic sources and soil conditions, to make predictions about the frequency and severity of earthquakes in various parts of the country. To lessen the destruction caused by earthquakes, this data can be used to modify building codes and emergency procedures.

South of West Malaysia, on an island, is the city-state of Singapore. Wenqi and Pan (2020) provide a probabilistic evaluation of Singapore's seismic risk. The assessment considers several variables, including regional seismicity and soil geology, to provide an estimate of the frequency and magnitude of earthquakes in Singapore. The results of the study can be used to modify the city-building state's codes, emergency response strategies, and other precautions against earthquake damage. Ten percentile PGA values in Singapore range from 0.048 g to 0.052 g. Meanwhile, the PGA values range from 0.143 g to 0.146 g at a 2% chance of exceedance. The risk of natural disasters, such as earthquakes, in Cambodia is evaluated in the Country Report Cambodia (2015). The purpose of this report is to help businesses prepare for natural disasters by pinpointing the areas of the country that are most at risk. The report only includes one map, and that map is the GSHAP map for a threshold of 10% exceedance. Figure 12 displays the PGA values for all of Cambodia, which range from 0.4 to 0.8g.

Ornthammarath et al. (2010) provide a probabilistic evaluation of Thailand's seismic risk. The likelihood and intensity of earthquakes in various regions of Thailand are estimated by considering several factors, including seismic sources and soil conditions. The results of the study can be used to modify building codes, improve emergency preparedness, and take other preventative steps against earthquake damage. The PGA map from 0.0 to 0.3g (10% probability of exceeding). However, at a 2% chance of exceeding, the PGA values are between 0.00 and 0.70g. Pailoplee and Charusiri (2017) use a seismicity approach to look at seismic activity and risks in Laos. The goal of the study is to find out which parts of the country are most likely to be affected by earthquakes and to come up with ways to lessen the effects of earthquakes. The Laos seismic hazard map shows that the PGA are between 0.0 and 0.24g with a 10% chance of being greater. At a 2% chance of going over, the PGA shows that the values are between 0.0 and 0.4g.

A seismic risk assessment for Myanmar is provided by Nanthaporn and Pailoplee (2017). The study considers a variety of factors, including seismic sources and soil conditions, to estimate the probability and intensity of earthquakes in various regions of Myanmar. This data can be utilized to inform building codes, emergency response plans, and other measures designed to mitigate the effects of earthquakes. PGA map with a 10% probability of exceeding values between 0.0 and 0.2g and 2% probability of exceeding the PGA values places them between 0.0 and 0.35g. Nguyen and Pham (2014) provide a probabilistic assessment of the seismic hazard in the South-Central region of Vietnam. The evaluation considers various factors, such as the seismicity of the region and the geological characteristics of the soil, to estimate the probability and magnitude of earthquakes in the region. The assessment provides information that can be used to inform building codes, emergency response plans, and other measures designed to reduce the impact of earthquakes in the region. The 10% probability of exceeding within the ranges 0.0 to 0.198g and the 2% probability of exceeding within the ranges 0.0 to 0.24g. The Brunei Country Report (2015) assesses the risk of natural disasters, such as earthquakes, in Brunei. The purpose of this report is to identify the areas of the country most susceptible to natural disasters and to develop business continuity plans to mitigate their effects. Since the Brunei map uses Modified Mercalli Intensity (MMI), Figure 1 displays the USGS Approximate Correlation Between MMI and PGA extracted from Chock et al. (2006). Brunei has an MMI between I and IV. The conversion will be roughly between 0.0017 and 0.039g PGA.

