



A note of ground motion interpretation and site response analysis during the 2007 Bengkulu–Mentawai earthquakes, Indonesia

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Abstract

This paper presents the interpretation of ground motions and comparison of site response analysis due to the 2007 Bengkulu–Mentawai earthquakes in Mukomuko regency, Bengkulu Province, Indonesia. Mukomuko regency was reported as the most impacted area during the earthquakes. The recorded ground motions of the Bengkulu–Mentawai earthquakes were analysed to obtain the interpretation of ground motions. Furthermore, the site response analysis to the sites in Mukomuko regency was performed to observe the spectral acceleration. The results showed that the first aftershock tends to have more played the key role in yielding the damage in Mukomuko regency. It was shown by the high level of Modified Mercalli Intensity (MMI) and the high ground motion parameters resulted by the first aftershock. The comparison of spectral acceleration showed that spectral acceleration of first aftershock is critical at a short period. The result also showed that the propagated seismic waves could amplify at ground surface. In general, the results of this study could provide a better understanding of earthquake impact in Mukomuko regency, Indonesia.

Keywords Earthquakes · Site response analysis · Spectral acceleration · Ground motion parameters

Introduction

It has been known that Sumatera Arc was categorised as the vulnerable region to earthquake. The activity of the subduction zone between Indo–Australia Plate and Eurasia Plate frequently resulted in the major earthquake events in this region. Several earthquake events, such as Aceh Earthquake in 2004, Nias Earthquake in 2005, Bengkulu Earthquake in 2000 and 2007, and Padang Earthquake in 2009, had occurred under this subduction activity (Mase 2017). On September 2007, in the first decade of the millennium, the earthquakes, which were later known as the Bengkulu–Mentawai earthquakes, occurred in the southern Sumatera subduction. Mase (2018a) mentioned that those earthquake sequences occurred under the Sumatra subduction mechanism. The mainshock with magnitude of M_w 8.6 occurred in 12 September 2007 which

ruptured at 4.520° S; 101.734° E and was followed by two aftershocks occurred at 2.506° S; 100.96° E with magnitude of M_w 7.9 and 2.160° S; 99.580° E with magnitude of M_w 7.0 (Fig. 1). The mainshock occurred in 12 September 2007 at 18:10 UTM, whereas the first aftershock occurred in 13 September 2007 at 06:49 UTM. It was then followed by the second aftershock at 10:46 UTM (Centre of Earthquake Strong Motion Database or CESMD 2017).

During the Bengkulu–Mentawai earthquakes, Mukomuko regency, Bengkulu Province was identified as the most impacted area, especially in Air Hitam, Pasar Bantal, and Mukomuko. In addition, the earthquakes had triggered the soil damage phenomena, such as ground failures on the slopes and liquefactions along the coastal area of Bengkulu Province (Mase et al. (2017), Karnawati et al. (2007), Earthquake Engineering Research Institute or EERI (2007)). Learning from those earthquake events, the intensive studies of earthquake characteristic and ground response are focused.

Douglas and Aochi (2008) mentioned that there are two major concerns in identifying the earthquake impacts. The first one is the understanding of ground motion and spectral response, and the second one is the site effect during seismic wave propagation and its impact to the structural building. Olafsson et al. (2001) stated that there are two basic

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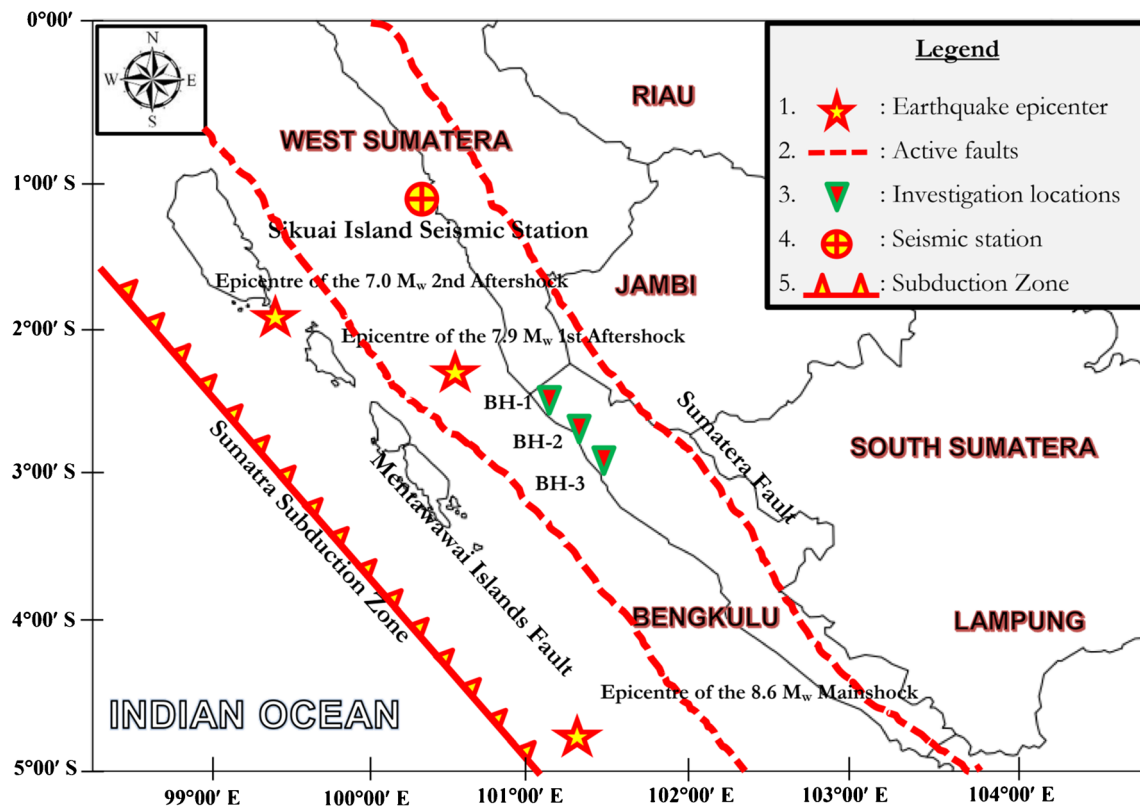


