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Preliminary analysis of amplified ground motion in Bangkok basin using HVSR curves from recent moderate to large earthquakes

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Abstract

Background The Bangkok Basin has been known from non-instrumental observations of the local population to be subject to ground motion amplification due to the deep alluvial sediments and basin geometry. This study analyzes available seismic data to confirm that basin effects are significant in the Bangkok Basin. The paper contributes to the evaluation of basin effects by characterizing the engineering ground motion parameters and HVSR curves for the Bangkok basin which produce lengthening of ground motion duration with respect to nearby rock sites, albeit with very low ground motions. For this purpose, we analyzed ground motion records from seismic stations located within the Bangkok alluvial basin from 2007 to 2021. Recorded peak horizontal ground acceleration (PGA) for seismic stations inside the basin always exceeded 1 cm/s^2 during eight earthquakes with Mw ≥ 5.5. Of these, two were intraslab events and six were shallow crustal earthquakes. These recorded ground motions shook high-rise buildings in Bangkok even though their epicentral distance exceeded 600 km.

Methods Several time and frequency domain analyses (such as analysis of residual, HVSR, Hodogram plots, etc.) are used on the ground motion records in the Bangkok basin to determine the frequency content of recorded ground motion and to demonstrate the significance of surface waves induced by the deep basin in altering the engineering ground motion amplitudes. In addition, centerless circular array microtremor analysis is used to determine the depth of sedimentary basin to the bedrock.

Results Based on comparisons from those stations located outside the Bangkok basin, we observed the capability of alluvial deposits in the Bangkok basin to amplify ground motion records by about 3 times. We observed that there is a unique site amplification effect between 0.3 and 0.1 Hz due to local surface waves and other moderate amplifications between 2 and 0.5 Hz due to a soft layer like other deep alluvial basins in other metropolitan areas.

Conclusion We noticed that there is a unique site amplification effect between 0.1 and 0.3 Hz and smaller peaks around 2 and 0.5 Hz consistent with expectations for site amplification effects associated with deep basins. Moreover, we noticed the presence of low frequencies content of the surface wave generated within the basin which deserved further studies using the 2D/3D ground motion modelling through basin topography and velocity models.

Keywords Earthquake, Basin effect, Long period, HVSR, Ground motions, Earthquake effects

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Introduction

Although Bangkok is situated a long distance from known active faults, recent moderate earthquakes (Mw ≥ 5.5) a large distance away (R > 600 km) in Myanmar, Northern Thailand, and the Andaman Islands always shake high-rise buildings as far away as Bangkok (Fig. 1a; Table 1). The reason is mainly due to the ability of deep, low shear-wave velocity alluvial deposits in the Chao Phraya River delta that amplify strong motion about 2 to 3 times compared to seismic stations located outside this alluvial basin. These amplification ratios have not yet been verified and it is essential for a thorough and comparative study of the observed ground motions in and outside Bangkok basin from these recent earthquakes to

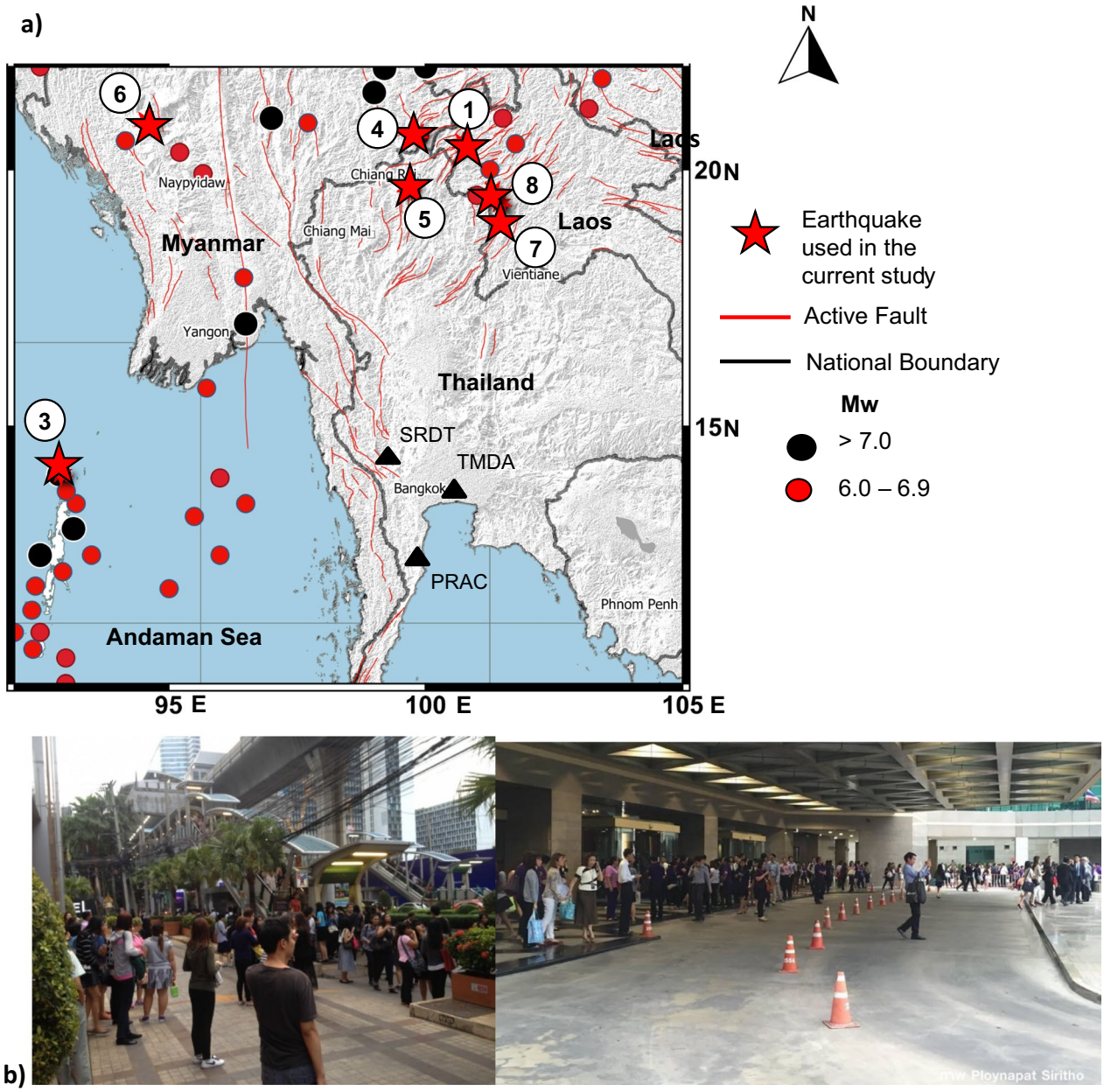

Fig. 1 **a** Map showing the epicenters of earthquakes since 1912 with magnitudes greater than Mw 6.0 and earthquakes used in the current study after 2007 (red star). Black triangles represent seismic stations operated by TMD used in the current study before upgrading in 2018. Noticed that event # 2 is not located in the map since long distance. **b** Tall building occupants in BMA scurried out of the buildings in panic at about 5.34 pm on 24 August 2016 after they felt the buildings were shaking because of the Mw 6.8 earthquake in Myanmar at 1000 km epicentral distance, event # 6

Table 1 Summary of earthquakes widely felt by public in tall buildings in BMA and adopted in the current work with available ground motion records inside and outside Bangkok basin since 2007

EQ ID	Date[a]	Time (UTC)	Lat	Long	Mw	Depth (km)	R_{epi} (km)	MMI[b]
1	16/5/2007	08:56:14	20.503	100.732	6.3	9.0	740	III
2	12/5/2008	06:28:01	31.002	103.322	7.9	19	1900	II
3	10/8/2009	19:55:38	14.099	92.902	7.5	24	810	III
4	24/3/2011	13:55:12	20.687	99.822	6.8	8	770	III
5	5/5/2014	11:08:43	19.656	99.670	6.1	6	680	III
6	24/8/2016	10:34:54	20.923	94.569	6.8	82	1000	III
7	20/11/2019	23:50:43	19.360	101.440	6.2	10	640	III
8	19/12/2021	04:06:15	19.561	101.311	5.5	10	642	III

[a] Global CMT (http://www.globalcmt.org); R_{epi} is the epicentral distance from the epicenter to Bangkok; [b]MMI is the Modified Mercalli Intensity Level Observed in Bangkok reported by NEIC PDE Catalog (http://earthquake.usgs.gov/earthquakes/eqarchives/epic/)

be carried out. Such a study would not only be useful in validating this observation but will also provide guidance to structural engineers to properly design high-rise buildings in the Bangkok basin which are vulnerable to long-period earthquake ground motions.

There was general concern during recent earthquakes since they occurred during working hours and several tall buildings had significant structural and non-structural responses. Building residents did not feel safe and chose to evacuate from tall buildings (Fig. 1b). An attempt to perform seismic microzonation and quantify site amplification effects in Bangkok basin has been made in several past studies (Tuladhar et al., 2004; Poovarodom and Plalinyot 2013; Jirasakjamroonsri et al. 2018; and Subedi et al. 2021). These earlier studies seem to be in good agreement and reveal that there are deep alluvial deposits in the Bangkok basin that could amplify long-period ground motions. However, there have never been any studies analyzing the set of recorded ground motions in the Bangkok basin similar to those observed in other metropolitan areas (such as in Mexico City (Bard et al. 1988), Gubbio, Central Italy (Pacor et al. 2007), and Tokyo (Yamanaka et al 1989)). This might also be due to the lack of well-maintained seismic stations in BMA as Thailand's seismic network has recently been improved after the 2004 Northern Sumatra earthquake and has been operating since 2007. The recorded ground motions from recent earthquakes in the Bangkok basin (TMDA and TMDB), which were widely felt by people in high-rise buildings (Zaw et al. 2019; Foytong and Ornthammarath 2020), have always been greater by those observed than those located outside this deep alluvial basin (SRDT and PRAC) (Fig. 1).