Results

In many regions of the world, including Malaysia, Brunei, Indonesia, Philippines, Singapore, Myanmar, Vietnam, Laos, Thailand, and Cambodia, the compilation of seismic hazard data is a crucial aspect of earthquake risk assessment and disaster management. Due to their location on the Pacific Ring of Fire, an area with intense tectonic activity, these Southeast Asian countries are susceptible to seismic activity. Seismic hazard compilation entails gathering information on past earthquakes, fault lines, and geological structures in the region to generate earthquake hazard maps. These maps can then be used to evaluate the probability of earthquakes with varying magnitudes and frequencies. In recent years, these nations have experienced a number of devastating earthquakes and their associated effects, including loss of life, population displacement, and infrastructure damage. Consequently, there is a growing need for accurate seismic hazard maps to strengthen the region's resilience to future seismic events. Numerous entities, including government agencies, academic institutions, and international organizations, have contributed to the compilation of seismic hazard maps for these nations. These efforts have resulted in a better understanding of the region's seismic activity and have contributed to the development of earthquake mitigation strategies.

Results PGA for 10% and 2% Probability of Exceedance

This study will provide an overview of the seismic hazard compilation efforts for Southeast Asian countries namely, Malaysia, Indonesia, Thailand, Singapore, the Philippines, Myanmar, Vietnam, Laos, Cambodia, and Brunei as well as highlight the key findings and implications of these studies for two distinct parameters, namely 10% and 2% probability of exceedance. The colour of each contour is determined by Irsyam et al. (2017)'s PGA map colour code. The minimum PGA ranges from 0.00 to 0.05 g, while the maximum exceeds 0.80 g. In the development of seismic hazard maps for Southeast Asian countries, the 10% probability of exceedance is an important metric. This metric represents the likelihood that an earthquake of a certain magnitude or greater will occur within a specified period, typically 50 years. In these nations, the 10% probability of exceeding is frequently used as the basis for seismic building codes and design requirements. This entails that buildings, bridges, and other infrastructure must be designed to withstand the ground motion and other seismic effects anticipated from earthquakes with a 10% probability of exceedance. Figures 2 and 3 show the final compilation of seismic hazard maps for 10% and 2% probability of exceedance, respectively.

In general, the 10% probability of PGA value varies for these nations based on their tectonic setting, seismicity, and geology. The 10% probability of PGA value may be greater in regions with high seismic activity and strong ground motions than in regions with lower seismic activity and weaker ground motions. For instance, in the Philippines, which is situated in the Pacific Ring of Fire and is prone to large earthquakes, the 10% probability of PGA value varies between 0.0g and 0.8g depending on the location. Depending on the location in Indonesia, which is also situated within the Pacific Ring of Fire, the 10% probability of PGA value ranges are the same as Philippines. The 10% probability of PGA value is generally low and moderate in Malaysia, ranging from 0.0g to 0.15g. Similarly observed in Myanmar, the PGA values are the same as Malaysia. In contrast, in Cambodia, Singapore and Brunei, which is situated in a relatively low earthquake activities and stable tectonic environment, the 10% probability of PGA value ranges from 0.0g to 0.05g. In Laos, the PGA value is in the range of 0.1 to 0.25g, Vietnam is 0.0 to 0.2g and Thailand is 0.0 to 0.3g. The 2% probability of PGA value may be greater in regions with high seismic activity and strong ground motions than in regions with lower seismic activity and weaker ground motions. In the Philippines, the 2% probability of PGA value varies between 0.0g and 2.0g. Depending on the location in Indonesia, the 2% probability of PGA value ranges are the same as Philippines. The 10% probability of PGA value is generally low and moderate in Malaysia, ranging from 0.00g to 0.25g.

