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Effect of spatial variability in soft soil layers on long-period ground motion amplification

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Abstract. The Bangkok Basin is characterised by deep alluvial deposits predominantly composed of soft soils, which are highly susceptible to ground shaking induced by distant earthquakes. Previous studies have utilised ground motion parameters, such as shear-wave velocity, together with historical earthquake records, to develop microzonation maps of soil amplification. However, the recent 2025 Mandalay earthquake has highlighted an important gap in the understanding of long-period ground motions, as the observed effects extended well beyond prior expectations. Despite the considerable distance between the epicentre and Bangkok, occupants of high-rise buildings clearly experienced perceptible seismic vibrations. Given the potential for stronger earthquakes to occur at closer distances, it is crucial to investigate the long-period ground response of Bangkok's soft soil deposits. This study examines the soil amplification factors of Bangkok subsoil under long-period ground motion, using the 2025 Mandalay earthquake as a representative case. One-dimensional site response analyses were performed to simulate the vertical propagation of low-frequency seismic waves from the engineering bedrock through the overlying basin deposits. The results demonstrate that variations in depositional sequences and the thickness of soft clay layers produce distinctive site amplification patterns across the basin.

1 Introduction

Bangkok subsoil consists of a thick soft-clay deposit that is well known to create difficulties for construction because of its low shear strength and high compressibility. Bangkok clay also plays an important role in seismic site response by amplifying ground motions, including those generated by distant earthquakes. This effect was clearly demonstrated in Bangkok during the M_W 7.7 Mandalay earthquake on 28 March 2025, as evidenced by the spectral acceleration curves in Fig.1, which show long-period spectral accelerations exceeding the local seismic design code.

Although Bangkok is located far from active faults, it can still experience relatively strong shaking from large, distant earthquakes. Seismic waves propagating through the thick soft-soil deposits can be significantly amplified and prolonged. The 2025 earthquake was widely felt in Bangkok, primarily because it generated strong long-period ground motions that resonated with mid- to high-rise buildings. The most severe consequence was the collapse of a 33-story building under construction, resulting in 109 reported fatalities. Apart from this collapse, post-event inspections of approximately 500 mid- to high-rise buildings identified three cases classified as red level (i.e., heavy to severe structural damage), while most inspected buildings exhibited minor to moderate damage, mainly affecting non-structural components such as ceilings and infill walls [1].

The objectives of this study are to: (1) quantify site amplification of the Bangkok subsoil based on recorded time histories; and (2) simulate ground behaviour using one-dimensional (1D) non-linear response analyses. To achieve these objectives, recorded ground motions from the 2025 earthquake are utilised and complemented by site-response modelling to clarify basin-related amplification characteristics in Bangkok. These efforts are particularly important considering ongoing revisions to Thailand's current seismic design provisions for Bangkok, which aim to better account for soft-soil amplification effects.

1.1 Background

Bangkok soft-clay basin is often compared with the Valley of Mexico because both settings contain thick clay inside the basins [2]. The effects of earthquakes to Mexico City are well-documented and thoroughly investigated. The 1985 earthquakes despite having epicentral distance over 430 km from the city caused the catastrophic losses in Mexico City mainly because the

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lacustrine deposits amplified and prolonged ground shaking showing a peak at about 2.2-s period [3]. The study concluded that ground motions in the lacustrine basin can be amplified by an order of magnitude relative to nearby firm ground, explaining the severe damage despite the large source-to-site distance.

The impacts of the 2017 Mexico City earthquake were slightly different from the 1985 earthquake. Because epicentral distance decreased to 120 km, the dominant ground motion tended to concentrate in shorter periods, 0.8-1.5 seconds. Low-frequency waves attenuate more strongly during propagation, while relatively higher-frequency waves can persist and be further amplified. The 2017 earthquakes caused severe damage to 5-8 story buildings [4]. These cases illustrated distance-dependent spectral filtering. It can shift the dominant period to be longer in the distant earthquake case, and shorter in nearby event.

Evidence from the recent earthquakes suggests that Bangkok can experience long-period shaking even when the epicentral distance is over 1000 km. In addition, the 2011 Tarlay earthquake causing a 6.8 M_W and the 2014 Mae Lao earthquake in northern Thailand with 6.1 M_W produced motions that were reported as being felt in Bangkok, particularly by occupants of high-rise buildings [5-7]. The widespread perception of these events supports the conclusion that Bangkok's thick, soft-soil deposits and basin setting can shift energy toward longer periods and increase the amplitude of ground acceleration on the surface [1].