Since amplified recorded ground motions like those observed in the Bangkok basin were reported in other places located in alluvial basins in other countries (Wald and Graves 1998; Michel et al. 2014; Rupakhety et al. 2017), an understanding of this behavior is essential to determine which characteristics could amplify the long-period ground motion observed in Bangkok from recent earthquakes. With this purpose, we analyzed both the time and frequency domain of the recorded ground motions at different accelerograph stations from 2007 to 2021 and compared the peak and other ground-motion values between those records inside and outside the basin. Similar to Pacor et al. (2007), time and frequency domain analyses are performed on the TMDA records to determine the frequency content of recorded ground motion and to demonstrate the significance of surface waves induced by the deep basin in altering the engineering ground motion amplitudes.

The measured 30-m shear-wave velocity (V_{s30}) recorded by several sites in Bangkok have low values (between 60 to 100 m/s) (Ashford et al. 1997, 2000; Ashford 2000). The first stiff clay layer shear wave velocity seems to be between 100 and 200 m/s. Shear wave velocity seems to increase to 250 m/s in the first sand deposit, and contiune to rise, although at a slower percentage, in the deeper layer. The Bangkok low shear wave velocity and the first stiff clay deposit is similar to the clay observed in Mexico City (Warnitchai et al. 2000). In addition, the strong increase in the shear wave velocity in the first sand deposit can intensify the amplified ground motion.

In this work, the past seismicity of Bangkok has been reviewed and seismotectonics of Thailand, specifically to the Bangkok basin, are provided. An analysis of ground motion records from recent moderate and major events that shook high rise buildings in Bangkok is presented. Instead of concentrating on the peak ground motion parameters, a thorough investigation of the spectral characteristics of the ground motion records is reported. The characteristics of the long period ground motions recorded by the TMDA station is discussed.

Bangkok seismotectonic settings and geology

Some major active faults are the Sagaing Fault, which could produce an earthquake magnitude of Mw 8.0 located 400 kms from Bangkok, and the Three Pagodas Fault (TPF), which could produce Mw 7.0 located 150 kms from Bangkok. The greatest earthquake in the vicinity of the TPF active faults was located at the central segment with a body-wave magnitude of 5.8 in 1983 150 km from BMA. It was felt intensely with slight damage to some structures (Baoqi and Renfa 1990). Previous regional seismic hazard studies have seen low hazard levels with PGA at 475- and 2475-year return period at 0.03 g and 0.07 g at rock site condition, respectively (Giardini et al. 1999; Ornthammarath et al. 2020). Due to low observed seismicity in and around Bangkok, in 1997 Thailand seismic design regulations recommend design requirements of the 1985 UBC Zone 2 for ten provinces. However, Bangkok is not located within this zone. In 2009, an updated seismic design code was issued by the Department of Public Works and Town & Country Planning, DPT1302-09 (2009), adopting ASCE 7-05 code. Based on this new regulation, high-rise buildings in Bangkok are required to be designed with seismic design for large earthquakes at a long distance. Therefore, most buildings in Bangkok constructed before 2009 had been built and designed without seismic design considerations.

Bangkok and its neighboring regions are built on the Chao Phraya delta, forming a large horizontal plain that becomes narrower in the northern part of this flat plain (Figs. 2 and 3a). This flat plain has dimensions of 125 km wide by450 km long with an average elevation of about 1.5 m above sea level. The central flood plains are a notable expression of a large, post-rift, and young feature basin. This basin started to cover the Late Oligocene–Miocene rift basins (Suphan Buri, Kampaeng Saen, and Phitsanulok basins) and interfering pre-Cenozoic rocks through the Pliocene or Mioceneras (Morley et al. 2011). Bangkok is located on a broad flat plain covered by deep delta sediments in the lower part of Chao Phraya basin, which is generally known as the Bangkok Basin (AIT 1980). The plain was below shallow water 5000–3000 years in the past, and the regression of the ocean occurred between 2000 and 3000 years ago, leaving behind the soft soil sediments, which now form the

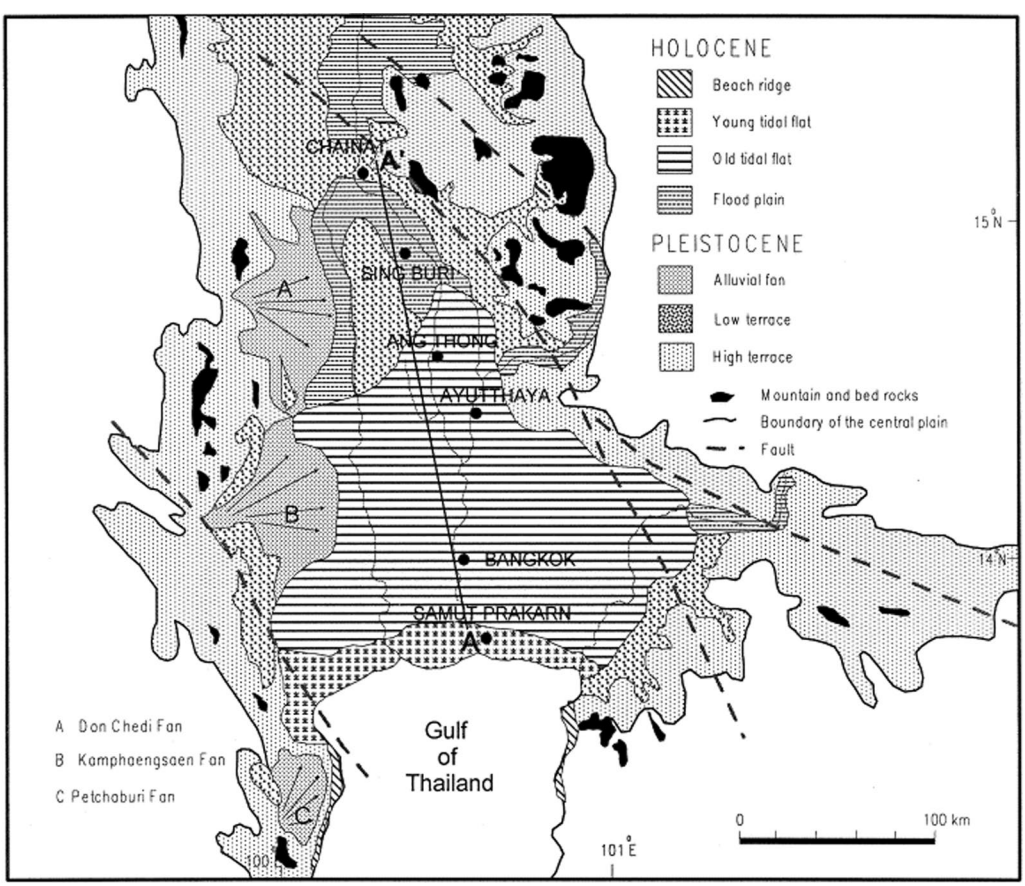

Fig. 2 Quaternary deposit and Geologic map of the Chao Phraya delta (Sinsakul 2000)