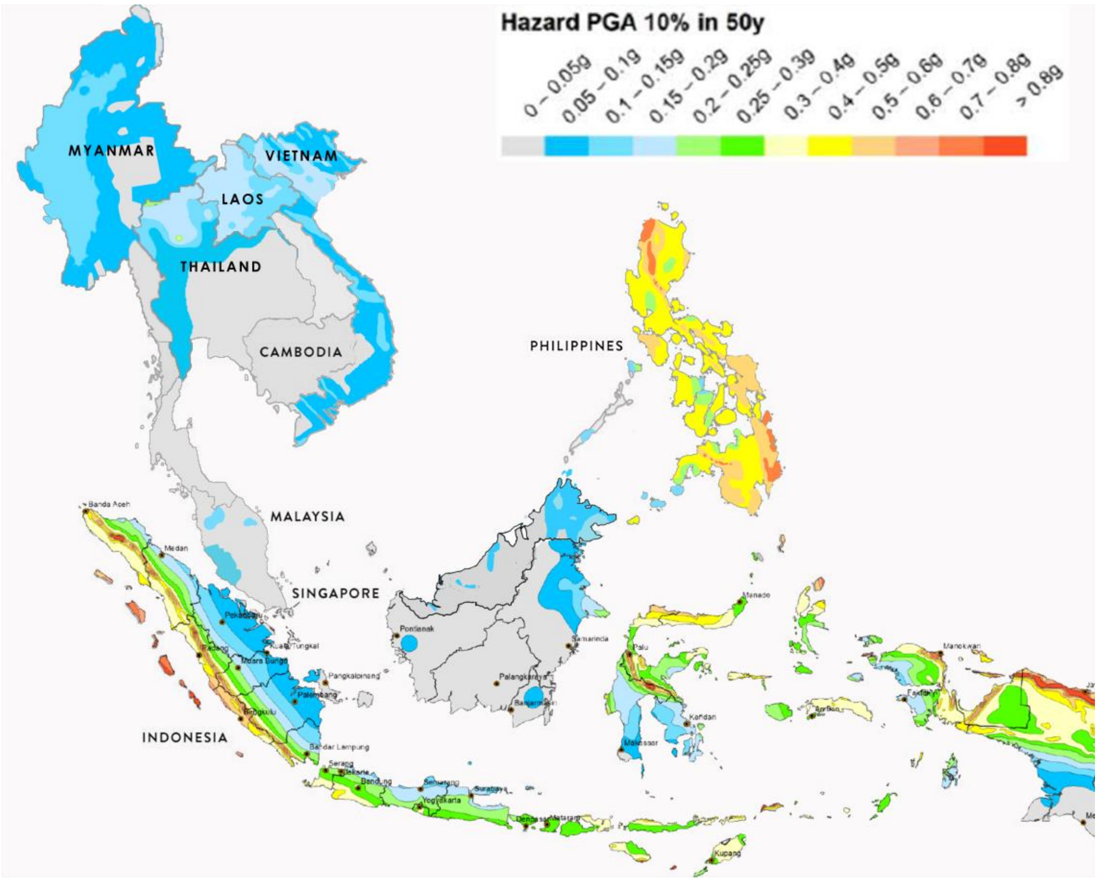


Figure 2. Final compilation of Southeast Asia seismic hazard map at 10% probability of exceedance in 50-year design period