1.2 Geological conditions of Bangkok subsoils

1.2.1 Bangkok Clay Basin

The Bangkok Clay Basin began developing approximately 1–2 million years ago during the Pleistocene epoch [8]. The basin was filled with Quaternary sediments deposited through fluvial, deltaic, and estuarine processes, primarily associated with sea-level fluctuations and tectonic subsidence. During the Holocene epoch, depositional environments were predominantly influenced by the Chao Phraya River. As the river flow velocity decreased near the coast, massive accumulations of fluvial sediments were deposited, forming the young Bangkok Clay sequence [9].

The soft Quaternary Bangkok Clay, often containing sand lenses, is typically 10–30 m thick, and is underlain by Pleistocene interbedded sand–clay strata. Total sediment thickness increases toward the basin centre and can reach 900–1,000 m [10]. According to Ornthammarath et al., the BKKA and BKSI seismic stations are situated over basin depths of 700-900 m, whereas the KMUA station is located in a shallower zone with a thickness of approximately 530–560 m. Although the depth to seismic bedrock varies substantially across the basin, the average near-surface shear-wave velocity remains relatively consistent [11]. These low-velocity deposits are known to significantly amplify seismic ground motions.

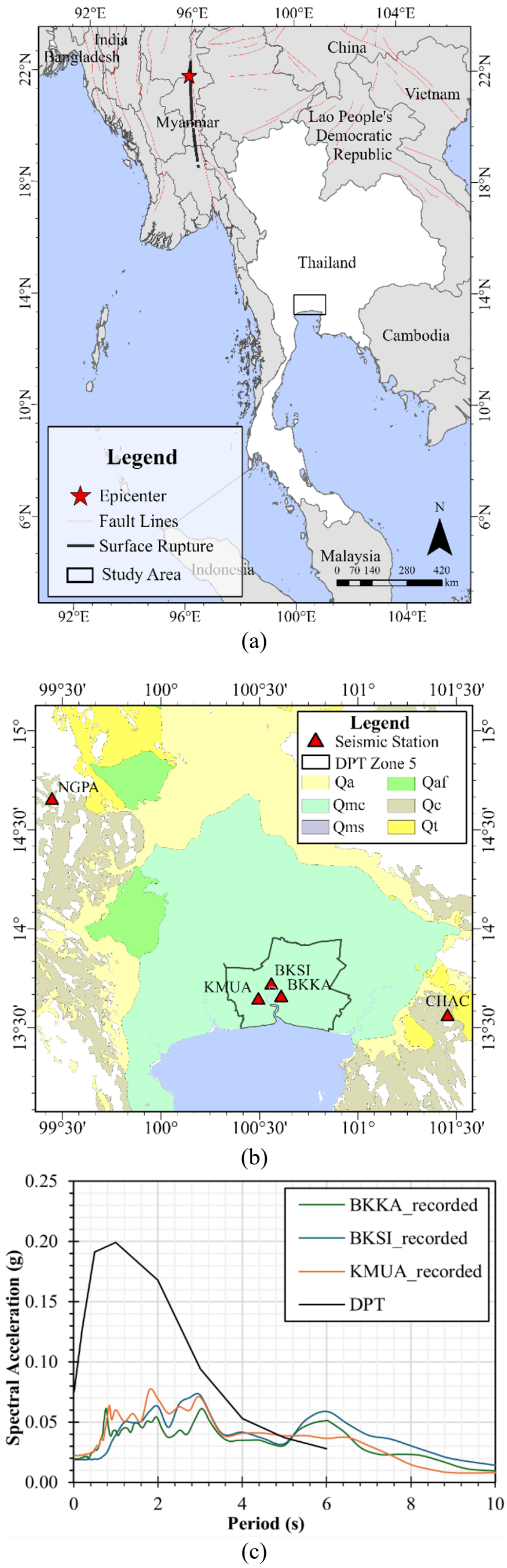

Fig. 1. Ground response in Bangkok during the Mw 7.7 Mandalay earthquake on 28 March 2025: (a) Map showing the distance from the epicentre of the Mw 7.7 Mandalay earthquake to the Bangkok Basin; (b) locations of seismic stations on the Quaternary map; and (c) spectral acceleration curves recorded at three seismic stations within the Bangkok Basin during the Mw 7.7 Mandalay earthquake, compared with the seismic design spectra of the Department of Public Works and Town & Country Planning (DPT).

Regarding local engineering standards, the DPT1301/1302-61 seismic design code [12], issued by the Department of Public Works and Town & Country Planning in 2018, assigns 10 distinct seismic zones to Bangkok to account for spatially variable amplification and the presence of soft clays [13]. The seismic stations utilised in this study (BKKA, BKSI, and KMUA) are all located within Zone 5.

1.2.2 Tectonic Setting

The Department of Mineral Resources (DMR) has identified active faults in Thailand based on prior paleoseismic investigations. Of particular concern to Bangkok are the Kanchanaburi fault zones in western Thailand, specifically the Three Pagodas and Sri Sawat faults, due to their close proximity and their capacity to trigger M_W 7.0+ earthquakes. These active right-lateral strike-slip faults are interconnected components of the regional tectonic setting, which accommodates the northward movement of the Indian Plate [14].