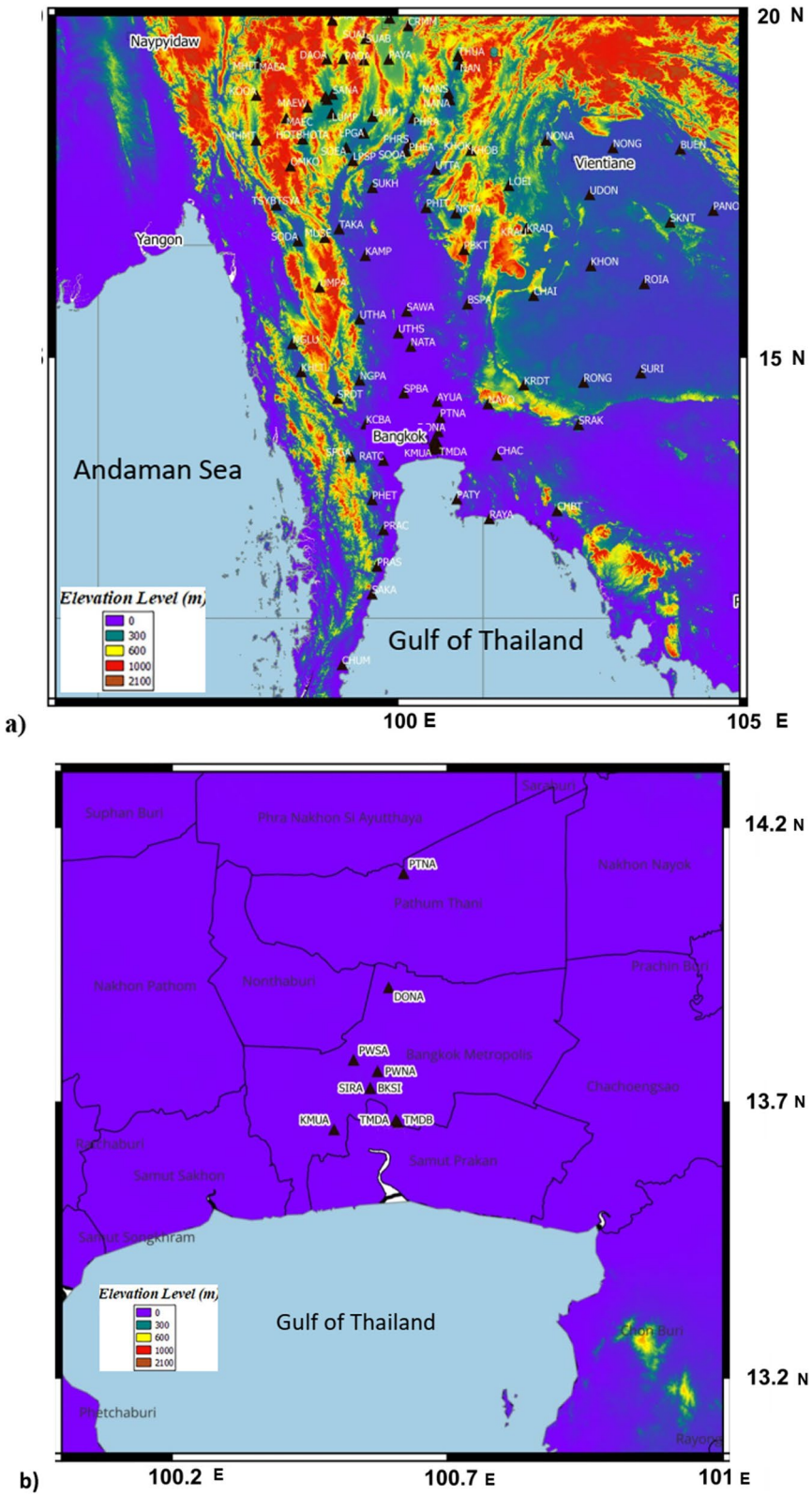

Fig. 3 **a** The SRTM elevation model of Thailand and surrounding regions developed by Reuter et al. (2007) is shown. **b** Black triangles represented permanent seismic stations operated by TMD in Bangkok. It is worth mentioning that only TMDA and TMDB have operated since 2007

Bangkok basin. This basin is comprised of dense clay on the top level, with thickness between 15 to 30 m in the Bangkok Metropolitan region. The soft clay is highly compressible and has very low shear wave velocity and strength. This soft clay has not been put in to any consolidation.

The topmost worn crust occurs between 1 and 5 m depth. The soft clay depth increases to the southern part close to the Gulf of Thailand and reduces quickly in the northern part of Bangkok. The first stiff clay layer is located below the soft clay deposit. In general, the thickness is between 5 and 7 m in central Bangkok and its depth becomes shallower to the west and north of Bangkok. The first sand layer is located under the stiff clay layer at around 50 m depth. At deeper depths, alternate layers of sand layers and stiff clay are observed. The bedrock is located at the deeper depths variable between 500 and 2000 m beneath the unconsolidated deposits, but its structure is not well understood (AIT 1980; Poovarodom and Plalinyot 2013).

Centerless circular array method (CCA) for Bangkok seismic stations

The effect of the amplified ground response in a basin which can resonate and amplify earthquake ground shaking parameters, such as PGA, PGV, or frequency content has been known for many years. To characterize the local site effects for the Bangkok seismic stations, investigation of geotechnical engineering properties of sedimentary deposits is essential. The key parameter is shear wave velocity (Vs) structure. As a result, the CCA method has been applied for considering Bangkok seismic stations. This procedure was proposed based on Cho I. et al. (2006) with the representations of spectral ratio. The spectral ratio has information of different phase velocities, which is a combination of related data in the vertical component of ambient vibration. Since the integration does not separate incoming waves with different azimuth angles, this procedure could determine higher resolution in long wavelength. Hence, ground surveys are needed to arrange a circular array of r radius and measure the ambient vibration in the vertical direction z(t, r,q). Express the mean value Z_0 (t r) along the perimeter and its weighted mean Z_1 (t r) as:

$$Z_0(t,r) = \int_{-\pi}^{\pi} z(t,r,\theta)d\theta \tag{1}$$

$$Z_1(t,r) = \int_{-\pi}^{\pi} z(t,r,\theta)\exp(i\theta)d\theta \tag{2}$$

Supposing that the fundamental Rayleigh wave mode controls the observed vertical direction of the ambient data, the ratio of these power spectra densities, represented by G0(r,r;w) and G1(r,r;w), can be described as:

$$\frac{G_0(r,r;\omega)}{G_1(r,r;\omega)} = \frac{J_0^2(rk(\omega))}{J_1^2(rk(\omega))} \tag{3}$$

where J0 and J1 are the Bessel function of the first kind with the zero-th order and the first order, respectively. The wavenumber k, and phase velocity c, are then assessed by correcting the observed spectral ratio with J02(rk(w))/J12(rk(w)). This condition holds in noise-free conditions, where noise is considered as non-propagating components contained in the field of ambient vibration. In general where noise is contained, Eq. (3) can be presented for the case of the fundamental mode dominating as:

$$\frac{G_0(r,r;\omega)}{G_1(r,r;\omega)} = \frac{J_0^2(rk(\omega)) + \varepsilon(\omega)/N}{J_1^2(rk(\omega)) + \varepsilon(\omega)/N} \tag{4}$$

where ε is the noise-to-signal ratio, representing the ratio of the power of the incoherent noise to the power of the coherent signal. Consider that the fundamental mode is dominate, ε can be assessed as:

$$\epsilon \approx \left(-B - \sqrt{B^2 - 4AC}\right)/2A \tag{5}$$

$$\begin{aligned} A &= -\rho^2, \quad B = \frac{\rho^2}{coh^2} - 2\rho^2 - \frac{1}{N}, \\ C &= \rho^2\left(\frac{1}{coh^2} - 1\right) \quad \text{and} \\ coh^2 &= \frac{|G_0(0,r;\omega)|^2}{G_0(r,r;\omega)G_0(0,0;\omega)} \end{aligned} \tag{6}$$

ρ is the spatial autocorrelation parameters, and N is the sensor numbers along the perimeter.

The measurement arrangement is composed of 4 sensitive velocity sensors with measured frequency range between 0.1 and 60 Hz, model VSE 15-D6 by Tokyo Sokushin Co. Ltd. Japan, and acquisition devices with 32-bit A/D, model McSIES-MT NEO by Oyo Corporation Japan. Time synchronizations among the different units are achieved by GPS timing. Before starting measuring, huddle-testing of sensors was carried out to make sure of the phase differences and coherency among all measuring units. The useable frequency range was found to be between 0.3 and 50 Hz.

The location of each sensor using the CCA method was a triangular array with a sensor located at the middle of a circle and the three additional units located on the circular boundary. Seven different measurement array sizes were placed at different seismic stations at

different radius (r) from 5 to 250 m. The deepest modelling distance from the surface for which shear wave velocity could reliably be determined is half of the longest measured wavelength (Park et al. 1999). For the current study, the deepest depth for inversion analysis is set at 1500 m.

The current explanation is try to identify the measuring data for the shear wave velocity profile from the measured ambient vibration records. Each set of measurement include at least 40 min with measured frequency of 100 Hz, creating 240,000 points, which were separated into 58 sections of 4096 points to be adopted in the current study. Samples of the CCA method for each seismic station are displayed in Additional file 1: Fig. S1. For the current study, Additional file 1: Fig. S1(a) displays the observed spectral ratio from the CCA method in which the thick blue line is an arithmetic mean from 150 m of array size. The theoretical spectral ratio was computed from the Eq. (4) in the right part shown in Additional file 1: Fig. S1(b). Phase velocities were calculated by selecting the spectral ratio data from the experiment for each frequency, then using the relationship between the theoretical spectral ratio and experimental to identify the value of rk for each frequency shown in Additional file 1: Fig. S1(b). After solving the Eq. (4) where the observed spectral ratio is shown in the left part of the equation, then the identified fi and rki can be obtained. Phase velocities are then computed by ci = 2pfi/ki and shown in Additional file 1: Fig. S1(c) for different frequencies. The phase velocities dispersion curves of all array sizes are plotted in Additional file 1: Fig. S1(d) as circle scatterplots. Finally, the best representative of phase velocity dispersion curve for the study sites as shown in Additional file 1: Fig. S1(e). The inversion analysis was calculated to determine the optimal velocity profile models that correlate well to the measured dispersion curves. The inversion analysis results of dispersive phase velocity are displayed as a wave velocity profile along the depth from surface of considered seismic stations (Fig. 4). The results indicate that for most of the considered sites the 30-m average shear wave velocity (V_{s30}) is particularly low (80–130 m/s). It is classified as soft soil. The depth of basement rock is considered from the depth levels that are much different in shear wave velocity (V_S) values, with a high V_S value of approximately higher than 2 km/s. The basement depths of sites located in the central area of Bangkok metropolitan area are approximately 600–850 m as shown in Fig. 4a. The basement rock in the southern part of Bangkok metropolitan area at TMDA and TMDB and KMUT stations is shallower than the central area. Figure 4b shows that the basement rock of TMDA and TMDB and KMUT stations are found at approximately 530–560 m. In the northern part of Bangkok metropolitan area at DONA and PTUM stations, the depth of the basement rock is deeper than the southern part with a depth of approximately 625–640 m, which is similar to velocity profiles obtained by Bidhya et al. (2021), were observed as shown in Fig. 4c.