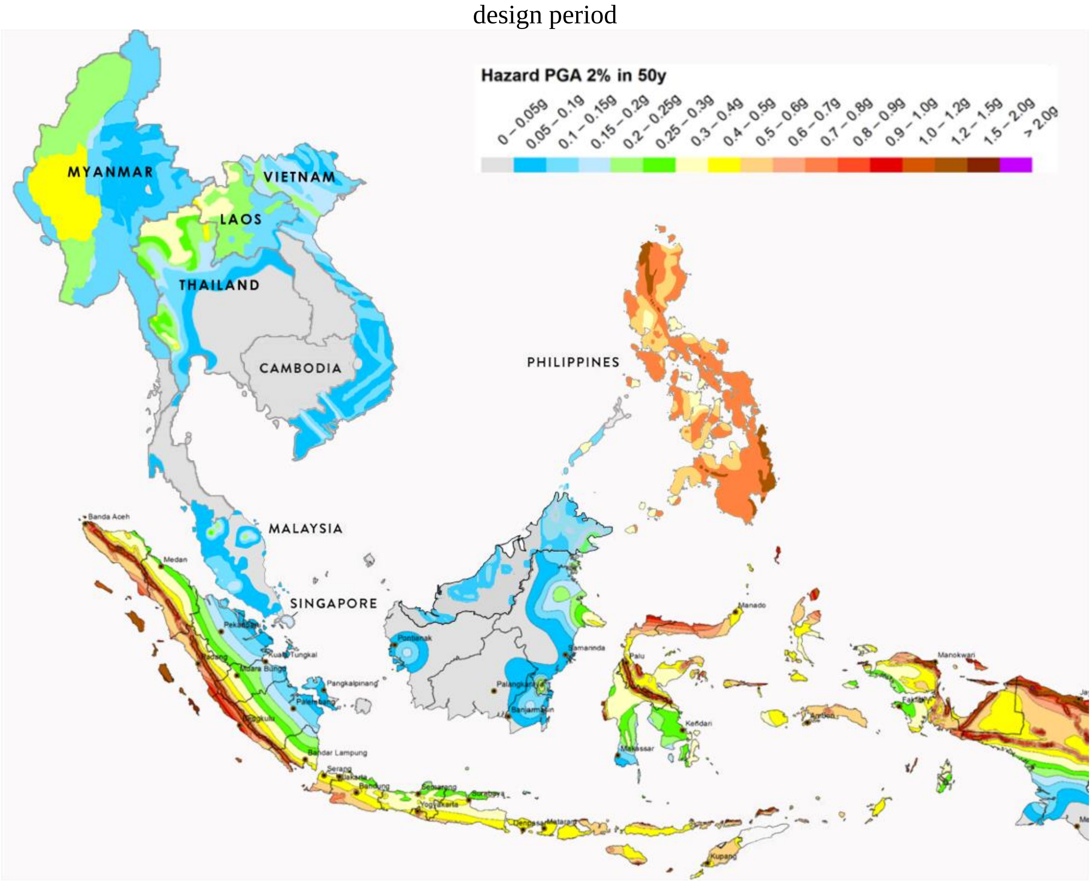


Figure 3. Final compilation of Southeast Asia seismic hazard map at 2% probability of exceedance in 50-year design period

Similarly observed in Myanmar, the PGA values are the same as Malaysia. In contrast, in Cambodia, Singapore and Brunei, which is situated in a relatively low earthquake activities and stable tectonic environment, the 10% probability of PGA value ranges from 0.0g to 0.05g. In Laos, the PGA value is in the range of 0.0 to 0.5g, Vietnam is 0.0 to 0.25g and Thailand is 0.0 to 0.5g. It is essential to note that the 10% and 2% probability of PGA value is only one metric used in seismic hazard evaluation and design. Depending on the application and design requirements, other metrics, such as spectral acceleration and response spectra, may also be employed.

Design Response Spectra of Southeast Asia

Response spectrum are graphical representations of the greatest acceleration, velocity, or displacement that a structure can experience during an earthquake. Generally, these spectra are developed for a particular geographical region, taking the geology and seismicity of the region into account. Response spectra are vital for building design and earthquake engineering because they measure the possible effects of an earthquake on a structure. By evaluating the reaction spectrum, engineers can estimate the maximum acceleration, velocity, and displacement that a structure may experience during an earthquake and design it to withstand these forces.

Design response spectra are often stated in terms of spectral acceleration, which is the greatest acceleration that a structure is anticipated to experience during an earthquake at a specific time interval. The design response spectrum is defined by a variety of criteria, including the seismic hazard level at the site, the building code requirements, and the intended use and occupancy of the building. In building design, the design response spectra are utilized to compute the seismic design forces that a structure must be able to endure. Engineers utilize design response spectra to determine the maximum acceleration, velocity, and displacement that a structure is likely to encounter during an earthquake, and then design the structure to withstand these forces. Design response spectra are a vital aspect of seismic design codes, which provide instructions for developing earthquake-resistant structures. By calculating the seismic design forces using the design response spectrum, engineers can ensure that structures are designed to resist earthquake forces and provide a safe environment for people.