Fig. 1 The location of the mainshock and aftershocks occurred in September 2007, Sikuai Island Seismic Station, the investigated location (redraw and modified from Mase et al. (2017))

approaches to perform the ground motion prediction and spectral response, i.e. the mathematical approach and the experimental approach. Generally, the mathematical approach is more preferred because of the practical aspect consideration. Several methods, such as the representative ground motions (Hancock et al. 2008), empirical ground motion prediction (Abrahamson et al. 2014), and spectral matching (Hancock et al. 2006), are proposed based on the mathematical approach which consider some earthquake parameters, such as magnitude of earthquake, source mechanism, site condition, and focal depth. The use of ground motion prediction is normally implemented prior to perform the site analysis, such as ground response and soil behaviour during earthquake.

The studies of earthquake and its related phenomenon had been performed by several local researchers. Mase (2015) predicted that the earthquake with peak ground acceleration (PGA) of 1.4 to 1.8g could happen in Bengkulu City, especially within return period of 500 to 2500 years. The earthquake study related to soil damage, i.e. liquefaction, in Bengkulu City was also investigated by some researchers. Misiniyati et al. (2013) and Mase and Somantri (2016) investigated the vulnerability of liquefaction in Bengkulu Province based on empirical analysis (Seed and Idriss 1971; and Idriss and Boulanger 2006). Those studies were focused on the coastal areas of Bengkulu City which underwent the

liquefaction in September 2007 (Mase (2018b, c)). Those studies also reported the liquefaction evidence during the earthquakes in September 2007. In general, those previous researchers still focused on understanding the characteristic of the earthquake and investigating the vulnerability of soil damage during the earthquakes, whereas the interpretations of ground motion parameters of the earthquakes and seismic response analyses in the most impacted area have not been achieved yet.

This paper presents the interpretation of the Bengkulu–Mentawai earthquakes ground motions recorded at the closest station to the epicentre (Sikuai Island Seismic Station) and the impact of the seismic wave propagation to the most impacted area during the earthquakes, i.e. Mukomuko regency. This study consisted of two main objectives. The first one is the analysis of ground motion during the Bengkulu–Mentawai earthquakes and a site response analysis in Mukomuko regency. In general, this study could provide a better understanding of the Bengkulu–Mentawai earthquakes in 2007 and help the local engineers to consider earthquake effect in the study area.

Study area

This study is focused on the analysis of ground motions during the Bengkulu–Mentawai earthquakes occurred in

September 2007. The earthquake ground motions were recorded at the Sikuai Island Seismic Station, which is also the closest station to the earthquake ruptures (Fig. 1). According to Mase et al. (2017), three sites which are noted as Mukomuko (BH-1), Pasar Bantal (BH-2), and Air Hitam (BH-3) were categorised as the most impacted areas during the earthquakes (Fig. 1). Therefore, site investigations to those sites were performed. At those sites, field measurements including standard penetration test (SPT) and shear wave velocity (V_s) were performed. Based on site investigation results (Fig. 2), subsoils of the study area are dominated by sandy soil. Loose sand (SP) with $(N_1)_{60}$ average of 4 blows/ft. and fine content (FC) of 5% exists at depth range of 0 to 7.5 m. Silty sand (SM) with $(N_1)_{60}$ average of 15 blows/ft. and FC of 12% was found at depth range of 7.5 to 22.5 m. At depth range 22.5 to 30 m, clayey sand (SC) with $(N_1)_{60}$ average of 35 blows/ft. and FC of 20% exists. Based on the National Earthquake Hazard Reduction Program or NEHRP (1998), the investigated locations are classified as site class D (stiff soils), with the time-averaged shear wave velocity for first 30-m depth (V_{s30}) of about 227 m/s. Mase et al. (2017) stated that in the study area, V_s of 760 m/s (minimum V_s value to indicate engineering bedrock) exists at 30-m depth. Therefore, the engineering bedrock surface can be assumed at the depth of 30 m (Miller et al. 1999).