This tectonic environment was highlighted on 28 March 2025, when a major M_W 7.7 earthquake occurred near Mandalay, Myanmar. This event was accommodated by the right-lateral Sagaing Fault, a 1,200-km-long strike-slip fault situated within the active convergence zone between the Indian and Eurasian plates [6]. The ongoing collision drives the Indian plate beneath Eurasia, forming the Himalayan subduction system and promoting significant strike-slip faulting across the eastern plate boundary [15].

This setting sustains active faults capable of generating large-magnitude earthquakes. The Sagaing Fault is particularly notable, exhibiting a slip rate of approximately 20 mm/yr and a shallow locking transition zone roughly 10–16 km deep [16]. Historical and instrumental records confirm a recurrence of M_W 7.0+ events along this fault, including earthquakes in 1930 (M_W 7.3-7.5), 1946 (M_W 7.3-7.7), 1956 (M_W 7.0), 1991 (M_W 6.9), 2012 (M_W 6.8), and most recently in 2025 (M_W 7.7) [17]. Furthermore, the absence of an M_W 8.0 earthquake since the 1839 Ava earthquake suggests an elevated potential for future large-scale ruptures in the region.

2 Methodology

This study presents a simplified and direct framework to analyse local seismic site response in Bangkok Basin using recorded time histories and finite element modelling. Time histories from three stations inside and two reference stations outside the basin are compiled for a comparative analysis of basin effect. Soil and V_S profiles of on-basin sites are defined from the 3D subsurface model. Subsequently, response spectra are computed, and amplification factors are derived using spectral ratios normalized by PGA and spectral amplitude. Finally, non-linear 1D site response analyses are performed using NGPA/CHAC inputs to simulate strain-dependent soil behaviour and evaluate whether the modelled response is consistent with the observed amplification.

2.1 Recorded earthquake time-histories

To quantify the impact of the Bangkok Basin effects, this study compares recorded ground motions from three within-basin stations located in Bangkok (i.e., BKKA, BKSI, and KMUA) with two external seismic stations, NGPA and CHAC, located in Kanchanaburi and Chachoengsao, respectively (as shown in Fig.1(b)). During the 2025 Mandalay earthquake, stations BKKA, BKSI, and KMUA were approximately 675 km from the source. The NGPA station, situated significantly closer at 515 km, serves as an outside-basin reference for the incoming wavefield [10].

In this study, stations NGPA and CHAC are categorised as stiffer, near-rock sites with relatively shallow bedrock compared to the deep basin deposits of Bangkok, providing baseline motions for amplification estimates.

2.2 Subsoil modelling and shear wave velocity profile

Subsurface geotechnical and V_S parameters were derived from a 3D DNN-based model of the Bangkok region [18]. Developed from over 1,800 boreholes, the model provides continuous stratigraphy across nine soil units, from which representative 1D soil columns were generated for the BKKA, BKSI and KMUA sites. These stations are situated on Bangkok clay, a 10-30 m thick Holocene marine deposit. This soft clay layer overlies Pleistocene interbedded sand and clay, which are notably stiffer. The overall site profile is characterized by low stiffness, with average shear wave velocity ($V_{S,30}$) below 180 m/s [11]. The average near-different, as shown in Fig.2.

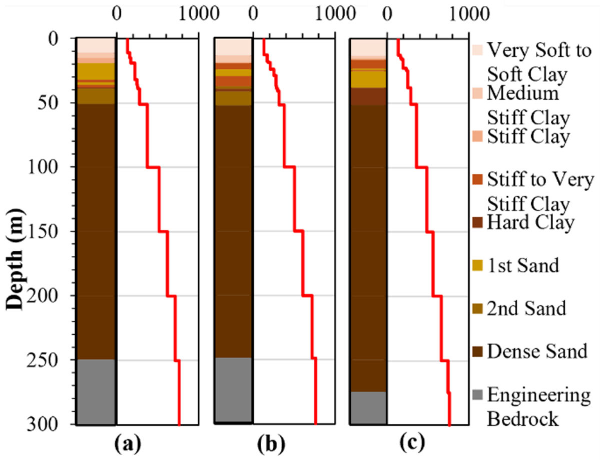

Fig. 2. Soil profiles at the (a) BKKA, (b) BKSI, and (c) KMUA seismic stations, generated from the 3D DNN-based model of the Bangkok Basin.

2.3 Ground motion characteristic evaluation

Acceleration time histories from five stations were converted into response spectra and their corresponding spectral acceleration curves. Key ground-motion parameters derived from these include peak ground acceleration (PGA) and the dominant spectral period.