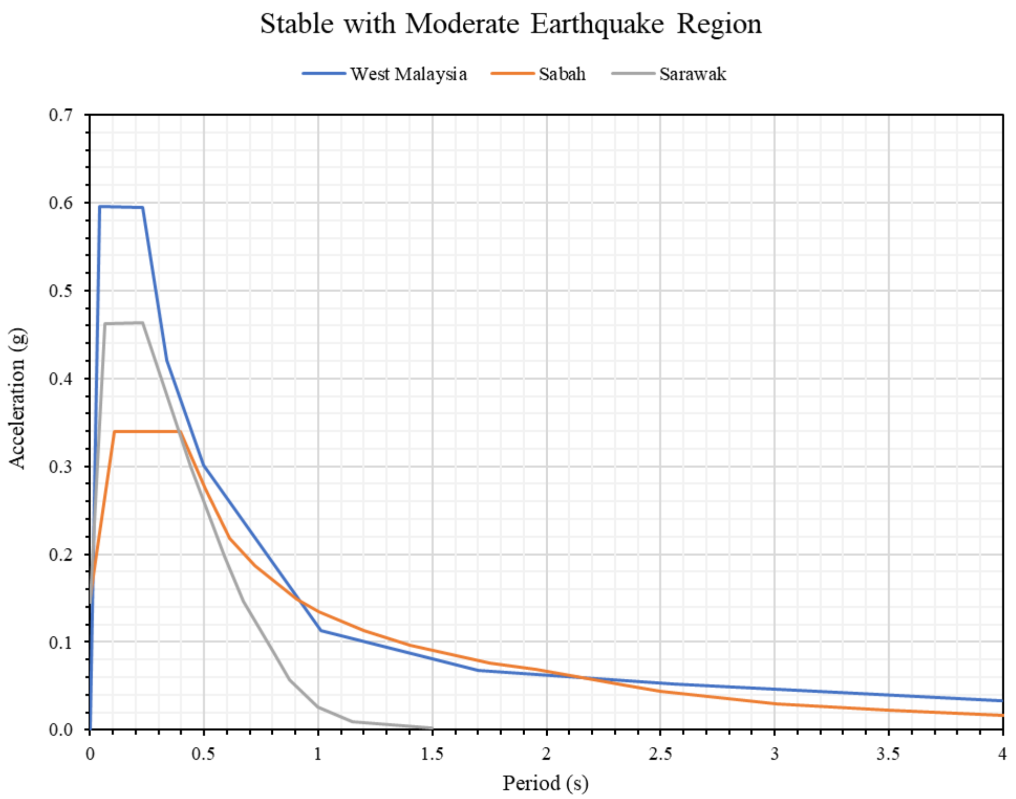


Figure 4. Design response spectra plotted at stable continental region by taking Malaysia as an example (the line shows three cities chosen for analysis (West Malaysia, Sabah and Sarawak)

The design response spectra are successfully derived from MS EN1998:2015 (2017) and Desain Spektra Indonesia (2021) for the current project. The design response spectra are centered on two design categories: the first type is stable with moderate earthquake region and second type is active earthquake region. Figure 4 depicts the spectrum distribution of the Malaysia region from 0 to 4 s (including West Malaysia, Sabah and Sarawak of East Malaysia). Figure 5 illustrates the distribution of spectra for active earthquake regions including Indonesian cities (including Acheh, Padang and Palu).