Theory and methodology

Ground motion parameters

Ma et al. (2019a) mentioned that it is important to investigate the source mechanism to quantify the ground motion. Several factors, such as the characteristics of the source mechanism, the medium through which the seismic waves travel, and the sensor response to the ground vibration, should be appropriately determined. Ma et al. (2019b) stated that ground motion at a certain location is controlled by the dual effects of the azimuth and the source focal mechanism as well as the distance and the source magnitude. Those effects are also identified to influence ground motion parameters. Ground motion parameters are used to essentially describe the characteristic of strong ground motions (Kramer 1996). Several parameters had been proposed to characterise the amplitude, frequency content, earthquake energy, and shaking duration. Several information, such as peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD), can be determined from the time history of ground motion. Meanwhile, several frequency content parameters, such as spectral acceleration (SA), spectral velocity (SV), and spectral displacement (SD), are derived from the concept of single degree of freedom (SDOF). The earthquake energy is normally defined as the energy flux. It also represents the

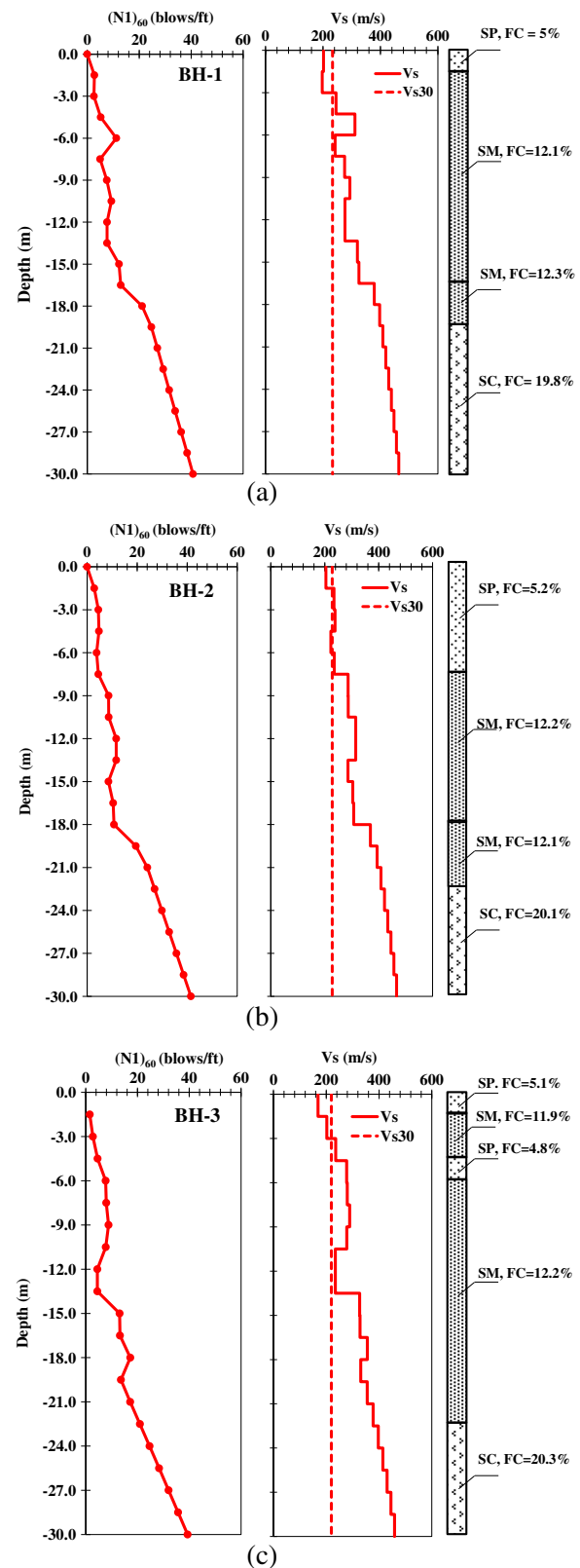


Fig. 2 Site investigation result in Mukomuko regency. **a** BH-1 (Mukomuko), **b** BH-2 (Pasar Bantal), and **c** (BH-3) (Air Hitam)

build-up of specific energy density (SED) (Bommer and Martinez-Pereira 1998). The energy flux is also associated

with the Arias Intensity. Arias Intensity is a parameter which represents the intensity of earthquake acceleration corresponding to the time history (Arias 1970). Shaking duration is also categorised as one of ground motion parameters. Several duration types, such as bracketed duration, uniform duration, and significant duration, are commonly used. In earthquake engineering, the significant duration is widely used to estimate the significant period during seismic wave propagation (Trifunac and Brady 1975). This parameter is defined as the difference of duration between 5 and 95% Arias Intensity or D_{5-95} .

Non-linear site response analysis

Equivalent linear soil model is the first-generation model to describe the soil behaviour under the dynamic load. This model is originally developed by Schnabel et al. (1972). So far, the model has been widely used for engineering practice. However, there were the limitations of the model, especially in terms of overestimation of the maximum acceleration and underestimation of amplification ratio (Finn et al. 1978). Therefore, the advanced soil models called non-linear soil models are proposed to handle the limitations (Mase 2017).