To quantify local site effects, specifically soft-soil amplification, spectral ratios between basin and reference stations were computed using both PGA-based and frequency-dependent amplitudes [2]. The soil amplification factor (AF) is defined by the ratio of peak ground surface acceleration to that of the reference motion [19]:

$$AF = \frac{PGA_{sf}}{PGA_{in}} \quad (1)$$

where PGA_{sf} denotes the PGA recorded at stations inside Bangkok Basin (BKKA, BKSI and KMUA), and PGA_{in} represents the PGA from out-of-basin reference stations (NGPA and CHAC).

Similarly, frequency-dependent spectral amplification ($SAMP_T$) is evaluated across the period range of interest as follows:

$$SAMP_T = \frac{SA_{T,sf}}{SA_{T,in}} \quad (2)$$

where $SA_{T,sf}$ and $SA_{T,in}$ are the spectral acceleration at period T for the surface and input reference motions, respectively.

2.4 One-dimensional site response analysis

One-dimensional nonlinear site-response analyses were performed using RSSseismic software, employing a nonlinear time-domain approach. To evaluate ground-surface acceleration time histories and response spectra, seismic excitation was propagated vertically from an elastic bedrock base through a horizontally layered soil column. Nonlinear soil behaviour was simulated using the general quadratic/hyperbolic (GQ/H) constitutive model with a non-Masing formulation for unloading and reloading [20]. In this nonlinear time-domain framework, strain-dependent modulus reduction and damping evolve continuously with shear strain during seismic loading, allowing the transient response of the soil to be captured [21, 22]. The shear modulus reduction (G/G_{max}) and damping curves were adopted from Vucetic and Dobry (1991) for cohesive soil [23] and from Seed and Idriss (1970) for granular soil [24].

The soil parameters used in the analysis included unit weight, shear wave velocity, and undrained shear strength. These values were derived from a 3D DNN-based soil model of Bangkok [18], as summarised in Table 1. For non-cohesive soil, shear strength was characterised using Mohr-Coulomb failure criterion based on the friction angle.

The friction angles of Bangkok soils were estimated from SPT-N values, as given in Equation (3) [25]:

$$\phi = (20N_1)^{0.5} + 20 \quad (3)$$

where ϕ is friction angle and N_1 is SPT N-value normalised at an overburden pressure of 98 kPa.

These values are consistent with those reported in a recent study that applied an alternative DNN-based approach to Bangkok sand under medium- to dense-state conditions [26].

Table 1. Soil parameters used in 1D site response analysis.

Site	Soil Type	H (m)	γ (kN/m^3)	PI (%)	ϕ (°)	S_u (kPa)
BKKA	Very soft to soft clay	11	15.9	50		13.5
	Medium Stiff Clay	4	16.3	45		34.2
	Stiff Clay	4	18.1	42		68.4
	Sand	13	20.3		38	
	Stiff to Vey Stiff Clay	2	19.3	39		126.4
	Sand	2	20.4		38	
	Hard Clay	1	20.4	31		243.1
	Hard Sand	12	20.4		38	
	Hard Sand	49	21		45	
	Hard Sand	50	22		45	
	Hard Sand	50	22		45	
	Hard Sand	50	23		45	
BKSI	Very Soft to Soft Clay	13	15.9	45		14.2
	Medium Stiff Clay	5	16.9	40		35.4
	Stiff Clay	1	18.4	38		78.0
	Stiff to Very Stiff Clay	5	19.8	29		136.7
	Sand	5	20.8		38	
	Stiff to Very Stiff Clay	8	19.8	28		147.3
	Sand	2	21		42	
	Hard Clay	2	20.2	32		246.8
	Hard Sand	11	21		42	
	Hard Sand	48	21		45	
	Hard Sand	50	22		45	
	Hard Sand	50	22		45	
	Hard Sand	49	23		45	
KMUA	Very Soft to Soft Clay	13	15.8	47		15.3
	Medium Stiff Clay	2	17.1	37		34.8
	Stiff Clay	1	19.1	34		71.9
	Stiff to Very Stiff Clay	7	19.4	32		124.6
	Sand	1	20.3		38	
	Stiff to Very Stiff Clay	1	19.9	29		140.7
	Sand	13	20.4		38	
	Hard Clay	13	20.4	28		253.4
	Sand	49	21		45	
	Sand	50	21		45	
	Sand	50	22		45	
	Sand	50	22		45	
	Sand	25	23		45	

Input motions were obtained from the NGPA and CHAC stations, located on rock outcrops outside the basin, and served as reference excitations for the 1D analyses, as shown in Fig.3. Due to closer proximity to the source, the seismograms at station NGPA exhibit earlier P- and S- wave arrivals and a significantly shorter duration of intense shaking. Peak amplitudes occur during the main S-wave phrase, followed by quick signal attenuation, compared to more distant station CHAC (see Fig.3).