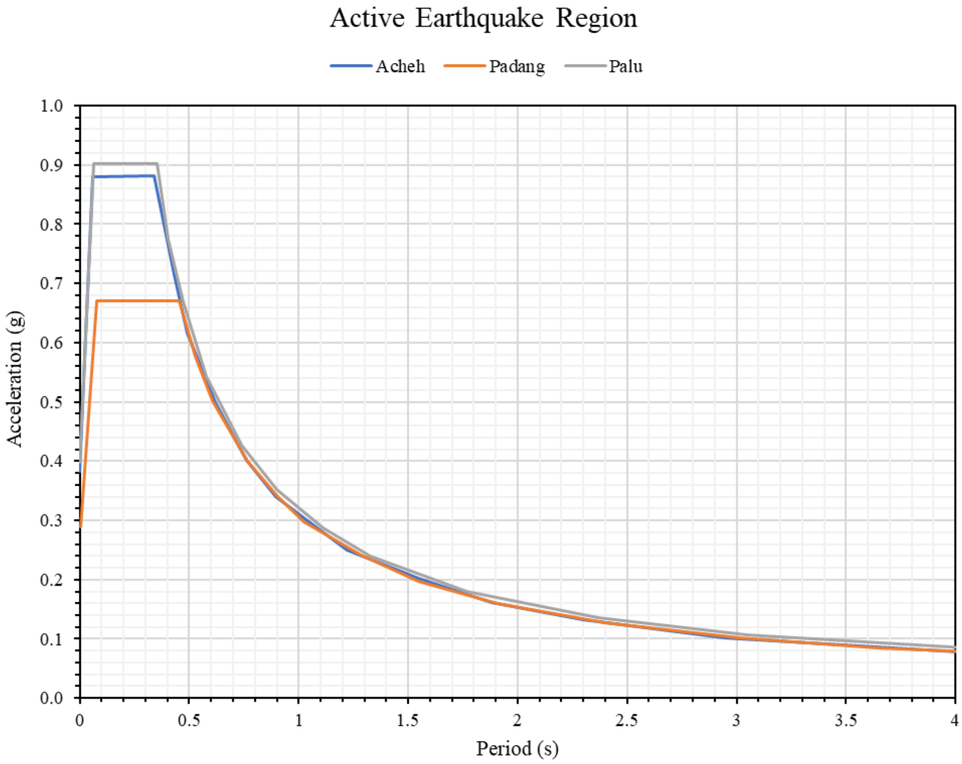


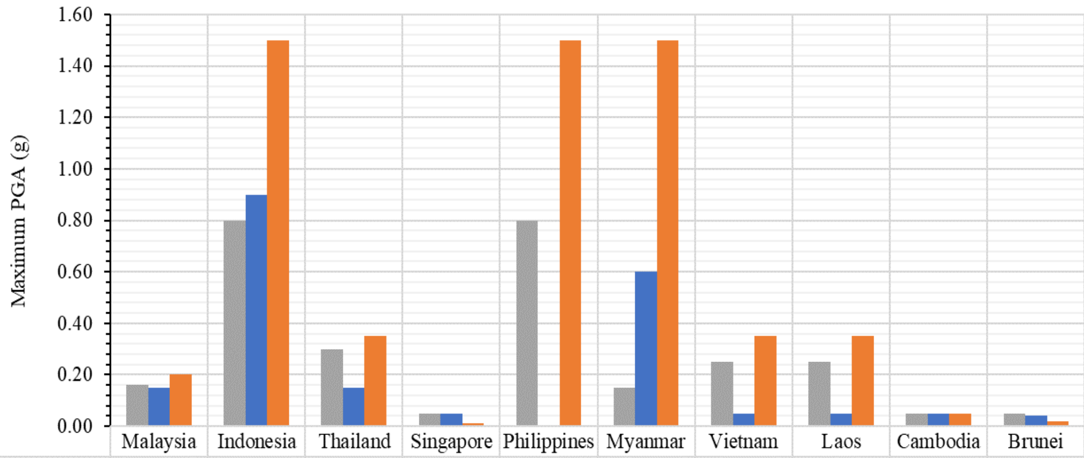
Figure 5. Design response spectra plotted at active earthquake region by taking Indonesia as an example, the line shows three cities chosen for analysis (Acheh, Padang and Palu)

Discussion

The Petersen et al. (2007) has limited results showed whereas in Indonesia, the PGA map only shows at Sumatra region only with no results found in other part Indonesia. Thus, the comparison displays the results from the region of Sumatra. In addition, a small portion of East Malaysia has been omitted from the report. Therefore, the results will be compared with what has been display in the report only. In the Philippines region, no PGA values have been calculated. Pagani et al. (2018) published at 10% probability of exceedance with no map for 2% probability of exceedance. Consequently, the comparison was based solely on the 10% probability of exceeding. Table 1 shows the comparison of PGA values for 10% and 2% probability of exceedance. Meanwhile, Figures 7 and 8 show the variation of PGA values in comparison to previous study by Petersen et al. (2007) and Pagani et al. (2018).