Numerous non-linear soil models had been proposed by many researchers, such as Streeter et al. (1974), Finn et al. (1976), and Bardet and Tobita (2001). Those models offer the realistic assumption, which is related to the effective stress analysis. Several sophisticated computer programmes as proposed by Lai et al. (1992) and Elgamel et al. (2015) had been also developed to perform effective stress analysis under the framework of the non-linear soil model. For the certain problem, such as liquefaction during earthquake, the non-linear soil model is also able to model the excess pore water pressure due to cyclic load (Ishihara et al. 1975). One of the well-known models developed within the non-linear soil model framework is the non-linear effective stress model proposed by Elgamel et al. (2015). The model is originally developed based on Parra (1996) and Yang (2000), which adopted the framework of multi-yield surface plasticity proposed by Prevost (1985). In this model, the non-linearity is simulated by incremental plasticity that allows to compute permanent deformation. The stiffness change on each incremental step is also evaluated. In addition, excess pore water pressure and pore water pressure dissipation are able to model under cyclic loading (Elgamel et al. 2015). Several researchers, such as Pender et al. (2016) and Mase et al. (2017), had confirmed that the results yielded from the numerical simulation under this model are generally consistent with the field evidence, especially for the liquefaction cases during the Christchurch Earthquakes in 2010 and 2011 and Bengkulu–Mentawai earthquakes in 2007. Misliniyati et al. (2019) also mentioned that the non-linear effective stress model is relevant in predicting ground motion of strong motion during the strong earthquake.

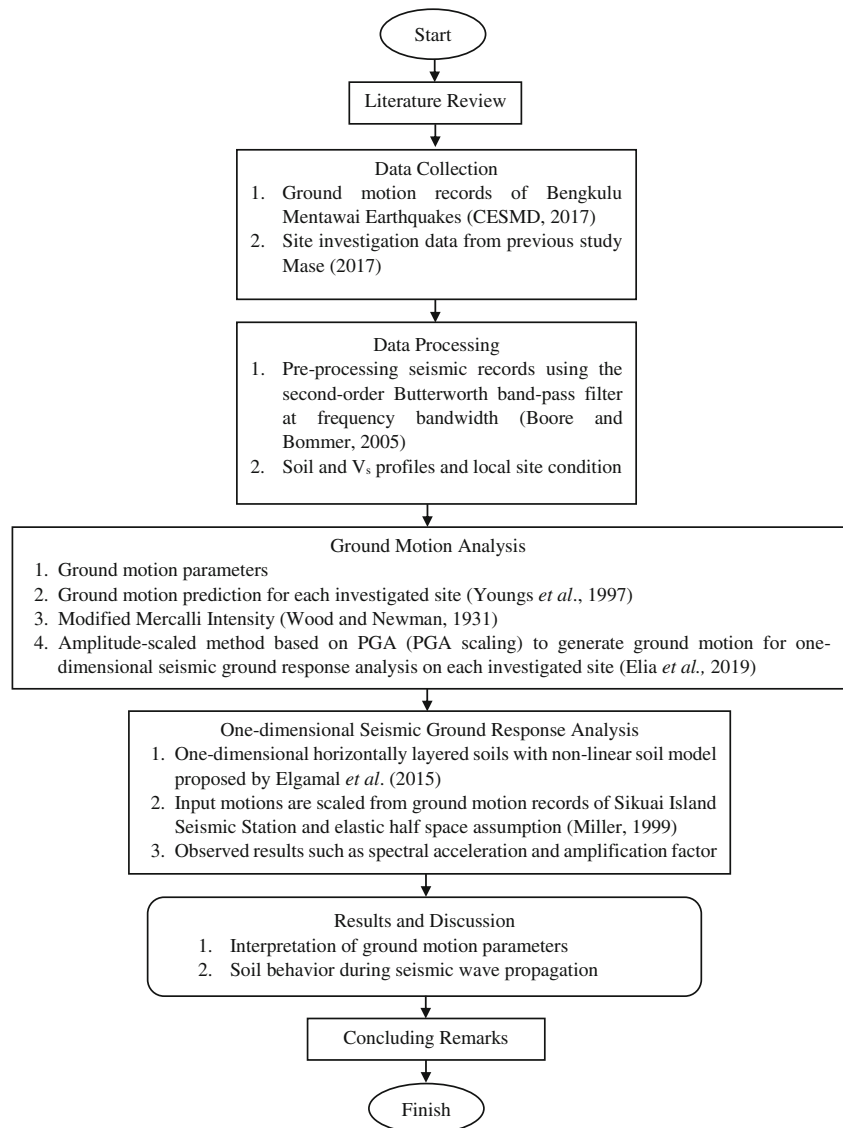
Methodology

The general framework of this study is presented in Fig. 3. This study was initiated by collecting the ground motions records of the 2007 Bengkulu–Mentawai earthquakes. The collected data of ground motions are the mainshock, first aftershock, and second aftershock events. Furthermore, the site investigation data from three locations in Mukomuko regency are collected. The regional geological conditions of studied area, such as the soil profile, V_s profile, and site classification, are also obtained from the site investigation data.

