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Seismic Hazard Microzonation Map for the Central Plain of Thailand

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Abstract

A study was conducted to investigate the seismic hazard microzonation of the central plain of Thailand, which is situated in an area with a thick quaternary basin. Unconsolidated sediments can lead to amplification of earthquake ground shaking at fundamental frequency and can cause a significant increase in damage to buildings. The research yielded significant results, including the development of a fundamental frequency map through the analysis of HVSR for 149 microtremor measurement sites. Subsequently, a Vs30 map was derived utilizing HVSR inversion techniques, and a soil classification map was constructed based on the NEHRP classification. The upper central plain along the Yom River and the Nan River had a low fundamental frequency of 0.3-0.5 Hz and low Vs30, which can be classified as soil type Class E. In the southern areas of Ayutthaya, Pathum Thani, and central Bangkok, an extremely low Vs30 of less than 100 m/s was observed, indicating soil class F or special soft soil. A comprehensive investigation was conducted on probabilistic seismic hazard analysis by considering the Vs30 sites condition for PGA, SA0.2s, and SA1.0s with a 2475-year return period. The northern region of the upper central plain and the western side of the central basin exhibit relatively high seismic hazards. Furthermore, the site effect significantly amplifies ground motion at the 1.0 second period, surpassing the earthquake-resistant design standard for buildings in Thailand by more than 5 times, particularly in the central region of the lower central plain.

Keywords: Seismic Hazard, HVSR Inversion, Vs30, Site Effect, Central Plain of Thailand

1. Introduction

The central plain of Thailand is the one of larger Cenozoic basins in the country, as shown in Figure 1a, covering the Chao Phraya Plain and several provinces nationwide, including Uttaradit, Sukhothai, Phitsanulok, Phichit, Kamphaeng Phet, Nakhon Sawan, Ayutthaya, Pathum Thani and Samut Prakan. It covers an area of over 50,000 km^2. It is divided into two parts, including the upper basin, which is an intermontane basin in the western highlands that is affected by the Mae Ping and Three Pagodas fault zones, and the lower basin, which is a larger extensional basin that lies beneath the central plain region (1, 2). According to the Department of Mineral Resources, the basin is filled with 300 – 2000 meters of thick quaternary sediments, including alluvial, terrace, and fluvial sediments (3). A cross-section showing the depth of the bedrock of the lower central plain is shown in Figure 1b (4, 5). This thick layer of unconsolidated sediment beneath further increases the amplification or damage from an earthquake.

One of the most crucial prerequisites for well-constrained seismic hazard analysis on the local scale is the understanding of site effect. Site effects refer to the alterations in seismic ground motions. One notable effect is the amplification and resonance of earthquake ground motion, which can have a significant impact on structures. The site effect depends on 5 factors beneath a site: soil or rock hardness, bedrock depth, sediment thickness, ground failure potential and topography (6).

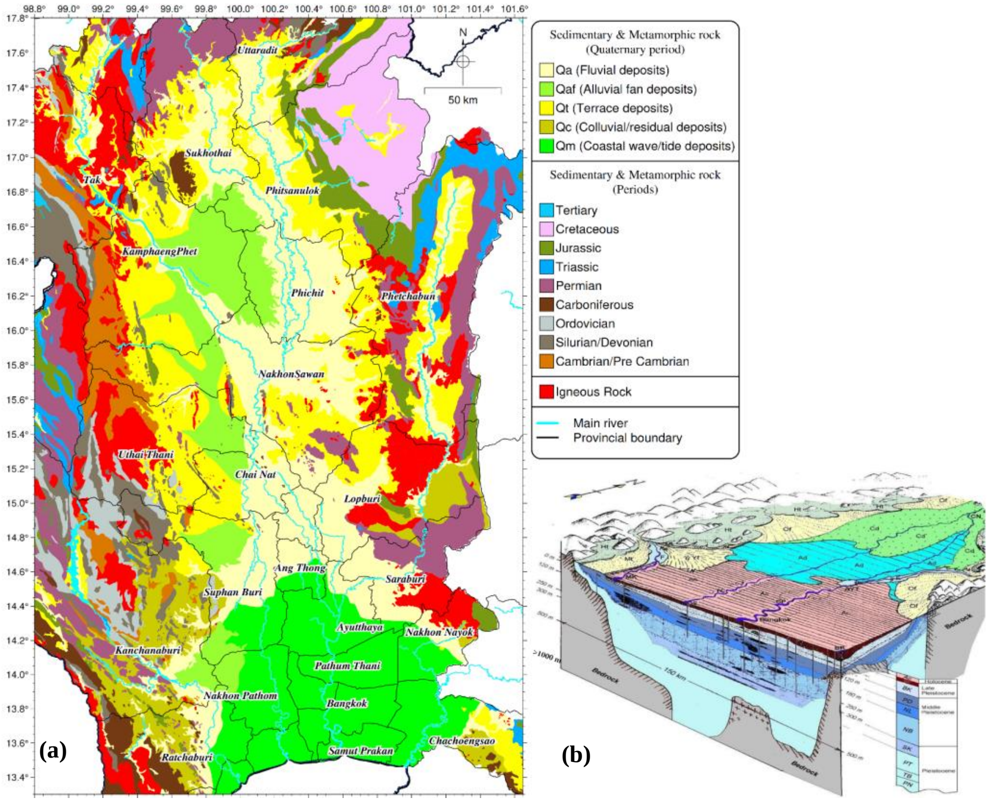

Figure 1 (a) Geologic map of central Thailand and the surrounding area; (b) Cross-section showing the sedimentary layers and depth of the bedrock in the lower central plain. (4, 5)