To represent the thick Bangkok deposits at the BKKS, BKSI and KMUA sites, each soil column was extended downward to the depth where engineering bedrock was reached. Following the NEHRP classification, this boundary was defined as having a shear-wave velocity (V_S) exceeding 760 m/s. Consequently, the representative soil columns for BKKA and BKSI were modelled to a depth of 250 m, while the column for KMUA reached a depth of 275 m.

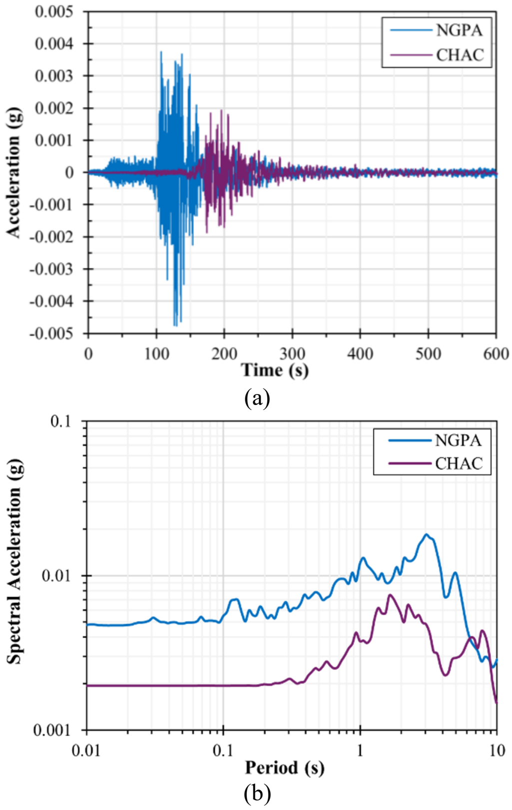

Fig. 3. Ground motion records from two seismic stations during the Mw 7.7 Mandalay earthquake on 28 March 2025: (a) Acceleration time histories recorded at the NGPA and CHAC seismic stations outside the Bangkok Basin; and (b) corresponding spectral acceleration curves.

3 Results and discussion

Fig.4 displays a clear separation between the two outside-basin rock stations (NGPA, CHAC) and the three Bangkok stations (BKKA, BKSI, and KMUA) in the response spectra. For peak ground acceleration, all stations recorded relatively low acceleration; however, the basin sites rise rapidly and remain consistently higher than the reference sites. CHAC exhibits low amplitudes with a small broad maximum around the short-period range, roughly about 1–2 s, while NGPA peaks around the intermediate-period range, about 3 s, due to its closer proximity to the fault. Notably, both rock stations remain below 0.02g.

In contrast, BKKA, BKSI and KMUA show a sharp increase in amplification for periods greater than 1 s, with dominant peaks in the 2–3 s range reaching approximately 0.07–0.08 g, as shown in Fig.5. This specific range coincides with the fundamental natural periods of high-rise buildings, typically 20 to 40 stories, which are common in the Bangkok skyline [27]. The combination of soil-site amplification with structural resonance can create a high risk of double resonance, which can cause considerable structural stress and indicates that tall buildings in Bangkok are vulnerable to far-field earthquake events.

A long-period amplification is also apparent for the BKKA and BKSI stations, which show a secondary long-period jump near 6 s. While this exceeds the natural period of most standard buildings, it poses a significant concern for ultra-high skyscrapers or long-span bridges [28].

According to Equation (1), the basin sites have accelerations of about 0.019-0.022g, yielding an amplification factor (AF) of approximately 3-5 relative to rock sites. Using Equation (2) at the dominant basin period (2-3 s), the spectral amplification relative to NGPA is roughly 4-6. Overall, the spectra indicate that basin stations are dominated by long-period motion, while the outside-basin stations concentrate energy at shorter-to-intermediate periods with much smaller amplitudes.

Fig.5 compares the spectral acceleration of three basin sites from RSSseismic (solid lines) with the corresponding recorded input spectra (dashed lines) from two rock sites (NGPA and CHAC). The 1D nonlinear simulations show clear amplification up to 4 s, indicating that vertical wave propagation through the Bangkok soft-soil column model can effectively simulate amplified motion at the dominant period range. This is consistent with prior Bangkok studies where nonlinear 1D seismic ground response analysis produced larger surface motions due to the soft clay layer.

At periods longer than 4 s, the 1D model cannot reasonably predict Bangkok soil amplification due to its inability to capture basin-edge effect and surface-wave contributions, such as Love waves. These multi-dimensional effects cannot be analysed by the simplified 1D approach [22].