The ground motions which are collected from the seismic station have been filtered out using the second-order Butterworth band-pass filter at frequency bandwidth of 0.1 to 25 Hz (Boore and Bommer 2005). After the filtering process, the ground motion parameter analysis is performed to the earthquakes. In this study, the amplitudes of acceleration, velocity, and displacement are analysed. The ground motions are further analysed to derive spectral acceleration, spectral velocity, and spectral displacement. The energy flux and significant duration of the earthquake (D_{5-95}) are also analysed. All information obtained from the ground motion parameter are presented to estimate the seismic damage during Bengkulu–Mentawai earthquakes in September 2007, especially in terms of prediction of peak ground acceleration and the possible damage intensity under Modified Mercalli Intensity. In this study, the model proposed by Youngs et al. (1997) is used to estimate the peak ground acceleration on the investigated sites, whereas Modified Mercalli Intensity (Wood and Neumann 1931) is used to quantify the seismic damage level.

Furthermore, one-dimensional seismic ground response analysis is adopted to investigate the soil behaviour on each investigated site. The non-linear effective stress model (Elgamel et al. 2015) is implemented in this study. The list of model parameters used in the simulation is summarised in Table 1. Several parameters, such as thickness (h), cohesion (c), internal friction angle (ϕ), FC, coefficient of permeability (k), coefficient of lateral earth pressure at rest (K_0), and V_s , are determined based on site investigation data, whereas other parameters such as effective reference pressure (p^*_{ref}), peak shear strain (γ_{max}), liquefaction parameter (Liq), contractive parameters (c_1 and c_2), and dilative parameters (d_1 and d_2) are determined corresponding to recommendation of Elgamel et al. (2015). As there are no seismic stations at the investigated locations, the ground motion generation method should be implemented. In this study, the amplitude-scaled method based on PGA (PGA scaling) has been performed to generate ground motions for the investigated sites. In another word, the ground motion recorded from Sikuai Island is scaled based on PGA value. Elia et al. (2019) mentioned that the seismic input signal is typically scaled to peak ground acceleration of specific site. However, the use of appropriate ground motion, for example the recorded ground motion from the closest station,

Fig. 3 Research framework



can be used to minimise the bias (Vemuri and Kolluru 2020). In fact, the input motion may be linearly scaled by using the suitable scale factor, such as peak ground acceleration (Elia et al. 2019). Ansal et al. (2012) mentioned that the amplitude-scaled method based on PGA tends to be applicable for one-dimensional seismic response analysis. This is due to the fact that the method could well capture the earthquake characteristic on the ground surface. However, the implementation of the amplitude-scaled method based on PGA is more appropriate for stiff soil site and far condition (Kurama and Farrow 2003; Heo et al. 2011). Considering those previous studies, the PGA scaling method is therefore performed to generate input ground motion for the investigated sites in this study. The site response analysis is performed by propagating the input motion (scaled ground motion) at the bottom of the investigated sites. This procedure can be performed if the depth of engineering bedrock had been identified (Adampira

et al. (2014) and Mase et al. (2018)). Several results, such as ground motion at surface, spectral acceleration comparison, and amplification factor, are presented in this study.

Ground motion parameters of the earthquakes

Table 2 presents the summary of ground motion parameters. In this study, several key ground motion parameters, such as amplitude of ground motion, ground motion response spectrum, energy flux, and significant duration, are detailed. Figure 4 presents the time history of ground motions including acceleration, velocity, and displacement, which were recorded at the Sikuai Island Seismic Station. The duration of the earthquake is related to the magnitude since a larger area of fault which ruptured means the longer duration of earthquake. In

Table 1 Input parameters of one-dimensional seismic ground response analysis

Site	Material	Thickness (m)	γ (kN/m ³)	c (kPa)	ϕ (°)	FC (%)	k (m/s)	V_s (m/s)	K_0 (-)	p'_{ref} (kPa)	γ_{max} (%)	Liq (-)	c_1 (-)	c_2 (-)	d_1 (-)	d_2 (-)
SPT-1	SP	1.50	17.32	20.01	28.74	5.00	6.6×10^{-5}	201.85	0.48	80.00	5.00	0.03	0.30	0.21	0.10	10.00
	SM	15.00	18.21	23.53	30.41	12.10	6.7×10^{-5}	276.33	0.45	80.00	5.00	0.02	0.06	0.51	0.45	10.00
	SM	3.00	18.52	25.47	30.72	12.30	6.8×10^{-5}	388.01	0.45	80.00	5.00	0.02	0.06	0.52	0.47	10.00
	SC	10.50	18.75	18.18	31.05	19.80	6.6×10^{-5}	437.24	0.44	80.00	5.00	0.02	0.06	0.55	0.49	10.00
SPT-2	SP	7.50	17.29	19.34	28.20	5.00	6.3×10^{-5}	223.12	0.49	80.00	5.00	0.03	0.30	0.21	0.10	10.00
	SM	10.50	18.18	22.67	30.56	12.20	6.6×10^{-5}	300.21	0.45	80.00	5.00	0.02	0.06	0.51	0.45	10.00
	SM	4.50	18.32	24.07	31.08	12.10	6.7×10^{-5}	390.62	0.44	80.00	5.00	0.02	0.06	0.52	0.47	10.00
	SC	7.50	18.82	17.98	31.56	20.10	6.9×10^{-5}	444.70	0.43	80.00	5.00	0.02	0.06	0.55	0.49	10.00
SPT-3	SP	1.50	17.32	20.87	28.73	5.10	6.6×10^{-5}	168.85	0.48	80.00	5.00	0.03	0.30	0.21	0.10	10.00
	SM	3.00	18.38	24.34	30.27	11.90	6.7×10^{-5}	218.97	0.45	80.00	5.00	0.02	0.06	0.51	0.45	10.00
	SP	1.50	17.57	21.01	28.85	4.80	6.3×10^{-5}	277.19	0.48	80.00	5.00	0.03	0.30	0.21	0.10	10.00
	SM	16.50	18.25	25.36	31.78	12.20	6.8×10^{-5}	308.02	0.43	80.00	5.00	0.02	0.06	0.52	0.47	10.00
	SC	7.50	18.88	18.24	31.64	20.30	6.9×10^{-5}	429.35	0.43	80.00	5.00	0.02	0.06	0.55	0.49	10.00