Near-surface geophysics is commonly employed to estimate the average shear-wave velocity within the uppermost 30 meters of the surface (Vs30), which is a crucial parameter for site effect estimation. The horizontal vertical spectral ratio (HVSR) technique, introduced by Nakamura in 1989 (7), is a widely recognized and efficient investigation tool that is extensively employed to assess the amplification factor and predominant frequencies of the subsurface. This technique is known for its convenience in operation and cost-effectiveness. Additionally, the HVSR inversion method can be utilized to ascertain the Vs30.

The objectives of this study were to produce a seismic microzonation map utilizing the HVSR technique and to establish a probabilistic seismic hazard map for the central plain of Thailand by examining the correlation between site effects (Vs30), seismicity, and active fault sources in the area. The seismic hazard microzonation results obtained from this study can serve as valuable inputs for conducting earthquake hazard assessments and devising effective mitigation strategies for the central plain of Thailand.

2. Materials and Experiment

2.1 HVSR measurements and analysis

For the HVSR survey, we used a SARA SL-06 24bit A/D datalogger connected with an SS-05 tri-axial velocity seismic sensor operating at a natural frequency of 0.5 Hz (2 sec) and sensitivity of 400 V/m/s. SS-05 sensors are effective for HVSR survey as they have high stability and robustness and can withstand better tilting. The instrument response indicates that it can measure signals down to ~5 sec, with the upper-corner frequency of 100 Hz. Time synchronization of data and survey positions were equipped with GPS receivers. We used 12-volt batteries as a power source. The microtremor data was recorded in continuous mode at 100 sps. The seismic records obtained from the SL-06 datalogger are in miniSEED format. The sensors were set up on a soil, concrete base, or concrete slab that was properly connected to the ground and away from the noise source. It took around 1-3 hours to gather data for each survey point.

A total of 149 microtremor measurement sites were surveyed across 23 provinces in the central plain of Thailand. The HVSR analysis was conducted using Geopsy software (8) to extract subsurface information from ambient noise recorded during single station measurements. The data were segmented into non-overlapping 90-second windows to cover low fundamental frequencies, and each window was tapered with a Hamming window. The ratio of short-term average (STA) and long-term average (LTA) of 1 and 90 sec was used, with minimum and maximum ratios of 0.2 and 2.4, respectively, to reject transient signals. The individual HVSR spectra were smoothed using a Konno-Ohmachi smoothing function (9) with a smoothing coefficient of 50%. The horizontal component spectra were computed by averaging E-W and N-S components using a squared average and then taking an average over all windows. These average HVSR curves represent the amplification factor and predominant frequencies of the subsurface. Figure 2 shows a field survey site with HVSR analysis results.

Significant peaks for the fundamental frequency of mean HVSR curves were evaluated based on three criteria to ensure a reliable HVSR curve. Additionally, the SESAME guidelines recommend considering at least five out of six criteria for a clear HVSR peak (10). The random decrement technique (11) is utilized to assess the damping of signals in the vicinity of the narrow frequency range of interest and to identify sources of industrial vibration such as machines, water pumps, buildings, and trees. If the damping ratios are low, at 1% or less, it indicates that the HVSR peaks are derived from anthropogenic sources, which are not considered in the interpretation.

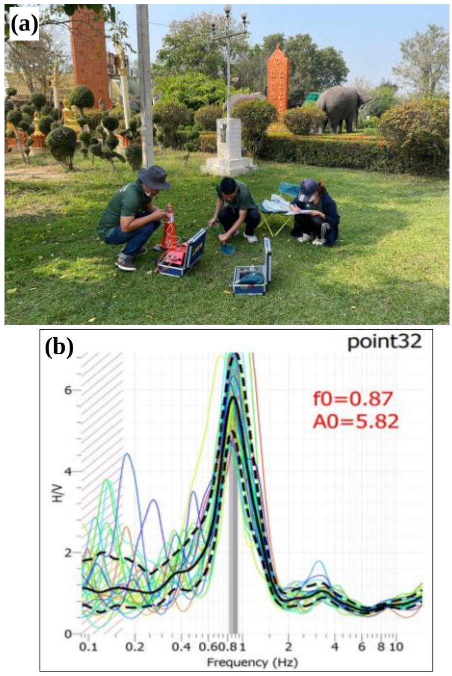

Figure 2 (a) Installation of equipment in the field at survey point 32, located in the vicinity of Wat Kaew Sriwilai, Sai Thong Watthana District, Kamphaeng Phet; (b) Analysis of HVSR for point 32, revealing the average HVSR curve denoted by the black solid. This curve indicates the fundamental frequency at 0.87 Hz and an HVSR amplification of 5.8.