Results and discussion

Ground motion records

The recorded ground motion considered in the current study was obtained from Thai Meteorological Department (TMD). Accelerometer stations outside the Bangkok basin including SRDT equipped with TSA-100 model of Nanometrics and PRAC installed with 24-bit

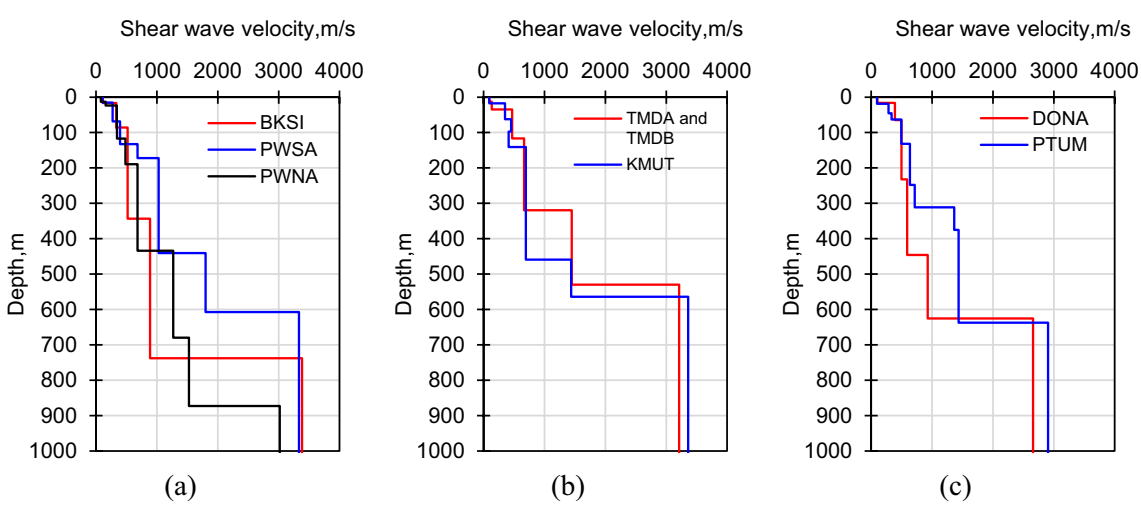

Fig. 4 Results from inversion analysis; **a** shear wave velocity profile for BKSI, PWSA, and PWNA stations **b** for TMDA and TMDB and KMUT stations **c** for DONA and PTUM station

PA-23 model of Geotech.Inside Bangkok basin with a vertical array consisting of two PA-23 accelerometers on the ground level (TMDA) and in the borehole (TMDB) at 47-m depth located in the seismological bureau, Thai Metrological Department in Bangkok has been operating since 2007. However, only ground motion data from 2008 and 2009 events could be recovered from TMDB due to system malfunction in 2010. Furthermore, Thailand's seismic stations have been upgraded since 2018 with a further seven strong motion stations located within the Bangkok basin operated with the CMG-5TC Guralp sensors (i.e. DONA, PWSA, PWNA, BKSI, SIRA, PTNA, and KMUT) (Fig. 3b). In addition to previous geophysical measurements, the topographic slope in Bangkok basin is flat plain (Morley et al. 2011). All free-field stations are located on flat terrain, not near bank slope structures which could have a local site amplification effect.

All ground motion within the Bangkok basin considered in this study shook high-rise buildings in central Bangkok causing panic and mass evacuations of people from skyscrapers (Table 2). These instruments have an internal GPS which was used to register the time of each measurement. All ground motion has been visually reviewed to eliminate any noticeable noise. Recorded ground motion is then scaled based on different sensor gain to change to acceleration values. The standard zero-order correction has been adopted to remove non-zero means. The bandpass filtering of ground motion has not been performed since this might eliminate long period content of the signal containing information from moderate to large earthquakes. Accelerometers are installed and maintained by the Thai Metrological Department (TMD) so there is enough pre-event measuring data to determine the pre-event average with certain accuracy. No significant drifts of the pre-event motion for velocity and displacement records shows that there is a stability of baseline records from pre-event data.

Time domain analysis

SRDT and PRAC stations are located outside Bangkok basin. Based on available geological information as well as shear wave velocity testing, SRDT and PRAC sites can be classified as very dense soil or soft rock corresponding to the NEHRP site category as soil type C. Figure 5 presents the acceleration and velocity time histories at TMDA, TMDB, SRDT, and PRAC stations from the Mw 7.9 12 May 2008 Wenchuan earthquake. The TMDA and TMDB recordings show important contributions since both PGA and PGV, Table 2, are always greater than that of stations positioned outside the basin (SRDT and PRAC) by at least a factor of 3 for the horizontal directions, and a factor of 2 for the vertical component. A ratio of at least 2 is observed when PGV is considered for both horizontal and vertical directions. We noticed that PGA and PGV were normally seen at the arrival of surface wave; however, the longer low-frequency duration could only be observed at TMDA and TMDB stations.

In addition, the horizontal components at TMDA station generally exceeded 1 cm/s^2 for all eight earthquakes after 2007. The acceleration records at TMDB (borehole) station in Fig. 5 with the integrated velocity traces contain two separate traces (body & surface waves) which can be obviously located due to the different travel times from distant earthquakes indicating the reliability of weak ground motion records due to low instrumental self-noise. The early part of the acceleration records contains the high frequency P- and S-waves (body wave), which occur at 130 and 350 s, respectively. The long period surface waves start from 400 to 900 s. However, only surface wave could be observed from TMDA (surface) records due to high cultural noise. In addition, the amplification of PGA between surface and borehole stations could be observed by at least a factor of 1.5 for horizontal and 1.3 for vertical directions. The difference in frequency content as well as duration for basin stations compared to stations located outside the basin could be clearly observed. The longer low-frequency duration observed at TMDA and TMDB were not found in the SRDT and PRAC stations.

Some ground motion parameters of TMDA and PRAC and SRDT records from stations located outside the Bangkok basin are shown in Table 2. The north–south, east–west PGA values at the soft site are higher than those two stations, which are situated close to the western and south-western boundaries of Bangkok basin, respectively. The degree of variability of peak value of horizontal ground acceleration for basin stations (i.e. BKSI, PWSA, PTNA, PWNA) records from 2019 and 2021 (Additional file 2: Table S1) could be observed with PGA generally exceeding 1 cm/s^2. This range of PGA is rather uncommon from a distant earthquake.

In addition, it is worthwhile to make a comparison of the observed ground motion with other well-constrained (global) models. The analysis of residuals is introduced in this study in order to assess the level of variability of observed ground motions compared to global ground motion models (GMMs). For shallow active and intra slab earthquakes, Boore et al. (2014), hereinafter as BSSA14, and Zhao et al. (2006), hereinafter as Z06, have been selected to represent a global model, respectively. For BSSA14, a basin amplification has also been introduced with information regarding basin depth (z1) and vs30 following CCA soil profile inversion. The normalized residual for each ground motion records compared to that estimated by GMMs are described as:

Table 2 Main ground motion parameters recorded at the seismic stations inside basin (TMDA & TMDB) with those outside basin (PRAC & SRDT)

No	Year	Mw	R_{epi} Bangkok (km)	TMDA (surface)			TMDB (borehole)			PRAC			SRDT		
				PGA (cm/s^2)	PGV (cm/s)	D 5–95 (s)	PGA (cm/s^2)	PGV (cm/s)	D 5–95 (s)	PGA (cm/s^2)	PGV (cm/s)	D 5–95 (s)	PGA (cm/s^2)	PGV (cm/s)	D 5–95 (s)
1	2007	6.3	740	0.5	0.3	201	–	–	–	–	–	–	–	–	–
				0.5	0.3	214									
				0.3	0.1	232									
2	2008	7.9	1900	1.0	0.6	768	0.6	0.5	468	0.2	0.2	197	0.2	0.2	191
				1.0	0.5	828	0.5	0.6	452	0.1	0.1	264	0.1	0.1	290
				0.8	0.2	978	0.2	0.3	682	0.1	0.1	258	0.2	0.1	228
3	2009	7.5	810	1.0	0.6	489	0.5	0.4	383	0.1	0.0	463	–	–	–
				0.9	0.7	487	1.1	0.8	278	0.1	0.1	472			
				0.3	0.1	1222	0.2	0.1	671	0.1	0.0	463			
4	2011	6.8	770	1.0	0.6	240	–	–	–	0.2	0.2	136	–	–	–
				1.1	0.5	234				0.1	0.1	177			
				0.4	0.2	251				0.1	0.1	143			
5	2014	6.1	680	0.8	0.1	86	–	–	–	0.1	0.0	140	0.3	0.1	110
				0.9	0.1	101				0.1	0.0	180	0.3	0.1	109
				0.3	0.0	175				0.2	0.0	153	0.2	0.1	100
6	2016	6.8	1000	1.1	0.5	196	–	–	–	0.1	0.0	153	0.2	0.1	104
				0.8	0.3	215				0.1	0.0	164	0.1	0.0	112
				0.4	0.6	250				0.2	0.0	130	0.1	0.0	125

PGA peak ground acceleration, PGV peak ground velocity, and D 5–95 significant duration between 5 and 95% of total energy. For each event, the first, second, and third lines correspond to the north–south, east–west, and up-down components