γ unit weight of soil

c soil cohesion

ϕ internal friction angle

FC fines content

k permeability index

V_{s30} corrected SPT value

K_0 coefficient of lateral earth pressure at rest

p'_{ref} effective confining pressure reference (based on Elgamal et al. 2015)

γ_{max} peak shear strain (based on Elgamal et al. 2015)

Liq liquefaction parameter ((based on Elgamal et al. 2015)

c_1 contractive parameter (based on Elgamal et al. 2015)

c_2 contractive parameter (based on Elgamal et al. 2015)

d_1 dilative parameter (based on Elgamal et al. 2015)

d_2 dilative parameter (based on Elgamal et al. 2015)

another word, a larger magnitude of earthquake tends to have a larger fault areas (Chung and Bernreuter 1981). Therefore, there is a general relationship between duration and magnitude. In Fig. 1, it can be seen that the epicentre of first aftershock is very close to the Sikuai Island Seismic Station. It means that the fault areas are relatively larger than other two earthquakes. Accordingly, the first aftershock earthquake has the longest duration, whereas the mainshock tends to have a longer duration than the second aftershock. In Fig. 4, the acceleration propagates progressively and reaches PGA of 0.015g at the 60th second. For the first aftershock, PGA of 0.126g was at the 41st second. For second aftershock, PGA of 0.041g was recorded at the 34th second. In terms of velocity, the PGV for mainshock, first aftershock, and second aftershock is 4.191 cm/s, 6.121 cm/s, and 1.882 cm/s, respectively. Similar to velocity and acceleration, PGD of the first aftershock is the highest one. From the ground motion time history, it can be observed that the first aftershock is the most

impacted earthquake during the Bengkulu–Mentawai earthquakes.

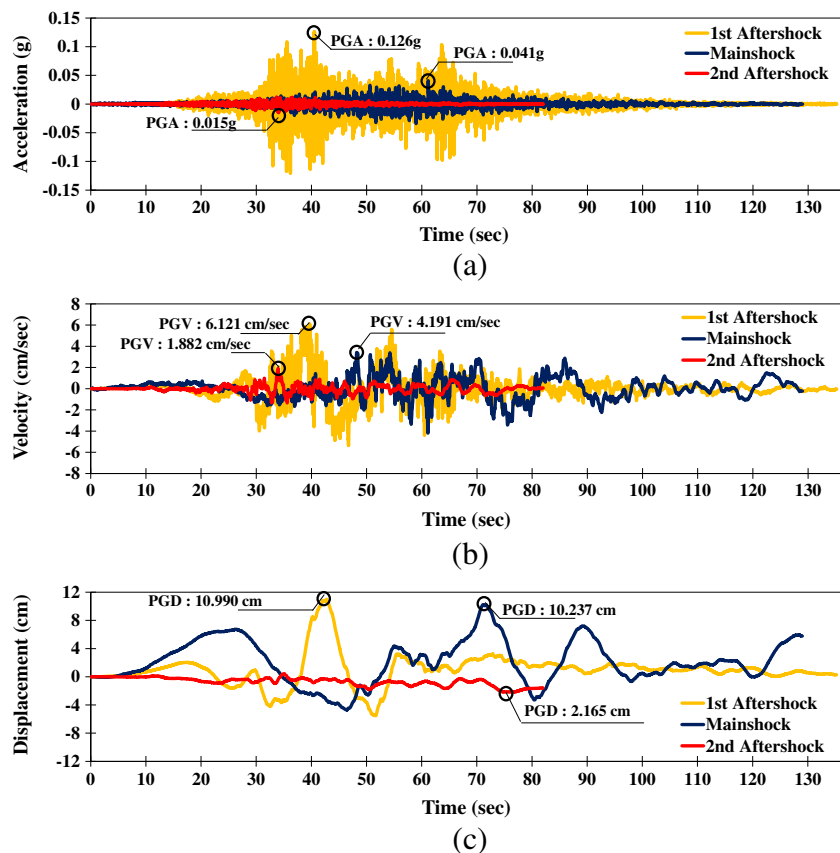
Spectral components including spectral acceleration, spectral velocity, and spectral displacement are presented in Fig. 5. For spectral acceleration, the first aftershock tends to have the highest peak spectral acceleration. The earthquakes generally have predominant period between 0.1 to 0.3 s. In general, the spectral acceleration of the Bengkulu–Mentawai earthquakes is still below seismic design code of Indonesia, i.e. SNI-1726-2012 (for 2% probability of exceedance in 50 years) (SNI 03–1726-2012 2012) and SNI-1726-2002 (for 10% probability of exceedance in 50 years) (SNI-1726-2002 2002). For spectral velocity, the first aftershock also has the highest value among all earthquakes. Similar to spectral velocity, spectral displacement of the first aftershock also has the highest value among the earthquakes.