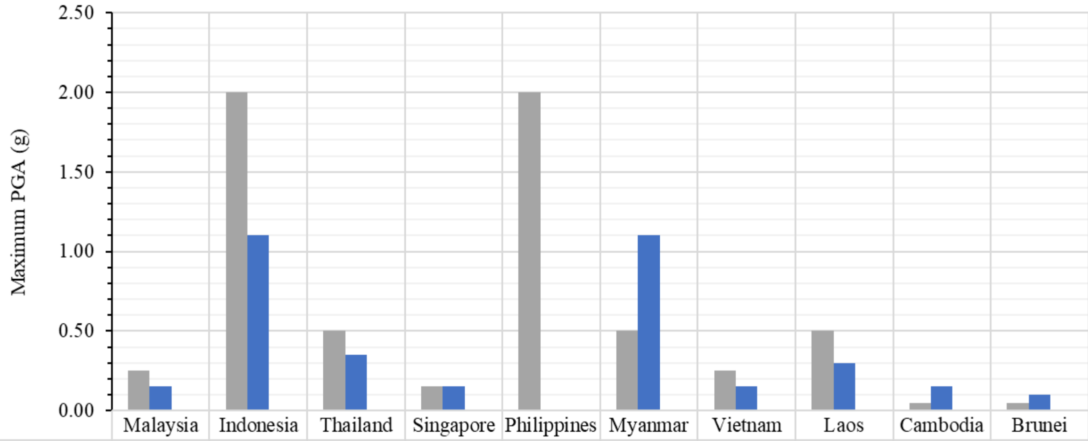
Table 1. Summary and comparison of peak ground acceleration values at 10% probability of exceedance in 50-year design period for Southeast Asia countries (unit g).

	10 % Probability of Exceedance			2% Probability of Exceedance		
Country	Petersen et al. (2007)	Pagani et al. (2018)	This Study	Petersen et al. (2007)	Pagani et al. (2018)	This Study
Malaysia	0.001-0.15	0.02-0.2	0.0-0.15	0.001-0.15	-	0.0-0.25
Indonesia	0.2-0.9	0.0-1.5	0.0-0.8	0.15-1.1	-	0.0-2.0
Thailand	0.01-0.15	0.0-0.35	0.0-0.3	0.02-0.35	-	0.0-0.5
Singapore	0.02-0.05	0.0-0.01	0.0-0.05	0.10-0.15	-	0.1-0.15
Philippines	-	0.08-1.5	0.0-0.8	-	-	0.0-2.0
Myanmar	0.02-0.6	0.02-1.5	0.0-0.15	0.02-1.1	-	0.0-0.5
Vietnam	0.02-0.05	0.0-0.35	0.0-0.2	0.10-0.15	-	0.0-0.25
Laos	0.02-0.05	0.0-0.35	0.1-0.25	0.02-0.3	-	0.0-0.5
Cambodia	0.02-0.05	0.0-0.05	0.0-0.05	0.10-0.15	-	0.0-0.05
Brunei	0.001-0.04	0.0-0.02	0.0-0.05	0.06-0.1	-	0.0-0.05



	Malaysia	Indonesia	Thailand	Singapore	Philippines	Myanmar	Vietnam	Laos	Cambodia	Brunei
This Project	0.16	0.80	0.30	0.05	0.80	0.15	0.25	0.25	0.05	0.05
Petersen et al. (2007)	0.15	0.90	0.15	0.05	0.00	0.60	0.05	0.05	0.05	0.04
Pagani et al. (2018)	0.20	1.50	0.35	0.01	1.50	1.50	0.35	0.35	0.05	0.02