2.2 HVSR inversion

The inversion technique is employed to convert measurement data into model parameters. In the context of the HVSR method, the utilization of the inversion technique enables the estimation of the subsurface’s shear wave velocity, density, and Poisson's ratio.

To generate shear wave velocity profiles, we utilize HV-inv (12), a computer code that employs the diffuse field assumption (13) for inversion of the HVSR curve for ambient noise. HV-inv considers the initial model parameter ranges with a minimum and maximum value as independent variables; layer thicknesses, Vp velocities, Vs velocities, and densities are provided to the inversion algorithms for optimization.

Four starting model parameter ranges (Table 1) with a Poisson's ratio ranging from 0.2 to 0.45 were utilized for HVSR inversion, with each model chosen based on the fundamental frequency of the target HVSR curve (14). Some starting shear wave velocity model parameters for HVSR fundamental frequencies less than 0.4Hz, 0.4-0.65Hz and greater than 3.0Hz are shown in Figure 3.

The shear wave velocity profiles were generated through the inversion of the HVSR curve. In this process, a constant standard deviation of the target HVSR curve was assumed to be 0.25%. To optimize the model parameters, a Monte Carlo sampling global optimization technique was employed, allowing for perturbations within a range of 5% of the initial model. This optimization was performed through 1000-2000 iterations. To obtain the best fitting model for the shear wave velocity structure, the inclusion of a low-velocity zone for both Vp and Vs, as well as a low-density zone, were considered. Additionally, the maximum Vs for half-space was utilized.

Table 1 Starting model parameters ranges.

f_0 Hz	Thickness m	Vp m/s	Vs m/s	Density kg/m^3
< 0.4	10-30	40-650	30-400	900-1800
	20-60	120-850	80-500	1200-2000
	30-80	150-1100	100-600	1500-2500
	0*	400-1500	200-800	1500-3000
0.4-0.65	10-30	100-1000	50-580	900-2200
	20-60	200-1200	120-700	1200-2500
	30-80	250-1500	150-800	1500-2800
	0*	1000-2800	300-900	1500-3000
0.65-3.0	10-30	200-1800	100-650	1000-2500
	20-60	400-2000	300-760	1200-2500
	30-80	500-2500	300-900	1500-2800
	0*	1000-3000	300-1200	1500-3000
>3.0	10-30	300-2800	150-760	1000-2600
	20-60	700-3000	400-850	1200-2700
	30-80	900-3000	420-1200	1500-2800
	0*	1000-3000	400-1800	1500-3000

* A thickness of 0 is designated for the half-space.

An example of the inversion process for survey point 111 located at the Kamphaeng Saen Meteorological station in Nakhon Pathom is shown in Figure 4. These HVSR curves show significant peaks with fundamental frequencies around 1.0 Hz, which reproduced a best-fitting model after 1000 iterations, in which the misfit decreased from 261 to 26. The best-fitting model with the observed HVSR curve is highlighted in red. The Vs30 calculated from shear the wave velocity profile derived from the inversion process for this site was approximately 313 m/s.

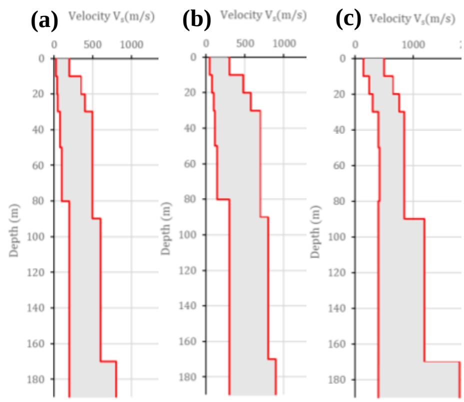

Figure 3 Some examples of the shear wave velocity model range used in the HVSR inversion for the fundamental frequency of the site, including (a) below 0.4Hz, (b) between 0.4Hz and 0.65Hz, and (c) above 3.0Hz, respectively.

3. Results and Discussion

3.1 Seismic microzonation of Central Plain, Thailand

The fundamental frequency map beneath the central plain of Thailand was presented by gridding the results of the HVSR analysis conducted at 149 microtremor measurement sites using Generic Mapping Tools (15) surface interpolation.

The HVSR analysis showed that the central plain of Thailand can be divided into two distinct regions by the fundamental resonance frequency of sediment deposits. A thick sediment layer is indicated by a low fundamental frequency, whereas a shallow bedrock layer is indicated by a high fundamental frequency, as shown in Figure 5. The upper central plain area, from Nakhon Sawan city to the north, had a relatively low fundamental frequency of 0.3 to 0.9 Hz (red – orange in Figure 5) in Kamphaeng Phet, Phichit, Phitsanulok, and certain parts of Uttaradit Province. On the other hand, the provinces of Nakhon Sawan and Chainat had a higher fundamental frequency of over 1.2 Hz, along with a low HVSR amplitude, which separated the upper and lower central plain zones. In the middle of the lower central plain, the Chao Phraya River Basin had an average fundamental frequency below 0.5 Hz, while the western part, including the Mae Klong River Basin, had a higher fundamental frequency. Particularly, Bangkok and Pathum Thani had an exceptionally low fundamental frequency of 0.2 to 0.5 Hz, and the sediment layer thickness was estimated to be around 300-2000 m (3).