Figure 6 presents the interpretation of energy flux of the Bengkulu–Mentawai earthquake ground motions. In Fig. 7, the energy flux resulted during the mainshock gradually

Table 2 The ground motion parameters of Bengkulu–Mentawai earthquakes

Ground motion parameters	Mainshock	The first aftershock	The second aftershock
PGA (g)	0.041	0.126	0.015
Time of PGA (sec)	61.155	40.516	34.040
PGV (cm/sec)	4.191	6.121	1.882
Time of PGV (sec)	61.110	39.684	33.945
PGD (cm)	10.237	10.990	2.165
Time of PGD (sec)	71.140	42.744	75.230
PGV/PGA (sec)	0.105	0.049	0.129
Root mean square (RMS) acceleration (g)	0.006	0.017	0.002
Root mean square (RMS) velocity (cm/sec)	1.001	1.178	0.351
Root mean square (RMS) displacement (cm)	3.736	2.506	0.912
Arias Intensity (AI) (m/sec)	0.066	0.600	0.006
Characteristic intensity (I_c)	0.005	0.026	0.001
Specific energy density (SED) (cm ² /sec)	129.371	187.653	10.127
Cumulative absolute velocity (CAV) (cm/-sec)	439.719	1220.263	104.688
Acceleration spectrum intensity (ASI) (g.sec)	0.037	0.112	0.012
Velocity spectrum intensity (VSI) (cm)	14.682	20.948	5.806
Housner intensity (HI) (cm)	13.457	17.269	5.560
Sustained maximum acceleration (SMA) (g)	0.033	0.118	0.012
Sustained maximum velocity (SMV) (cm/-sec)	3.416	5.816	1.337
Effective design acceleration (g)	0.041	0.119	0.013
Acceleration level < 95% of AI (A95) (g)	0.039	0.122	0.015
Predominant period (T_p) (sec)	0.260	0.180	0.220
Mean period (T_m) (sec)	0.415	- 1.000	0.538

Fig. 4 Ground motion time history of the sequence of Bengkulu–Mentawai earthquakes recorded at the Sikuai Island Seismic Station. **a** Acceleration, **b** velocity, and **c** displacement



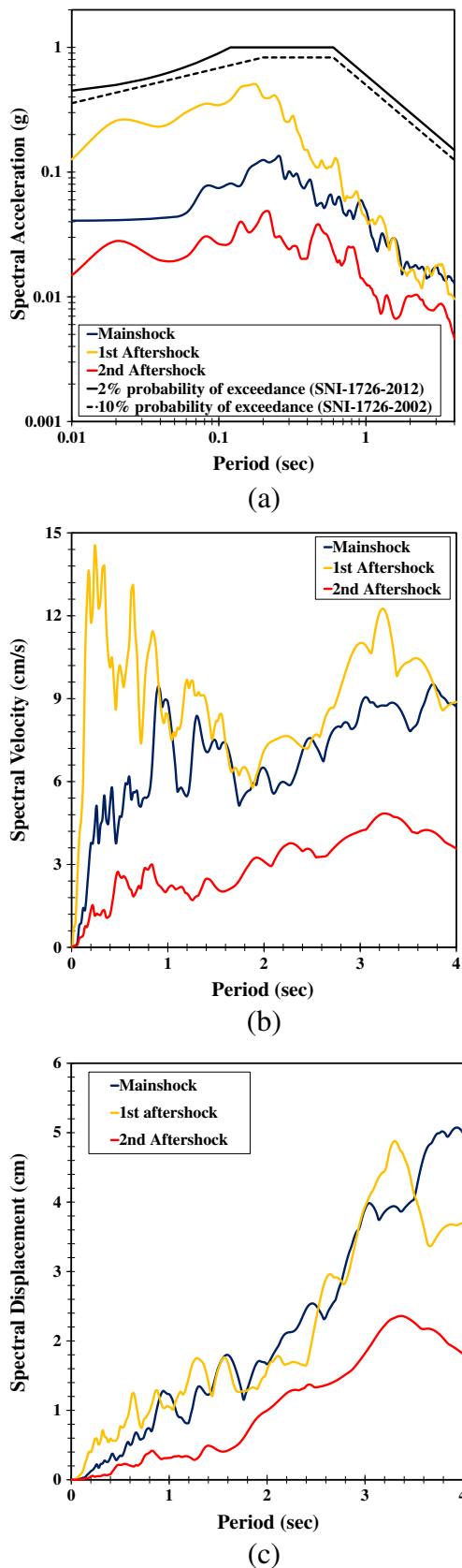


Fig. 5 Ground motion spectrums of Bengkulu–Mentawai earthquake in 2007 recorded at the Sikuai Island Seismic Station. **a** Spectral acceleration, **b** spectral velocity, and **c** spectral displacement