Although a 1D site-response analysis cannot account for three-dimensional basin effects, multiple 1D site-response analyses incorporating the spatial variability of soil parameters can be used to demonstrate the influence of subsoil variability on ground motion response. It should be noted that three-dimensional basin effects refer to multidirectional wave propagation within the subsoil, whereas spatial variability refers to the non-uniformity of geological conditions and subsoil properties.

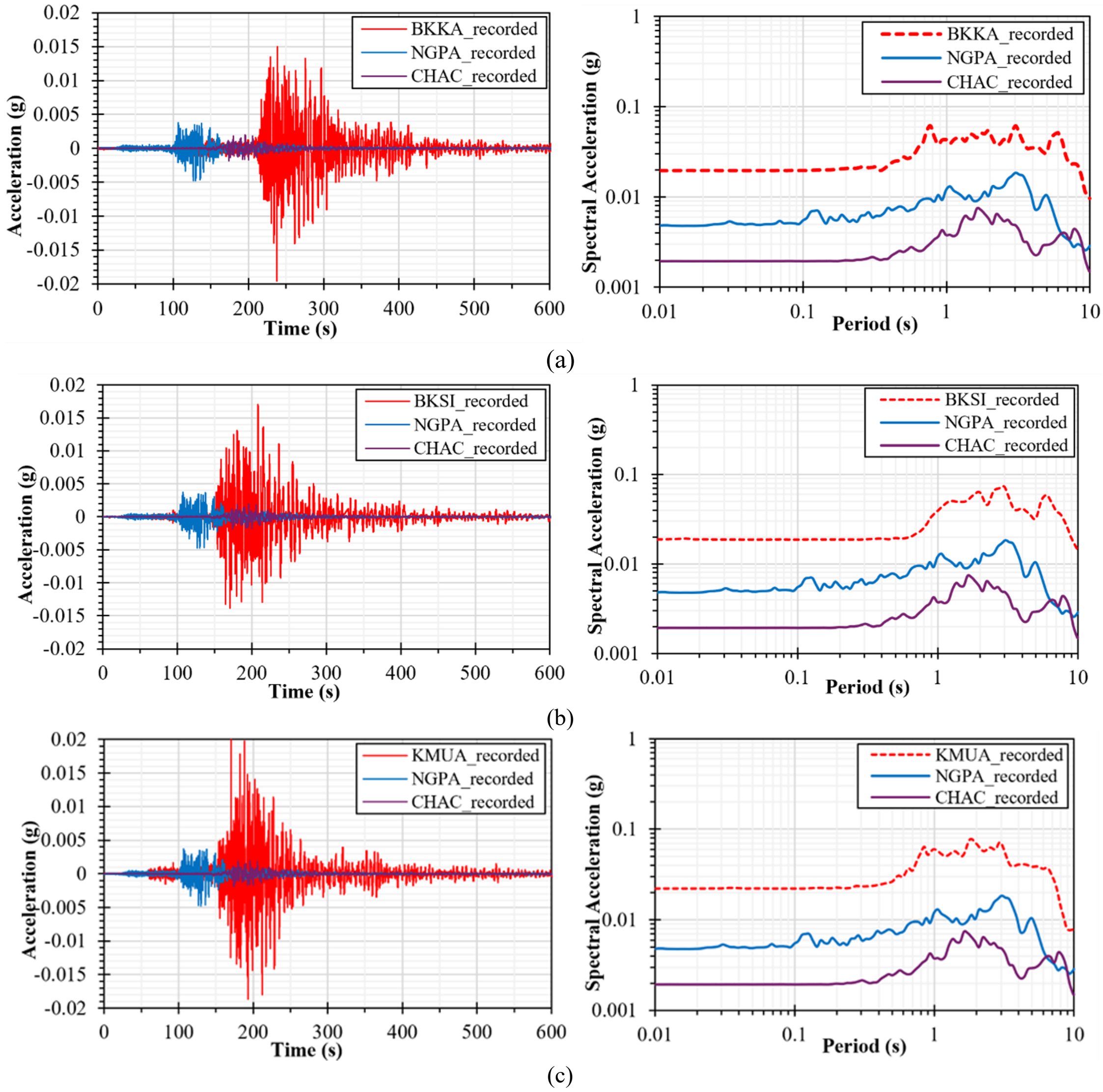

Fig. 4. Comparison of recorded acceleration time histories and corresponding response spectra between the reference stations outside the Bangkok Basin (NGPA and CHAC) and the Bangkok Basin stations: (a) BKKA, (b) BKSI, and (c) KMUA.