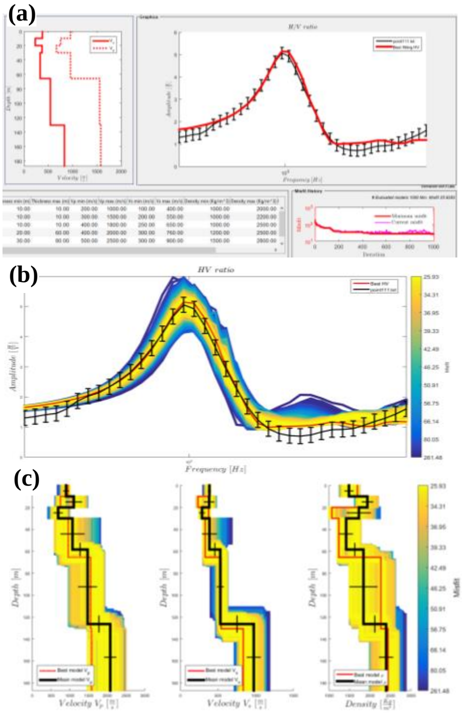

Figure 4 (a) The best fitting model from inversion of the HVSR curve (black lines) for survey point 111 from 1000 iterations; (b) The observed HVSR curve and the modeled HVSR curves (color lines); (c) The inverted Vp, Vs and density profile.

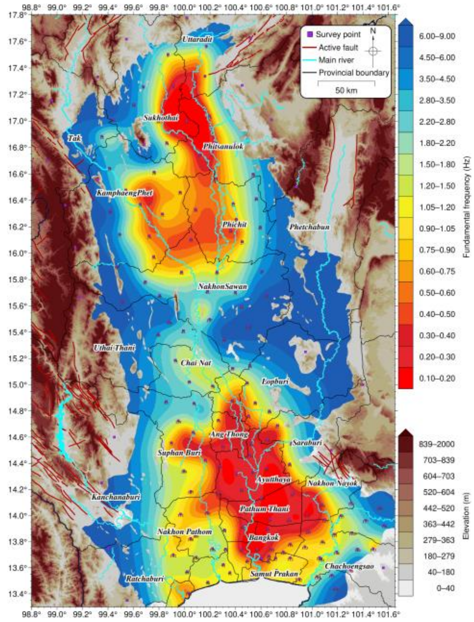

Figure 5 A map of the fundamental resonance frequency of sediment deposits in the central plain, Thailand derived from HVSR curves. The topography around the basin includes active faults and 149 microtremor measurement sites.

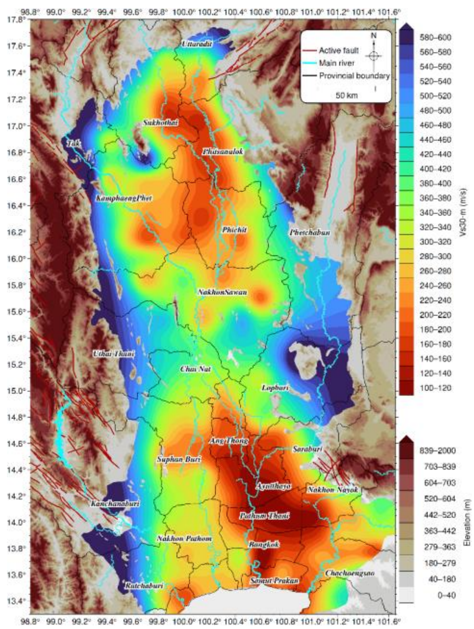

Figure 6 A map of the average shear wave velocity of the top 30 m of the subsurface is derived from HVSR inversion.

A subsurface model was created using HVSR inversion to determine the Vs30 values, as shown in Figure 6. The lowest Vs30 values were found in Ayutthaya, Prathum Thani, and Bangkok. These Vs30 values were less than 180 m/s and can be attributed to the presence of soft soil formed by river sediments or alluvial plains and river basin sediments or flood plain deposits. The Vs30 findings in the north, center, and south of the Bangkok Metropolitan Area, with a Vs30 below 140 m/s, align with the results obtained through the Centerless Circular Array survey method (16, 17). The Vs30 values obtained in this study are comparable to those obtained using the MASW method in (18). For instance, the MASW method yielded a Vs30 value of 163 m/s in Nong Suea District, Pathum Thani, whereas our study found a Vs30 of 161 m/s. The classification of soil types in the central plains of Thailand is shown in Figure 7, which was determined based on the Vs30 value, considering the U.S. National Earthquake Hazards Reduction Program (NEHRP) classification (19). The upper central plain along the Yom River and the Nan River had a low fundamental frequency of 0.3-0.5 Hz and low Vs30, which can be classified as soil type Class E. In the southern areas of Ayutthaya, Pathum Thani, and central Bangkok, an extremely low Vs30 of less than 100 m/s was observed, indicating soil class F or very soft soil. Additionally, regions with soft soil (Class E) had Vs30 values below 180 m/s, including Ang Thong, Ayutthaya, Pathum Thani, and Bangkok. On the other hand, regions with stiff soil had Vs30 values ranging from 180-360 m/s, representing class D soil. These areas of class D soil were distributed around the class F and class E soil regions.