Figure 7. Comparison of maximum PGA values at 10% probability of exceedance for Southeast Asia countries



	Malaysia	Indonesia	Thailand	Singapore	Philippines	Myanmar	Vietnam	Laos	Cambodia	Brunei
This Project	0.25	2.00	0.50	0.15	2.00	0.50	0.25	0.50	0.05	0.05
Petersen et al. (2007)	0.15	1.10	0.35	0.15	0.00	1.10	0.15	0.30	0.15	0.10
Pagani et al. (2018)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 8. Comparison of maximum PGA values at 2% probability of exceedance for Southeast Asia countries

Conclusion

In conclusion, seismic hazard data compilation is critical for earthquake risk assessment and disaster management in several Southeast Asian countries, including Malaysia, Brunei, Indonesia, Philippines, Singapore, Myanmar, Vietnam, Laos, Thailand, and Cambodia. These countries are in the Pacific Ring of Fire, which is a highly tectonically active region, making them prone to seismic activity. The 10% probability of PGA value varies depending on the tectonic setting, seismicity, and geology of each country. Regions with high seismic activity and strong ground motions have a greater 10% and 2% probability of PGA value compared to regions with lower seismic activity and weaker ground motions. For example, in the Philippines, which is prone to large earthquakes and situated in the Pacific Ring of Fire, the 10% probability of PGA value ranges from 0.0g to 0.8g meanwhile 2% probability of PGA value ranges from 0.0g to 2.0g depending on the location. The same range of 10% probability of PGA value is observed in Indonesia. Meanwhile, Malaysia and Myanmar have low to moderate 10% probability of PGA values ranging from 0.0g to 0.15g. The 2% probability of PGA values ranging from 0.0g to 0.25g for Malaysia, and 0.0g to 0.5g for Myanmar. On the other hand, Brunei, Singapore, and Cambodia, located in a relatively low earthquake activity and stable tectonic environment, have a 10% probability of PGA value ranging from 0.0g to 0.05g and 2% from 0.0 to 0.05g except Singapore, 0.1 to 0.15g. Laos has a 10% and 2% probability of PGA value in the range of 0.1 to 0.25g and 0.0 to 0.5g, respectively, Vietnam ranges from 0.0 to 0.2g and 0.0 to 0.25g for 10% and 2% probability, respectively, and Thailand ranges from 0.0 to 0.3g for 10% probability and 0.0 to 0.5g for 2% probability. However, the 10% and 2% probability of PGA value is only one metric used in seismic hazard evaluation and design. Depending on the application and design requirements, other metrics such as spectral acceleration and response spectra may also be employed. The design response spectra for seismic hazard evaluation and design in the Asian region are divided into two categories based on the level of seismic activity: stable with moderate earthquake region and active earthquake region. The spectrum distribution for selected cities in regions of moderate seismicity and active earthquakes, including West Malaysia, Sabah, Sarawak of East Malaysia, and Indonesian cities such as Acheh, Padang, and Palu, have been integrated for the range of 0 to 4 seconds. These spectra distributions are an essential aspect of earthquake risk assessment and disaster management, which can aid in the development of effective strategies for mitigating the impact of seismic events in the region.

Recommendations

It is recommended to provide details about the specific methods used to generate the seismic hazard map and associated design response spectra. Adding more information about the data sources, modeling techniques, and assumptions made during the analysis would make the study more transparent and credible. Providing some context about the potential consequences of not properly accounting for seismic hazards in building design and construction (e.g., increased risk of collapse, injury, and death) would make the study's findings more impactful. Since current study does not mention any sensitivity analyses performed to assess the robustness of the results or any assumptions made about the underlying seismicity or tectonic activity of the region, thus being transparent about these issues would make the study more reliable and useful.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

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