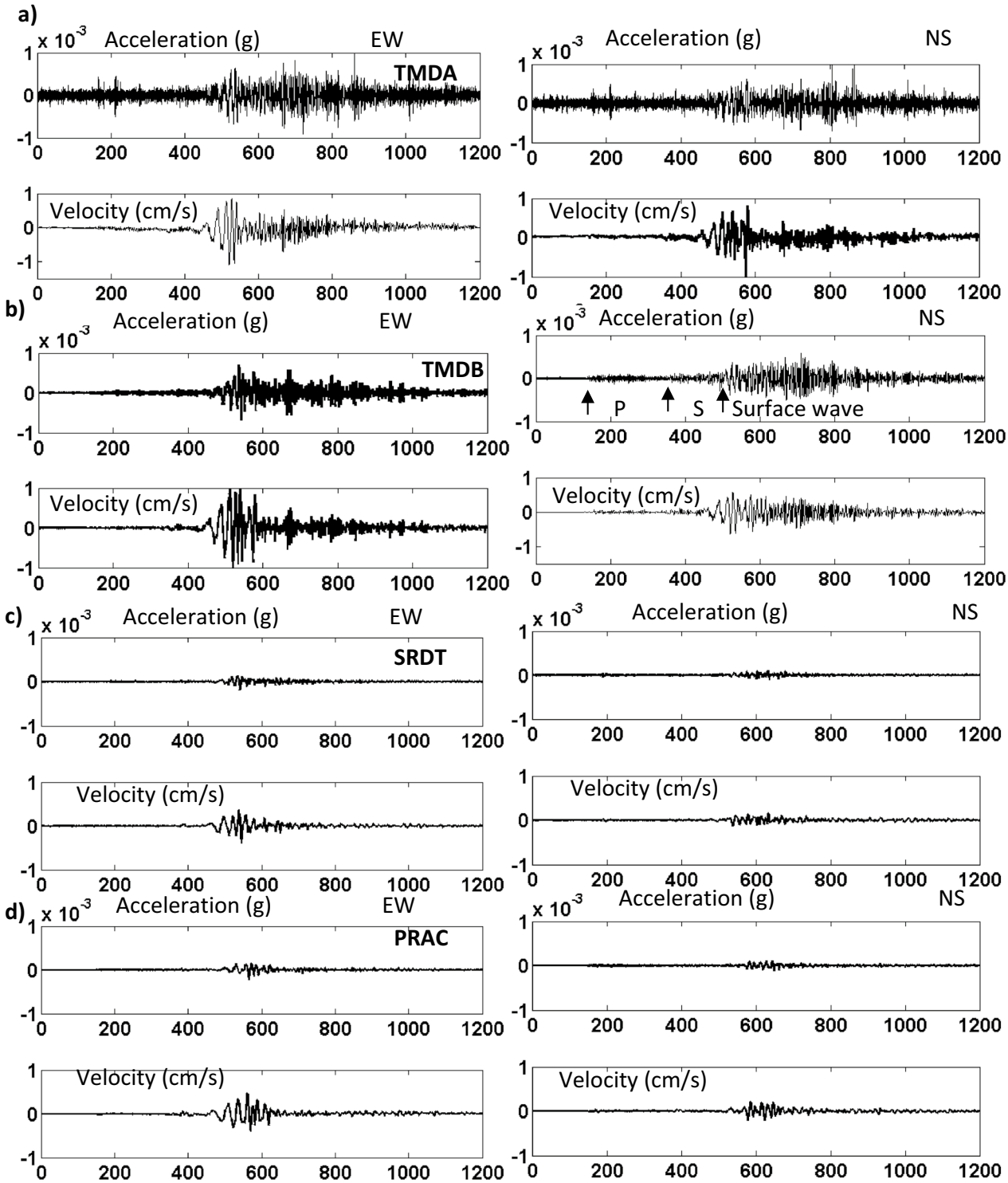

Fig. 5 Records of acceleration and velocity at TMDA (**a**), TMDB (**b**) SRDT (**c**), and PRAC (**d**) stations from the Mw 7.9 12 May 2008 Sichuan earthquake. The recorded PGA and PGV at TMDA and TMDB station are much higher than other stations situated outside Bangkok basin due to the soil amplification effect

$$r_i = \frac{\ln (SA_i)_{rec} - \ln (SA_i)_{GMM}}{\sigma} \quad (7)$$

where s is the total standard deviation of different GMMs, and $(SAi)_{rec}$ is PGA or SA (T = 1.0 s) of record i, $(SAi)_{GMM}$ is the median value of PGA or SA (T = 1.0 s) from the GMMs. To check if the predicted median values are similar to the ground motion record, the normalized residuals have been determined from 600 to 1000 km distance range. As the applicable range of selected GMMs (from 0 to 400 km) are shorter than the ones adopted in the current study; however, earlier studies from ground motion records in this region indicating that both GMMs well capture the attenuation characteristics at this range (Zaw et al. 2019).

From Fig. 6, the average residuals of PGA relative to BSSA14 and Z06 are presented. For basin stations, the average residuals are all positive (underestimated by both models) while the residuals from those recorded outside the alluvial basin are almost equal to zero. The large positive residual could be partially due to the fact that these GMMs have been adopted at longer distance than their applicable range. The high average residuals for the basin station imply that this station could produce larger soil amplification than that of outside basin stations for short structural periods. The bias for shallow active earthquakes for PGA is 3.9 with a normalized standard deviation of 0.65 while the bias for intra plate earthquakes for PGA is 3.0 with a normalized standard deviation of 0.2. In contrast to PGA, the mean residual at SA (T = 1.0 s) shows smaller negative bias (overestimation). This could be partly explained by the inclusion of basin amplification terms from the global models which typically show strong correlation at long structural periods (T > 1.0 s). However, the basin amplification term introduced into the global GMMs might represent the average of the NGA-West 2 site database, Boore et al. (2013). Further studies should focus on developing a site-specific effect with available geologic structure which could improve the applicability of predictions from the global GMM.

Figure 7 displays the acceleration records and the percentage of Arias Intensity at TMDA, SRDT, and PRAC station from the Mw 7.9 12 May 2008 event. The Arias intensity (AI) generally suggests the total energy content within earthquake ground shaking records. The horizontal component energy content for the TMDA record is 3.2×10^{-4} cm/s higher than the AI of the SRDT and PRAC 10^{-5} cm/s, as shown in Fig. 7. The comparison of significant duration, which is the interval between the 5% and 95% percentage of Arias Intensity, seems to indicate different energy content among these ground motion records despite a similar distance. The Arias Intensity for these three stations seems to build up rapidly when the surface waves begin to arrive. The significant duration in the AI at TMDA station is about 1.5 times greater than those recorded at SRDT and PRAC for horizontal and vertical directions, respectively. The long duration seems to be the presence of locally induced long period surface waves occurring inside the basin. Figure 7 also displays the comparison of cumulative AI of unfiltered and filtered acceleration records applying the zero-lag and 3nd order, Butterworth filtering with frequencies between 0.16 and 0.25 Hz (periods between 4 and 6 s). This is performed in order to investigate the low frequency content from recordings within this low frequency range, which has been observed in the elastic response spectra as the dominant frequency of amplified records in the basin. The influence of this low-frequency motion is comparatively high for stations in the Bangkok basin, e.g., the low-frequency energy content is about one-third of the entire

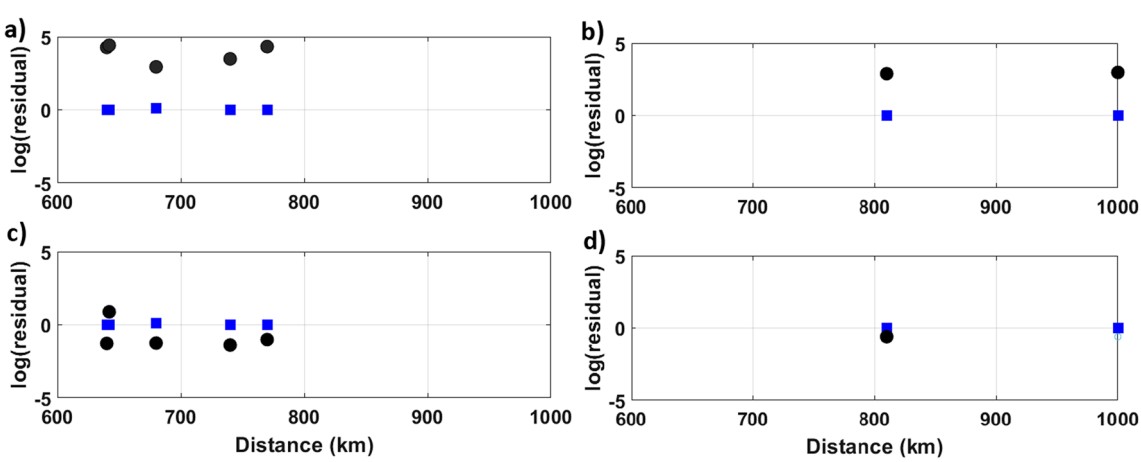

Fig. 6 Normalized residuals computed for PGA for BSSA14 (**a**) and Zhao et al. (2006) (**b**) against distance for PGA, and SA (T = 1.0 s) for BSSA14 (**c**) and Zhao et al. (2006) (**d**) The residual values from the basin and stiff sites are shown as black circles and blue squares, respectively