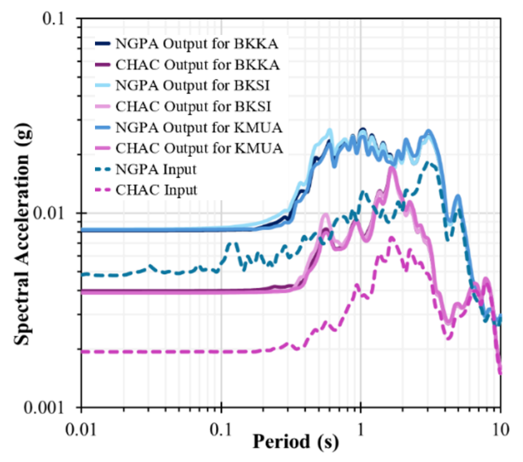

Fig. 5. Response spectra at the BKKA, BKSI, and KMUA stations obtained from 1D site response analyses using the recorded motions at the NGPA and CHAC reference stations as input, shown by solid lines; the response spectra of the input motions recorded at NGPA and CHAC are shown by dashed lines.

4 Conclusion

This study investigated the seismic response of the Bangkok Basin during the M_w 7.7 Mandalay earthquake of 2025. The analysis shows that basin stations (BKKA, BKSI, and KMUA) experienced spectral amplitudes approximately three times higher than those at outside-basin reference sites (NGPA and CHAC), confirming significant basin-induced amplification. A strong long-period spectral response was observed, particularly within the 1–3 s and 5–7 s ranges, which poses a substantial risk to high-rise infrastructure.

While the nonlinear 1D site-response model effectively reproduced soil amplification for periods up to 4 s, it was unable to capture the responses observed at longer periods. This discrepancy suggests that multi-dimensional phenomena, such as basin-edge effects and Love waves, contribute significantly to the long-period motion in deep sedimentary basins. Consequently, future 2D or 3D basin-response analyses are recommended to more accurately characterize the wave propagation in the Bangkok area.

Most importantly, the recorded response spectrum from the 2025 event surpassed the DPT1301/1302-61 [12] design spectrum for periods exceeding 5 s. This finding highlights a critical need to reconsider current Thai seismic design standards for long-period structures. Future definitions of design spectra for high-rise buildings must emphasize deep-basin amplification effects to ensure structural resilience against far-field seismic hazards.