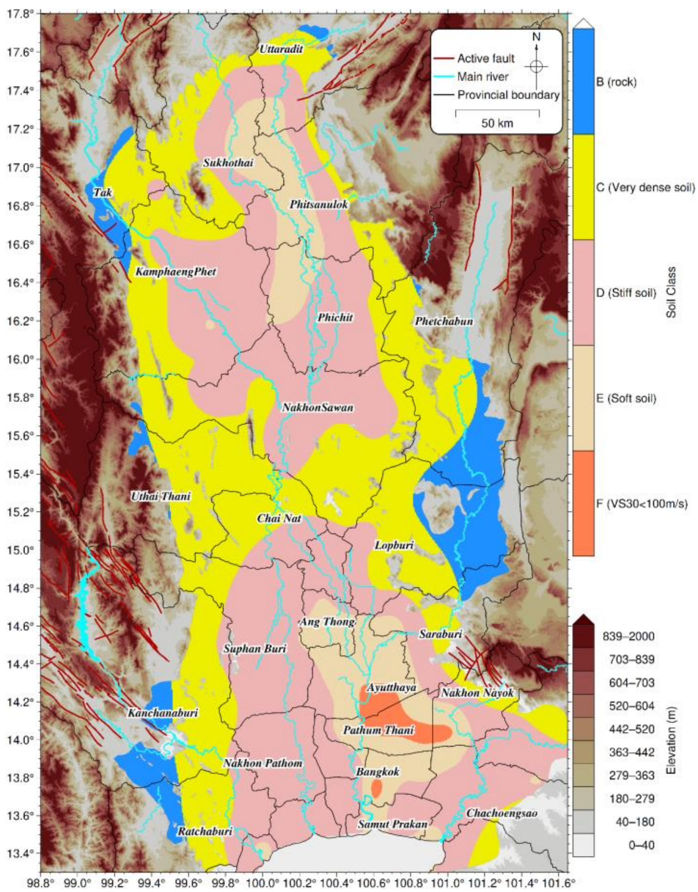

Figure 7 A soil classification map of the central plain in Thailand categorized according to the NEHRP classification.

3.2 Probabilistic Seismic Hazard Analysis (PSHA)

The central plain of Thailand classified in Zone 1 represents a low seismic zone (provinces in the east of the basin) and Zone 2 stands for a moderate seismic zone of Thailand Seismic Regulation B.E. 2564, known as DPT1301/1302-61 earthquake resistant design standard for buildings in Thailand (20), which was promulgated on 4 March 2021.

We calculated the probabilistic seismic hazard map of the Central Plain of Thailand analyzed from a background seismicity source that occurred in Thailand and nearby areas analyzed for smoothed seismicity rates from the decluttered earthquake using the USGS National Earthquake Information Center (NEIC) earthquake catalogue during 1912-2023. The earthquake that occurred in Sumatra-Andaman-Myanmar subduction plate boundary was assessed with a magnitude greater than 5.0 (gray circle in Figure 8) and the Thai Meteorological Department (TMD) earthquake catalogue during 2007-2023 detected by TMD seismic network (red circle in Figure 8) and active fault sources information (earthquake magnitude frequency relationships, recurrence rate and maximum magnitude) in Thailand and surrounding area including subduction interface sources.

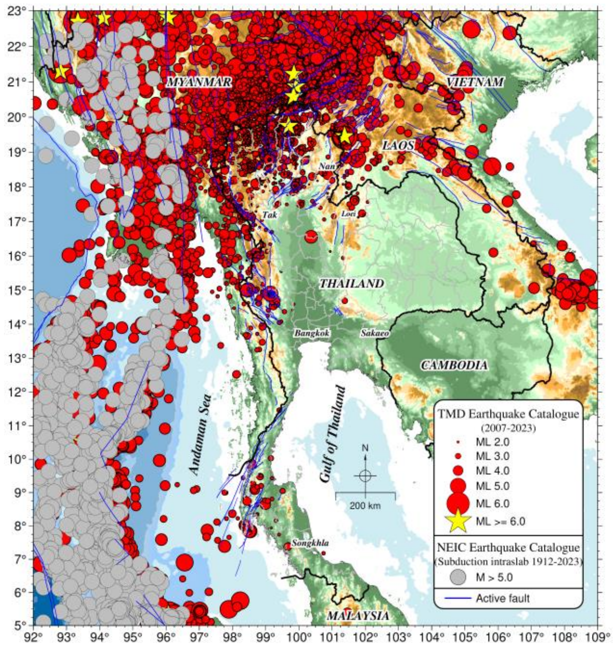

Figure 8 Seismicity map of Thailand and surrounding areas used in seismic hazard analysis, which comprises earthquake catalogue obtained from the USGS-NEIC (M>5, during 1922 – 2023) of subduction earthquake (gray) and TMD earthquake catalogue between 2007-2023 (red).