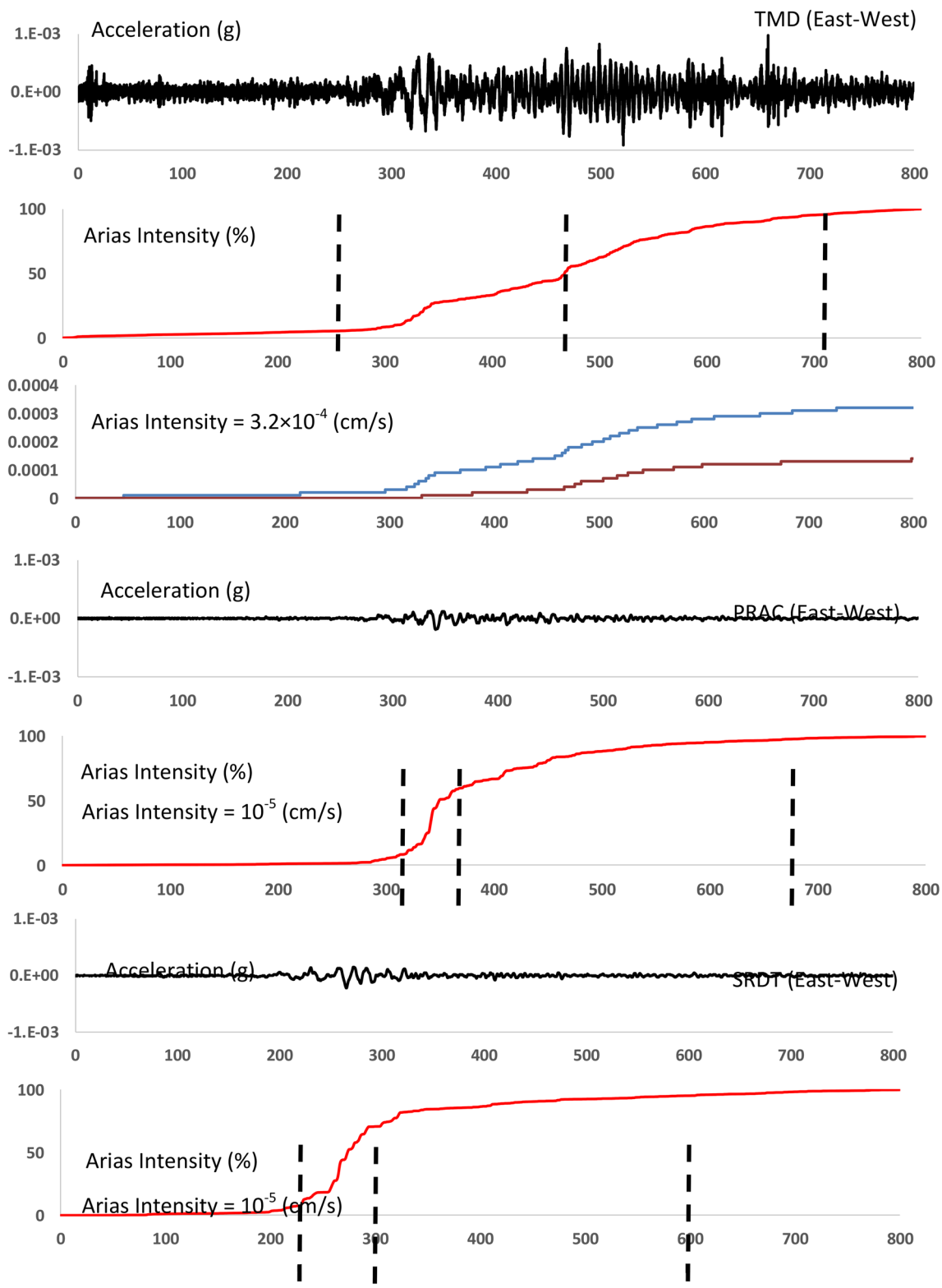

Fig. 7 Acceleration time histories and Arias Intensity percentages over time observed at TMDA, PRAC, and SRDT seismic station from Mw 7.9 12 May 2008 event with epicentral distance of 1900 km, 2000 km, 1890 km, respectively

energy at TMDA, but this effect could not be observed at SRDT and PRAC stations.

Frequency domain analysis

The horizontal elastic response spectrum of earthquake ground shaking recorded at TMDA recorded from all six considered events in Table 2 from 2007 to 2016 are displayed in Fig. 8. The thick black lines show the pseudo-spectral acceleration of TMDA (surface) while the thick black dash lines show horizontal elastic response spectra of TMDB (borehole) for the RotD50 component of horizontal SA directions. In addition, the grey lines show spectrum at SRDT and PRAC stations. It could be clearly observed that the spectrum in Bangkok is much larger than those from outside basin stations located at a similar distance for most structural periods. Furthermore, the horizontal spectra of TMDA show high energy at long periods observed between 0.5 and 2 s, similar to those reported using microtremor observations by Bidhya et al. (2021). It is interesting to note also that the amplification at spectral ordinate between 4 and 6 s could be observed from TMDB records from both 2008 and 2009 events. However, the spectral amplification at other periods, between 0.5 and 0.7 s, observed from all considered events in TMDA (surface) are missing from TMDB (borehole) spectrums. These results indicate that

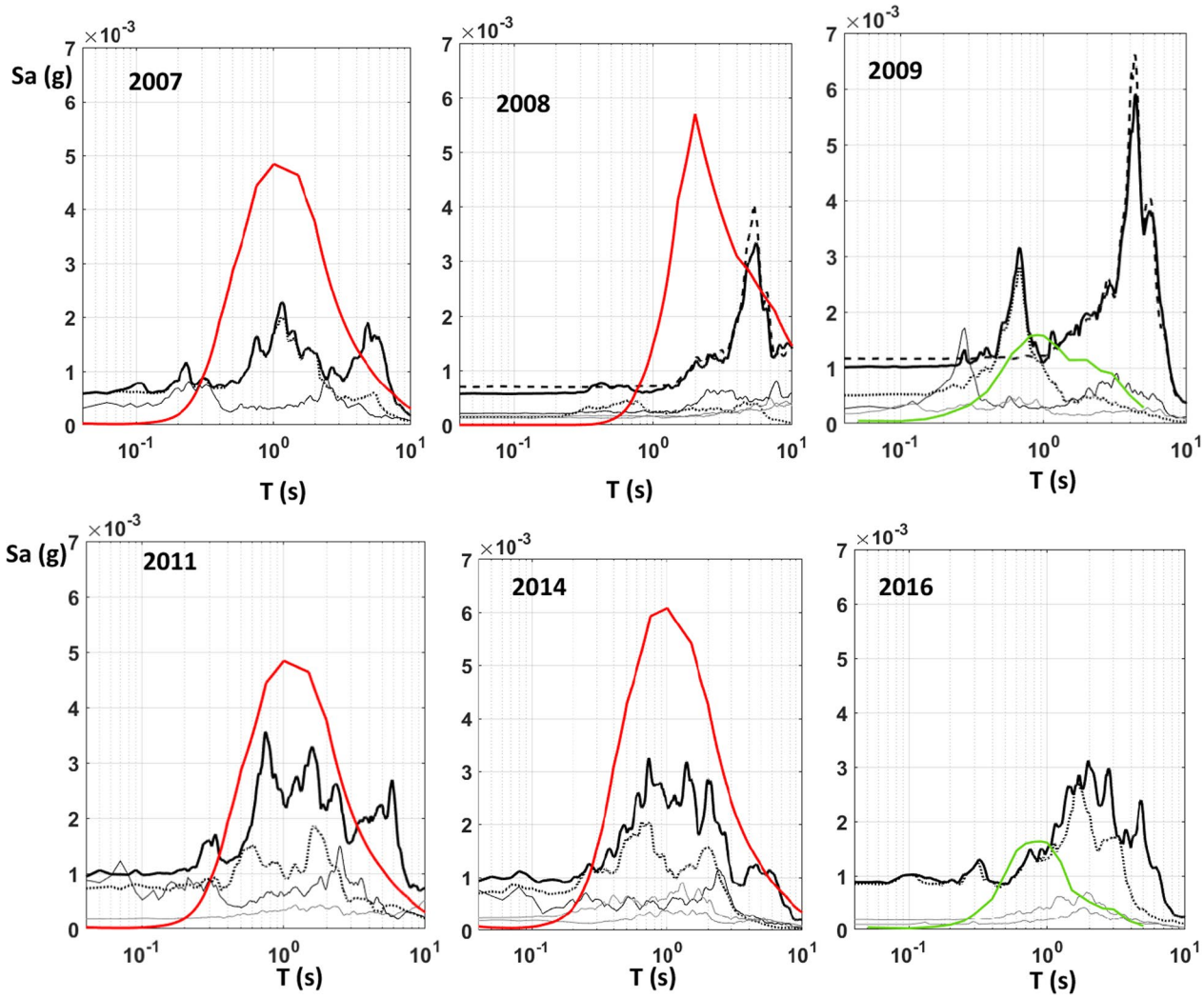

Fig. 8 Horizontal elastic spectral acceleration motion at TMDA (thick black line), SRDT, and PRAC (grey lines) during six events in Table 2 with 5% damping ratio. The thick dot lines show horizontal spectrum for selected windows contains only the body waves (without surface waves). The estimated median horizontal spectrum computed from Boore et al. (2014) and Zhao et al. (2006) are shown in red and green, respectively. The thick black dash lines show horizontal elastic response spectra of TMDB (borehole)

the top 47-m surface layer plays a key role in determining the pattern of the observed spectrum at short structural periods.