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References

1. T. Ornthammarath, P. Warnitchai, Y. Maruyama, Correction: far-field ground motion characteristics of the Bangkok basin, Thailand. Bull. Earthq. Eng. **23**, 6577-6602 (2025). https://doi.org/10.1007/s10518-025-02295-7
2. S. Likitlersuang, P. Plengsiri, L.Z. Mase, W.Tanapalungkorn, Influence of spatial variability of ground on seismic response analysis: a case study of Bangkok subsoils. Bull. Eng. Geol. Environ. **79**, 39 – 51 (2020). https://doi.org/10.1007/s10064-019-01560-9
3. H.B. Seed, M.P. Romo, J.I. Sun, A. Jaime, J. Lysmer, The Mexico earthquake of September 19, 1985 – relationships between soil conditions and earthquake ground motions. Earthq. Spectra. **4**, 687 – 729 (1988) https://doi.org/10.1193/1.1585498
4. J.M. Mayoral, D. Asimaki, S. Tepalcapa, C. Wood, A. R. Sancha, T Hutchinson, Site effects in Mexico City basin: past and present. Soil Dyn. Earthq. Eng. **121**, 369-382 (2019). https://doi.org/10.1016/j.soildyn.2019.02.028
5. L.Z. Mase, S. Likitlersuang, T. Tobita, Ground motion parameters and resonance effect during strong earthquake in northern Thailand. Geotech. Geol. Eng. **39**, 3 (2021). https://doi.org/10.1007/s10706-020-01619-5
6. L.Z. Mase, S. Likitlersuang, T. Tobita, Analysis of seismic ground response caused during strong earthquake in northern Thailand. Soil Dyn. Earthq. Eng. **114**, 113-126 (2018). https://doi.org/10.1016/j.soildyn.2018.07.006
7. W. Tanapalungkorn, L.Z. Mase, P. Latcharote, S. Likitlersuang, Verification of attenuation models based on strong ground motion data in northern Thailand. Soil Dyn. Earthq. Eng. **133**, 106145 (2020). https://doi.org/10.1016/j.soildyn.2020.106145
8. P. Nutalaya, J.L. Rau JL, Structural framework of the Chao Phraya Basin. In: Thailand proc. of the symposium of Cenozoic basins. Chaing Mai University, Thailand (1984), 106–129
9. M.F. Qodri, L.Z. Mase, S. Likitlersuang, Non-linear site response analysis of Bangkok subsoils due to earthquakes triggered by Three Pagodas Faults. Eng. J. **25**, 1 (2021). https://doi.org/10.4186/ej.2021.25.1.43
10. T. Ornthammarath, P. Warnitchai, K. Worakanchana, S. Zaman, R. Sigbjörnsson, C.G. Lai, Probabilistic seismic hazard assessment for Thailand. Bull. Earthq. Eng. **9**, 367–394 (2011). https://doi.org/10.1007/s10518-010-9197-3
11. T.S. Nguyen, K. Ngamcharoen, S. Likitlersuang, Statistical characterisation of the geotechnical properties of Bangkok subsoil. Geotech. Geol. Eng. **41**, 3 (2023) https://doi.org/10.1007/s10706-023-02390-z
12. DPT 1301/1302-61 Earthquake resistant design code DPT 1301/1302-61. Department of Public Works and Town &Country Planning, Ministry of Interior, Bangkok, Thailand (in Thai) (2018)
13. N. Poovarodom, A. Jirasakjamroonsri, Seismic site effects of soil amplifications in Bangkok. Sci. Tech. Asia. 21, 3 (2016)
14. P. Pananont, B. Wechbunthung, P. Putthapiban, D. Wattanadilokkul, Seismic activities in Kanchanaburi: past and present. Songklanakarin J. Sci. Technol. **33**, 355-364 (2011).
15. L.Z. Mase, S. Likitlersuang, T. Tobita, Verification of liquefaction potential during the strong earthquake at the border of Thailand-Myanmar. J. Earthq Eng. **26**, 4 (2022). https://doi.org/10.1080/13632469.2020.1751346
16. S. Pailoplee, P. Charusiri, Seismic hazards in Thailand: a compilation and updated probabilistic analysis. Earth Planets Space. **68**, 98 (2016). https://doi.org/10.1186/s40623-016-0465-6
17. K. Shahzada, U.A. Noor, Z.D. Xu, In the wake of the March 28, 2025 Myanmar Earthquake: A Detailed Examination. J. Dyn. Disasters. **1**, 100017 (2025). https://doi.org/10.1016/j.jdd.2025.100017
18. P. Pintusorachai, W. Tanapalungkorn, S. Likitlersuang, Enhancing 3D geological and geotechnical engineering model of Bangkok subsoil using optimal deep neural network models. Environ. Earth. Sci. **83**, 644 (2024). https://doi.org/10.1007/s12665-024-11942-2
19. S.L. Kramer, Geotechnical Earthquake Engineering (Pearson New International Ed, Essex, 1996)
20. D.R. Groholski, Y.M.A. Hashash, M. Musgrove, J. Harmon, B. Kim, Evaluation of 1-D non-linear site response analysis using a general quadratic/hyperbolic strength-controlled constitutive model, in Proceedings of the 6th International Conference on Earthquake Geotechnical Engineering (6ICEGE), Christchurch, New Zealand, November 1-4 (2015)
21. A.S.M.F. Hossain, A. Saeidi, M. Salsabili, M. Nastev, J.R. Suescun, Z. Bayati, A review of parameters and methods for seismic site response. Geosci. J. **15**, 128 (2025). https://doi.org/10.3390/geosciences15040128
22. J. Huang, D. McCallen, Applicability of 1D site response analysis to shallow sedimentary basins: a critical evaluation through physic-based 3D ground motion simulations. Earthq. Eng. Sruct. Dyn. **53**, 2876-2907 (2024). https://doi.org/10.1002/eqe.4142
23. M. Vucetic, R. Dobry, Effect of soil plasticity on cyclic response. J. Geotech. Eng. **117**, 89-107 (1991). https://doi.org/10.1061/(ASCE)0733-9410(1991)117:1(89)
24. H.B. Seed, I.M. Idriss, Soil moduli and damping factors for dynamic response analyses, Report No. EERC 70-10, Earthquake Engineering Research Centre, University of California, Berkeley (1970)
25. M. Hatanaka, A. Uchida, Empirical correlation between penetration resistance and internal friction angle of sandy soils. Soils Found. **36**, 1-9 (1996) https://doi.org/10.3208/sandf.36.4_1

26. S. Youwai, K. Wongsala, Predicting the friction angle of Bangkok sand using state parameter and neural network. Geotech. Geol. Eng. **42**, 5947-5965 (2024). https://doi.org/10.1007/s10706-024-02873-7
27. K. Warnitchai, C. Sangarayakul, S.L. Ashford, Seismic hazard in Bangkok due to distant earthquakes, in Proceedings of the 12th World Conference on Earthquake Engineering, Auckland, New Zealand, January 30–February 4 (2000), 1142
28. L.Z. Mase, W. Tanapalungkorn, P. Plengsiri, K. Ngamcharoen, S. Likitlersuang, Subsoil variability in the Bangkok metropolitan area of Thailand identified through ambient noise measurement. Indones. J. Geosci. **10**, 1 (2023). https://doi.org/10.17014/ijog.10.1.1-13