We applied Boore et al. (21), Campbell and Bozorgnia (22) and Chiou and Youngs (23) ground-motion models (GMMs) for seismicity and active fault sources and chose Atkinson and Boore (24), Zhao (25) and Abrahamson (26) GMMs model for subduction interface and slab with equal logic tree weight. The PSHA map was calculated by using a National Seismic Hazard Model Project computer code (nshmp-haz) (27) and was performed on a site condition with Vs30 from HVSR inversion results from our work shown in Figure 6. We present PSHA maps of the central plain of Thailand for a 2,475-year return period or 2% probability of exceedance (POE) in 50 years, consisting of peak ground acceleration (PGA) in Figure 9 as well as spectral acceleration at 0.2 sec (SA0.2s) in Figure 10 and spectral acceleration at 1.0 sec (SA1.0s) in Figure 11. To design civil engineering structures, spectral acceleration is the preferred parameter.

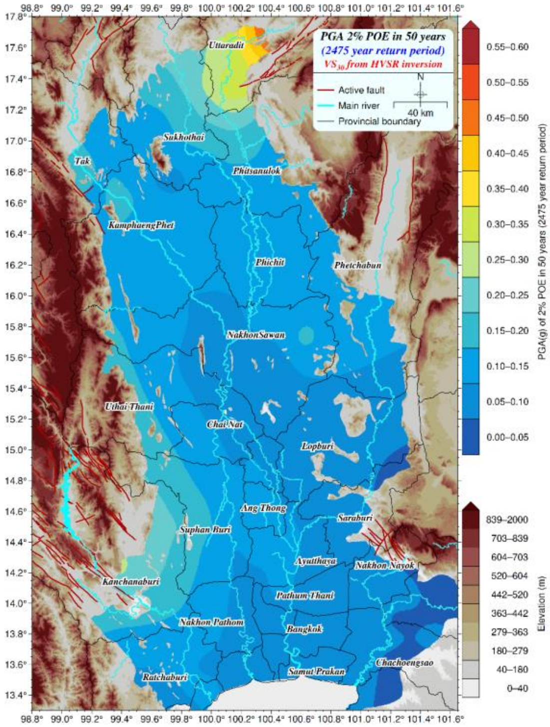

Figure 9 PSHA map for PGA at 2475-year return period on Vs30 site condition.

Based on the PSHA map presented in Figure 9, it can be observed that the upper central plain exhibits an average PGA of 0.1-0.15g, while the lower central plain has an average PGA of 0.05-0.10g. These PGA correspond to the modified Mercalli intensity scale (MMI) level VI, indicating a moderate level of seismic activity, which is slightly higher than those reported by Ornthammarath et al. (28), who conducted a PSHA for northern and southeast Asia performed on rock site conditions.

The seismic hazard risk area with the highest level was discovered in the northern region of the upper central plain and the western side of the central basin. This area, particularly in Uttaradit and Kanchanaburi, is near the earthquake source zone, resulting in a PGA ranging from 0.25g to 0.45g and an SA0.2s from 0.4g to 0.6g.

The SA at 0.2 sec for a 2,475-year return period shown in Figure 10 reveals that Uttaradit (Mueang Uttaradit, Phichai District and Tron District) has the SA0.2s in the range of 0.6-0.8g, corresponding to MMI level IX, slightly higher than the DPT1301/1302-61 standard, with the SA0.2s in the range of 0.58-0.68g because this DPT1301/1302-61 standard is based on rock site conditions.

For SA1.0s shown in Figure 11, this is equivalent to the natural frequency of a building roughly 10 stories high, found in the lower central region, especially around Ang Thong, Ayutthaya, Pathum Thani, and Bangkok. There was a noticeable increase in PGA values from 0.05-0.10g to 0.3-0.4g, or an increase of approximately 4-6 times when compared to surface PGA.

According to the DPT1301/1302-61 standard, it has been determined that Ayutthaya possesses a SA1.0s value of approximately 0.06g, in contrast to the SA1.0s value of 0.30-0.35g obtained from Figure 11. This indicates that the site effect amplifies ground motion in the 1.0 second period by over 5 times.

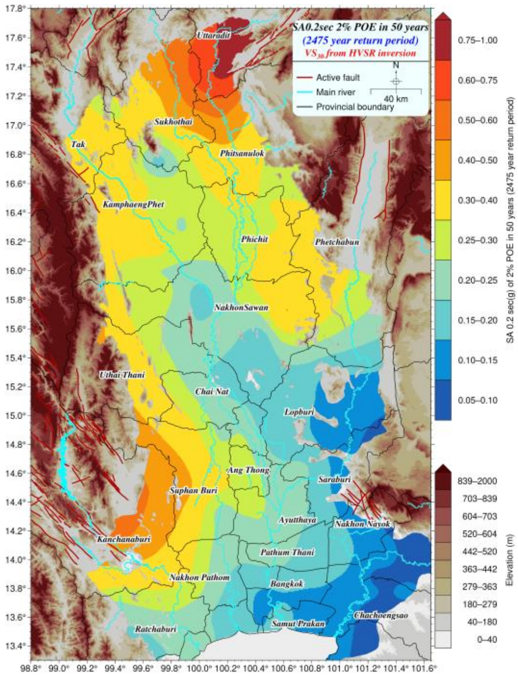

Figure 10 PSHA map for 0.2-sec spectrum acceleration at 2475-year return period on Vs30 site conditions.