In order to investigate the long period energy content within the basin, the calculated horizontal spectrum of the TMDA station using different parts of accelerogram are also considered. The thick dotted lines showing horizontal spectrums for selected window contains only the body waves (without surface wave) which do not show any peak for spectral ordinates greater than 2 s. This evidence shows that the long period energy content is related to the arrival of surface waves observed within the basin. Figure 8 also compares the estimated median horizontal spectrum computed from Boore et al. (2014) and Zhao et al. (2006) equations for shallow and intra slab earthquakes. The effect of basin amplification terms in BSSA14 tends to provide greater median values for moderate to long spectral ordinates (0.5 to 2 s) than the observed horizontal spectrums at TMDA station. However, the Zhao et al. (2006) equation with only soil amplification through Vs_{30} term seem to underestimate most of long structural periods (T > 1 s). It is interesting to mention also that the peak spectral ordinates related to surface waves seem to increase with increasing earthquake magnitude. The highest SA has been observed at a period around 5 s from the 2009 event with observed spectral ordinate around 6×10^{-3} g. In addition, the characteristic of the vertical spectrum (black line) is limited since there is low spectrum ordinates greater than 1 s.

Based on previous analysis, it is become clear that long period ground motion (T > 1 s) is due to the basin effect rather than source effect (Tuladhar et al., 2004; Poovarodom and Plalinyot 2013; Jirasakjamroonsri et al. 2018; and Subedi et al., 2021). To assess the time dependence and its effect on the spectrum amplitude for Bangkok basin stations, spectrograms are determined with a moving window of 10 s and 5-s overlapping time window. Additional file 1: Fig. S2 shows the spectral analysis for the 2019 Mw 6.2 event recorded at BKSI station. However, a similar pattern could also be observed from other Bangkok basin stations. After the arrival of the surface wave, the spectrogram shows that the low frequency content (from 1 to 0.3 Hz) dominates the spectral content for 3 and 4 min. These phases could be seen for all three directions in ground motion records. In addition, lower frequency phases (between 0.1 and 0.2 Hz) continue to dominate for the rest of the duration, especially between 3 and 6 min.

To gain better understanding regarding the characteristics of long period ground motion recorded inside the Bangkok basin stations (i.e. TMDA, SIRA, PWSA, PWNA, KMUT, and PTNA), in the current study, we analyst ground motion records from these 8 events and compute horizontal/vertical spectral ratios (HVSR) for seismic stations located inside and outside the Bangkok basin. Following original work by Nakamura (1989) and Mase and Sugianto (2021) (using microtremor data) and Lermo and Chavez-Garcia (1993) (using recorded ground motion), the HVSR analysis has been implemented extensively to determine basin-induced amplification, using both microtremor data and ground motion recordings. Following the SESAME guidelines (Bard 2005), only mean ± one standard deviation HVSR peaks and the standard deviation of the frequency of the HVSR peak, is derived for TMDA station. The HVSRs of Fourier amplitude spectra are developed for the current work.

The HVSR of the recorded ground motion uses the geometric-mean of the horizontal components of the north–south and east–west components and the selected 10 min signal long with signal to noise ratio greater than 5 by correcting any obvious noise from the recorded ground motion. The H/V spectrum results are then given smoothing again with the Konno-Ohmachi algorithm with a smoothing constant of 20, and a window sample of 40 percents. A different smoothing constant of 40 was also investigated, but we did not see a large deviation of HVSR results. The HVSR of these recorded motions in Table 2 are shown in Fig. 9. Though the peak amplitudes of these HVSR curves at TMDA station vary from 7 to 11, the mean HVSR and its standard deviations (± s) seems to have been typically high within the period between 5.1 and 5.5 s (corresponding to 0.19–0.18 Hz, respectively) with smaller peaks between 0.5 and 2 s (corresponding to 2 and 0.5 Hz, respectively). A double peak HVSR spectrum exhibiting two different peaks would normally indicate that there are two high impedance contrasts below the station at two different levels: one for a dense layer and another for a narrow layer. Similarly, double-peak mean HVSR curves could also be observed for other Bangkok basin stations. However, due to the small number of records, the data is still insufficient to draw a reliable dominant site period for each station. Nevertheless, we noticed that for stations located within the central part of Bangkok (i.e. SIRA, PWSA, and PWNA), which have the deepest basement depth, about 600–850 m, the pre-dominant periods vary between 6.5 and 7.5 s. Further studies should investigate the soil amplification effect of these long-period predominant peaks with reliable low-frequency seismometers through large-array observations. The comparison between peak periods of the HVSR curves and those recorded elastic spectra are consistent. In contrast, at PRAC and SRDT stations, HVSR

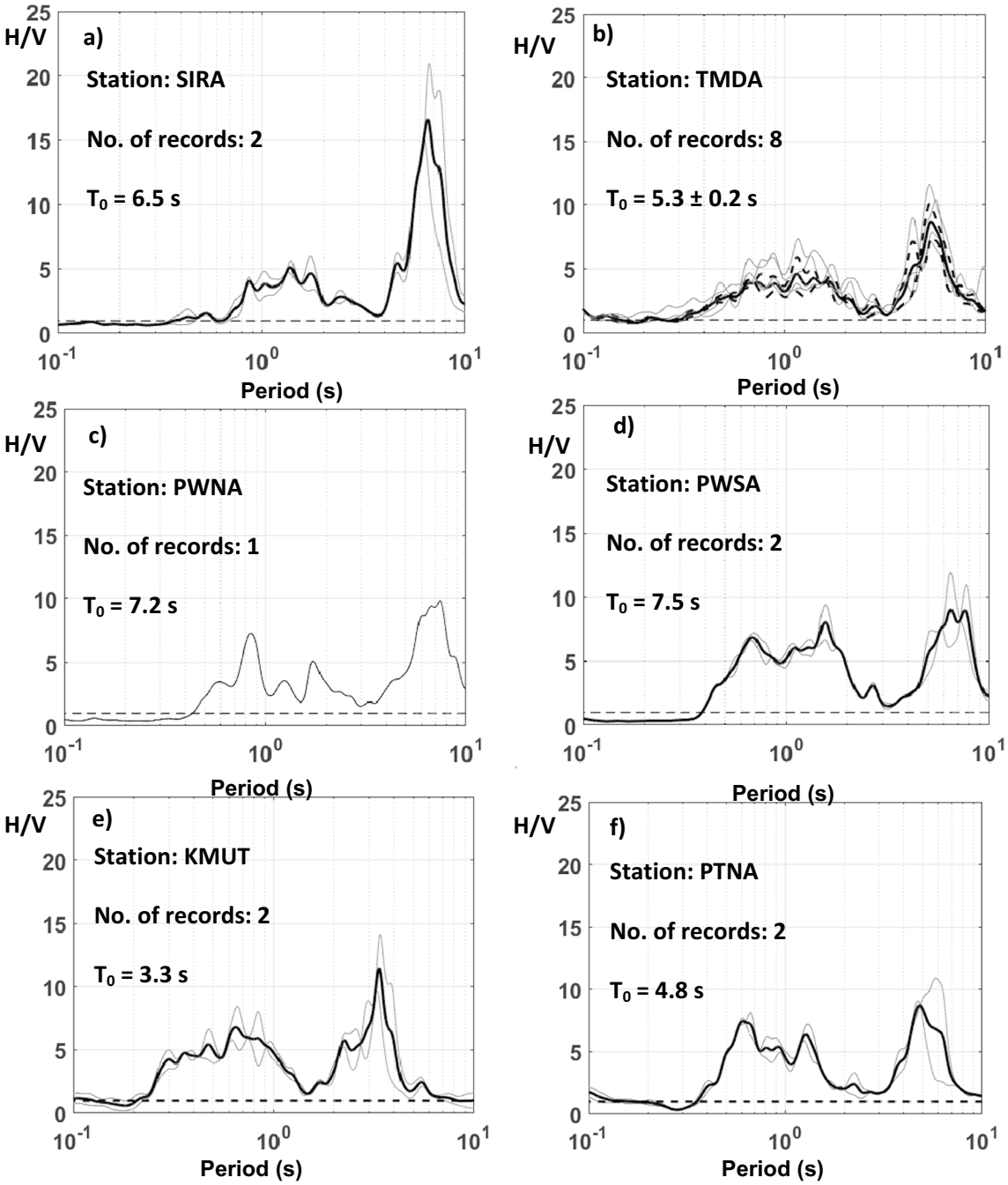

Fig. 9 Average HVSR curves for recorded ground motion at **a** SIRA, **b** TMDA, **c** PWNA, **d** PWSA, **e** KMUT, and **f** PTNA. Solid lines indicate mean; shaded region shows each individual event. Dash black line shows one standard deviation of HVSR curve

curves are close to 1, indicating very low amplification, Additional file 1: Fig. S3. This conforms to the previous soil profile information of these stations situated at the stiff soil or soft rock sites.

Based on previous analysis, it was become clear that long period ground motion between 0.1 and 0.3 Hz is due to the basin effect rather than source effect. However, it is still not clear what the cause of this mechanism is. In order to analyze the long period characteristics, velocity ground motion at TMDB station was band-pass filtered in the range of 0.1–0.3 Hz using a second order zero-phase Butterworth filter for the Mw 7.9 12 May 2008 event, Fig. 10. The time sequence of the particle motion (Hodogram plot) is illustrated in the lower half of the

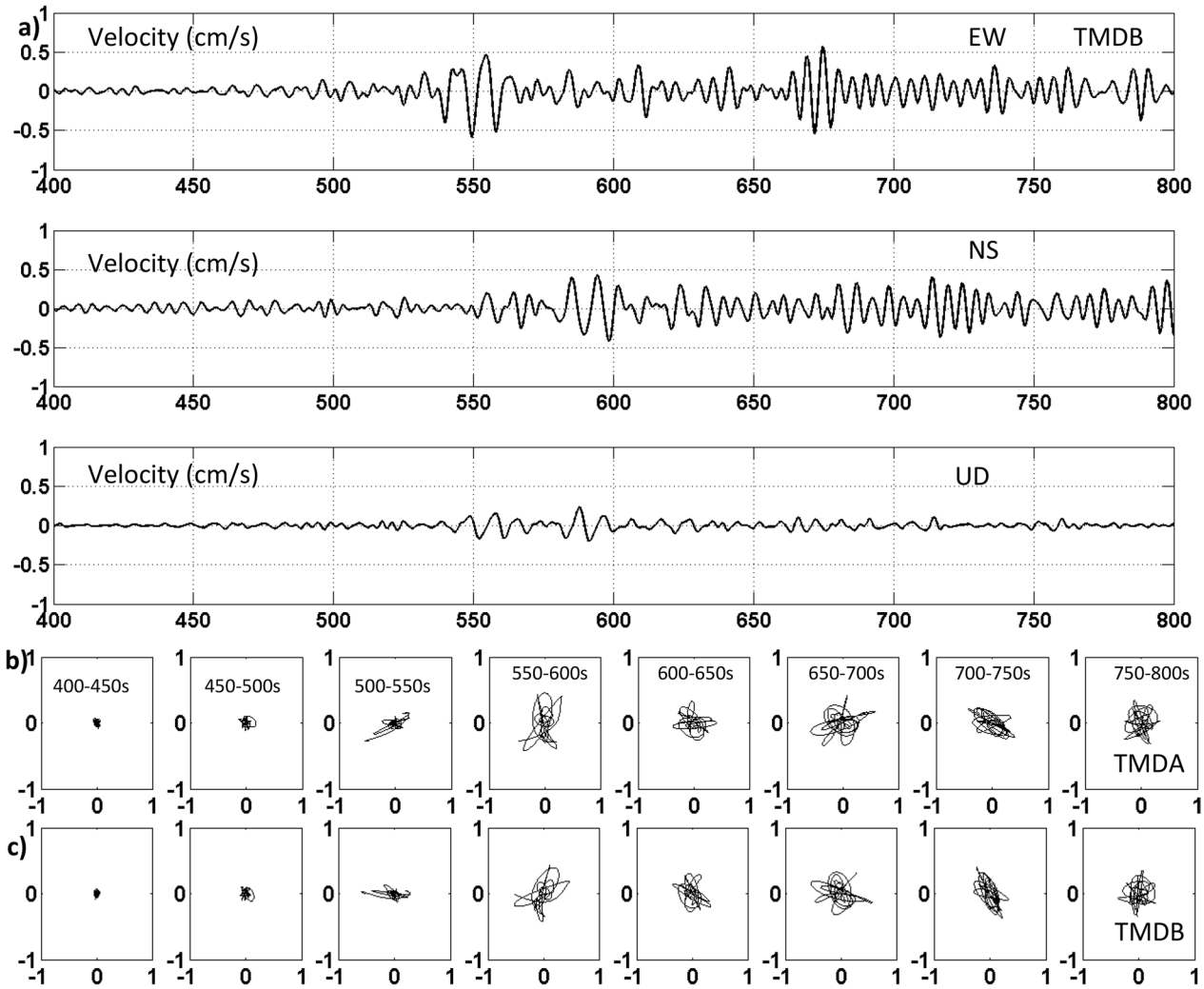

Fig. 10 **a** Butterworth band-pass filtered in the range of 0.1–0.3 Hz velocity time history (Hodogram plot) recorded at TMDB station from Mw 7.9 12 May 2008 event. **b** Particle motion of the filtered velocity at TMDA and **c** TMDB stations at 50 s time window

figure, in which the x- and y-axes of the graph show a series of plan views (EW and NS, respectively). The top trace of the velocity seismograms, east–west (EW) or almost transverse-component, indicates clearly dispersed wave train around the travel time 530–570 s, where the amplitude is the largest in the transverse direction. The particle motion of the dispersed waves indicates that these waves are almost transversely polarized in the horizontal plane around the above-mentioned travel time and hence these prominent phases are most probably Love waves. However, detailed inspection suggests a small deviation from purely polarized motion in the SH-direction. This deviation from the linear polarization is more remarkable after the travel time of around 570 s; the Rayleigh-type ground motion and other phases such as scattered waves may be coming after this time. It is worth mentioning also that a similar pattern of particle motion could be observed for recorded ground motion both at the surface and borehole (Figs. 5 and 10a) indicating long period energy developed through the deep soil profile.

As seen in Fig. 10, it is obvious that the dominated low-frequency (between 0.1 and 0.3 Hz) ground motion in the Bangkok basin is affected by the locally generated surface waves. These observations, in conjunction with observations reported in other sedimentary basins (Pacor et al. 2007; Yoshimoto and Takemura 2014; Tsai et al. 2017) show that the behavior of low-frequency ground motions, amplified by the basin-induced fundamental Love waves, is governed largely by the deep alluvial deposits. Predominant frequencies of low-frequency ground motion in the Bangkok basin show the tendency to decrease with the depth of bedrock, whereas it is nearly similar (approximately between

0.3 and 0.18 Hz) in the shallower part of the basin. With the possibility of great earthquakes at a much closer distance from the Three Pagodas Fault (M > 6.5 at 100 km), Sagiang Fault (M > 7.9 at 500 km), the significant and as yet still unquantified long period ground motion in the Bangkok Basin requires further investigation through maintain broadband and strong motion networks for better quantitative understanding how much long period ground motions could able to amplifiedyIn addition, a large aperture array with reliable low frequency (less than 0.3 Hz) seismometers should be deployed with longer collecting time periods than used in the current studies in order to clarify the long period behavior of the deep alluvial basin. In addition, further ground motion modelling should also take into account the effect of surface waves in Bangkok basin. Since there is a clear presence of surface waves both in the ground surface and borehole and the complicated S-wave amplification, a simple 1D ground response analysis might not be enough to model both observed Love and Rayleigh waves. Further studies considering the 2D/3D basin structure are necessary but are beyond the scope of this preliminary work.

Conclusion

Even though it has long been recognized that Bangkok is situated on a soft soil deposit, understanding of the site amplification periods and characterization of ground motion have been hindered by an absence of recorded ground motion. To supplement this, a preliminary comparative analysis of the recorded ground motions in BMA from recent earthquakes and the recently established seismic monitoring network have been analyzed and showed that the recorded acceleration in the Bangkok basin could increase both peak amplitude and duration compared to those stations outside basin with ratios of at least 3 for horizontal directions. The peak ground motion parameters (e.g., PGA and PGV) are mostly observed at the arrival of surface wave. Because of the high rate of seismicity surrounding Thailand, a growing volume of broadband and strong-motion data could be further used for developing site-specific basin amplification factors, the crustal quality factors.

In addition, the ground investigation for shear wave velocity profiles at different seismic stations from the surface down to several hundred meters was explored using the array CCA technique. The results indicate that for most of the considered sites the 30-m average shear wave velocity (VS30) is particularly low (80–130 m/s); classified as soft soil. The basement depths of sites located in the central area of the Bangkok metropolitan area are approximately 600–850 m, while, the basement rock in the southern part of Bangkok metropolitan area at TMDA and TMDB and KMUT stations is shallower than in the central area.

In this paper, we present a preliminary analysis of ground motion analysis and HVSR to assess station characteristics and illuminate the nature of basin induced site responses at Bangkok basin stations. We notice that there is a unique site amplification effect between 0.1 and 0.3 Hz and smaller peaks around 2 and 0.5 Hz consistent with expectations for the site amplification effect associated with deep basins. Moreover, we noticed the presence of low frequency content of the surface wave which deserved further studies through the 2D/3D ground motion modeling through basin topography and velocity models.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40677-023-00259-0.

Additional file 1. Fig. S1: CCA analysis examples; (a) Observed spectral ratio for 150-m array, (b) Theoretical spectral ratio, (c) Dispersion curve from 150-m radius circular dimension, (d) Dispersion curve from all measured radius, and (e) The dispersion curve. **Fig. S2**: Spectrogram analysis for Mw 6.2 2019 event recorded at BKSI station for north-south (a), east-west (b), and vertical direction (c). **Fig. S3**: (continued). Average HVSR curves for recorded ground motion at (a) SRDT, (b) PRAC. Solid lines indicate mean; shaded region shows each individual event. Dash line shows one spectral ratio.

Additional file 2. Table S1: Main ground motion parameters recorded at the seismic stations inside Bangkok basin and outside basin (PRAC & SRDT).

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Author contributions

T.O. developed the theoretical formalism, performed the numerical analysis, and written the manuscript. A.J. performed site investigation, written the manuscript and performed the inversion results. P.P. and T.T. collect and interpret ground motion data. R.R. verified the numerical HVSR results and correct the manuscript. Both N.P and P.W. propose the investigation and supervision of projects. All authors read and approved the final manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

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