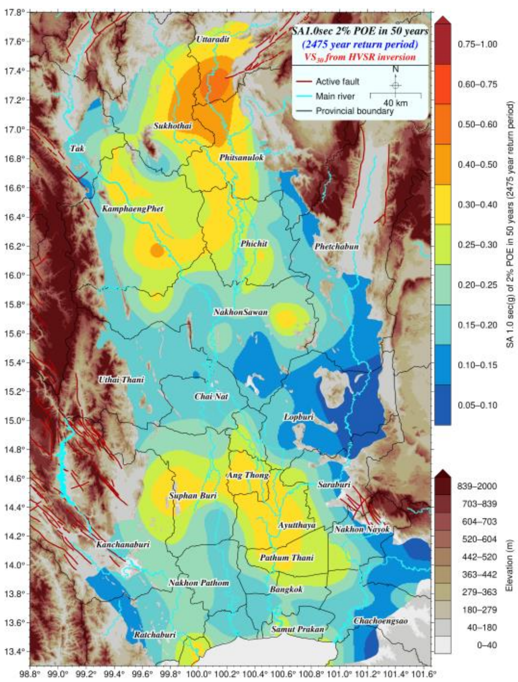

Figure 11 PSHA map for 1.0-sec spectrum acceleration at 2475-year return period on Vs30 site conditions.

4. Conclusions

This study investigated the seismic microzonation of the central plain of Thailand. The findings of this research are comprised of a fundamental frequency map that was developed through the analysis of HVSR for a total of 149 microtremor measurement sites, a Vs30 map derived using HVSR inversion techniques, and a soil classification map constructed based on the NEHRP classification.

In the upper central plain, which is situated along the Yom River and the Nan River, a notable characteristic was observed, namely a low fundamental frequency ranging from 0.3 to 0.5 Hz, accompanied by a correspondingly low Vs30 value, which can classify the soil type in this region as Class E. Moving towards the southern areas encompassing Ayutthaya, Pathum Thani, and central Bangkok, an even more pronounced feature was identified in the form of an extremely low Vs30 value, measuring less than 100 m/s. This observation indicates the presence of soil class F or special soft soil in these regions.

Seismic hazard maps for PGA, SA0.2s, and SA1.0s with a 2% probability of occurrence in 50 years were produced based on the Vs30 site conditions obtained from this study. Specifically, the northern region of the upper central plain and the western side of the central basin exhibit relatively high seismic hazard, with PGA around 0.25-0.45g and SA0.2s around 0.4-0.6g at a 2475-year return period. Moreover, the site effect amplifies ground motion at the 1.0 second period or SA1.0s, which is notably increased, exceeding 5 times the earthquake-resistant design standard for buildings in Thailand DPT1301/1302-61, particularly in the central region of the lower central plain. These results provide valuable insights into the seismic characteristics of the central plain of Thailand and can be used to inform future earthquake hazard assessments and mitigation strategies.

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Declaration of conflicting interests

The authors declared that they have no conflicts of interest in the research, authorship, and this article's publication.

References

1. Morley C, Charusiri P, Watkinson I. Structural geology of Thailand during the Cenozoic Modern tectonic setting of Thailand. In: M. F. Ridd AJB, and M. A. Crow (London, UK: Geological Society, Special Publications), editor. Geology of Thailand 2011. p. 273-334.
2. Ridd MF, Barber AJ, Crow MJ. The Geology of Thailand. Ridd MF, Barber AJ, Crow MJ, editors: Geological Society of London; 2011.
3. Nuchanong T, Chaodumrong P, Luengingkasoot M, Burrett C, Techawan S, Silakul T, et al. Geology of Thailand. Bureau of Geological Survey, Department of Mineral Resources, Bangkok. 2014
4. Japan International Cooperation Agency. The Study on Integrated Plan for Flood Mitigation in Chao Phraya River Basin Summary and Main Report. Royal Irrigation Department Kingdom of Thailand; 1999.
5. Mairaing W, Amonkul C. Soft Bangkok Clay Zoning. EIT-Japan Symposium on Engineering for Geo-Hazards : Earthquakes and Landslides-Surface and Subsurface Structures; September 6-7, 2010; Imperial Queen’s Park Hotel, Bangkok, Thailand,2010.
6. Site Effects. Last Updated: 29 October 2023. Available from: https://www.pnsn.org/outreach/earthquake hazards/site-effects.
7. Nakamura Y. A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. Quarterly Report of Rtri. 1989;30
8. Wathelet M, Chatelain JL, Cornou C, Giulio GD, Guillier B, Ohrnberger M, et al. Geopsy: A User-Friendly Open-Source Tool Set for Ambient Vibration Processing. Seismol Res Lett. 2020;91(3):1878-89. https://doi.org/10.1785/0220190360

9. Konno K, Ohmachi T. Ground-Motion Characteristics Estimated from Spectral Ratio between Horizontal and Vertical Components of Microtremor. B Seismol Soc Am. 1998;88. https://doi.org/10.1785/BSSA0880010228.
10. Bard P-Y, Acerra C, Aguacil G, Anastasiadis A, Atakan K, Azzara R, et al. Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations measurements, processing and interpretation. B Earthq Eng. 2008;6:1-2
11. Rodrigues J, Brincker R, editors. Application of the random decrement technique in operational modal analysis. Proceedings of the 1st International Operational Modal Analysis Conference, April 26-27, 2005, Copenhagen, Denmark; 2005: Aalborg Universitet.
12. García-Jerez A, Piña-Flores J, Sánchez-Sesma F, Luzon F, Perton M. A computer code for forward calculation and inversion of the H/V spectral ratio under the diffuse field assumption. Comput and Geosci 2016;97:67–78. https://doi.org/10.1016/j.cageo.2016.06.016.
13. Piña-Flores J, Perton M, García-Jerez A, Carmona E, Luzon F, Molina Villegas J, et al. The inversion of spectral ratio H/V in a layered system using the Diffuse Field Assumption (DFA). Geophys J Int. 2016;208. https://doi.org/10.1093/gji/ggw416.
14. Pornsopin P, Pananont P, Furlong KP, Chaila S, Promsuk C, Kamjudpai C, et al. Seismic Microzonation Map of Chiang Mai Basin, Thailand. Trends Sci. 2024;21(3): 7370. https://doi.org/10.48048/tis.2024.7370.
15. Wessel P, Luis JF, Uieda L, Scharroo R, Wobbe F, Smith WHF, et al. The Generic Mapping Tools Version 6. Geochem Geophys Geosystems. 2019;20(11):5556-64. https://doi.org/10.1029/2019GC008515.
16. Poovarodom N, Jirasakjamroonsri A. Seismic Site Effects of Soil Amplifications in Bangkok. Sci Technol Asia. 2016; 21(3):59-69.
17. Ornthammarath T, Jirasakjamroonsri A, Pornsopin P, Rupakhety R, Poovarodom N, Warnitchai P, et al. Preliminary analysis of amplified ground motion in Bangkok basin using HVSR curves from recent moderate to large earthquakes. Geoenvironmental Disasters. 2023;10(1). https://doi.org/10.1186/s40677-023-00259-0
18. Naksawee A, Hayashi K, Pananont P. Shear wave velocity estimation of the near-surface sediments of Bangkok and vicinity, Thailand for seismic site characterization. Chiang Mai J Sci. 2016;43:1269-78
19. Council BSS. NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, Part1 Provisions. FEMA302. 1997
20. Department of Public Works and Town & Country Planning. DPT1301/1302-61 standard 2021. Last Updated: 29 October 2023. Available from: https://www.dpt.go.th/th/dpt-standard/.
21. Boore D, Stewart J, Seyhan E, Atkinson G. NGA-West2 equations for predicting PGA, PGV, and 5% damped PSA for shallow crustal earthquakes. NGA-West2 Equations for Predicting PGA, PGV, and 5% Damped PSA for Shallow Crustal Earthquakes. Earthq Spectra. 2014;30(3):1057-85. https://doi.org/10.1193/070113EQS184M.
22. Campbell K, Bozorgnia Y. NGA-West2 Ground Motion Model for the Average Horizontal Components of PGA, PGV, and 5% Damped Linear Acceleration Response Spectra. Earthq Spectra. 2014;30: 1087-115. https://doi.org/10.1193/062913EQS175M.
23. Chiou B, Youngs R. Update of the Chiou and Youngs NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra. Earthq Spectra. 2014;30:1117-53. https://doi.org/10.1193/072813EQS219M.
24. Atkinson G, Boore D. Empirical Ground-Motion Relations for Subduction-Zone Earthquakes and Their Application to Cascadia and Other Regions. B Seismol Soc Am. 2003;93:1703-29. https://doi.org/10.1785/0120020156.

25. Zhao J. Attenuation Relations of Strong Ground Motion in Japan Using Site Classification Based on Predominant Period. B Seismol Soc Am. 2006;96:898-913. https://doi.org/10.1785/0120050122.
26. Abrahamson N, Kuehn, N., Zeynep Gulerce, Z., Gregor, N., Bozognia, Y., Parker, G., Stewart, J., Chiou, B., Idriss, I.M., Campbell, K., and Youngs, R.,. Update of the BC Hydro subduction ground-motion model using the NGA-Subduction dataset: PEER Report No. 2018/022018.
27. Powers P. National Seismic Hazard Model Project computer code (nshmp-haz), software. US Geological Survey, Reston, VA; 2017.
28. Ornthammarath T, Warnitchai P, Chan C-H, Wang Y, Shi X, Nguyen P, et al. Probabilistic seismic hazard assessments for Northern Southeast Asia (Indochina): Smooth seismicity approach. Earthq Spectra. 2020;36:22. https://10.1177/8755293020942528.