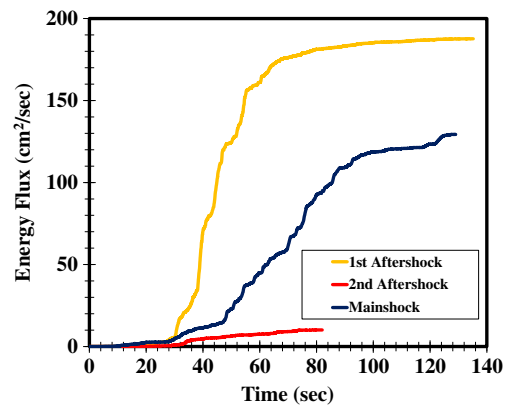


Fig. 6 Energy flux of Bengkulu–Mentawai earthquakes from Sikuai Island Seismic Station

increases within the first 50 s of seismic wave propagation, whereas for both aftershocks, the energy flux gradually increases within 30 s. Afterwards, the energy flux is relatively constant until the seismic wave propagation stops. In general, the energy flux resulted by the first aftershock is the largest one among the earthquakes. This is due to the fact that its magnitude and ground motion are the highest one among other earthquakes.

The Arias Intensity of each Bengkulu–Mentawai earthquake and significant durations (D_{5-95}) are presented in Fig. 7. The 5% Arias Intensity of the earthquakes is generally reached within 20 to 30 s. Furthermore, the Arias Intensity of each earthquake significantly increases up to 95% within 60 to 80 s. Afterward, the Arias Intensity increases constantly up to 100% within 40–150 s. From the interpretation of Arias Intensity, the significant duration of each Bengkulu–Mentawai earthquake is determined (Fig. 7). In general, the significant duration of Bengkulu–Mentawai earthquake ranges from 33 to 45 s. The mainshock has the significant duration about 33 s, whereas the first aftershock has the significant duration of 41 s. For the second aftershock, the significant duration is about 45 s. Based on the ground motion parameter analysis, it can be generally concluded that the first

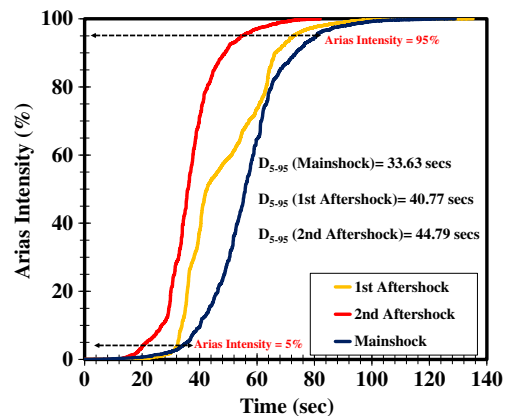


Fig. 7 Arias Intensity and significant duration for Bengkulu–Mentawai earthquakes from the Sikuai Island Seismic Station

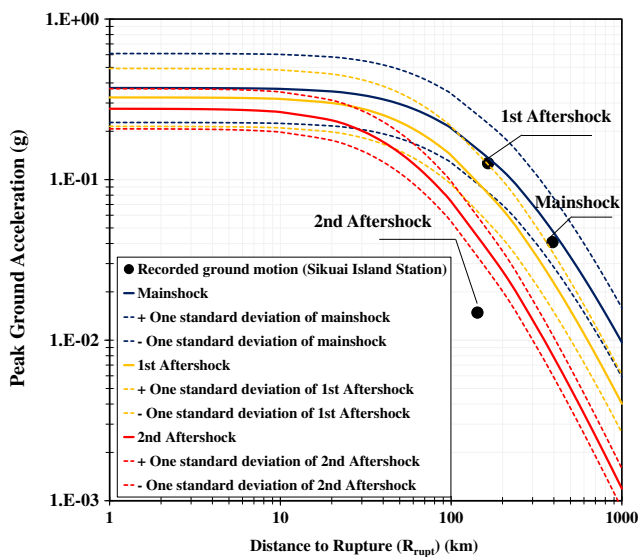


Fig. 8 Ground motion prediction for Bengkulu–Mentawai earthquakes based on the Youngs et al. (1997) model

aftershock is predicted as the most destructive earthquake among the Bengkulu–Mentawai earthquakes in September 2007.

Ground motion prediction based on the attenuation model

In this study, the ground motion prediction at the investigated sites is analysed. For those locations, the ground motion prediction based on the Youngs et al. (1997) model is presented in Fig. 8. Generally, the ground motion prediction shows the good agreement with the recorded ground motion, especially for the mainshock and the first aftershock. For the mainshock, the recorded ground motion (PGA) is a little bit underestimated. However, it is still within the standard deviation of ground motion prediction. For the first aftershock, the recorded ground motion overestimates the ground motion prediction, but it is also still within the standard deviation of ground motion prediction. Figure 8 also reveals that the second aftershock is not well estimated by the model. In general, the performance of the Youngs et al. (1997) model can be acceptable to predict the ground motion of Bengkulu–Mentawai earthquakes, especially for the mainshock and first aftershock.

Peak ground acceleration at the sites and damage level

Peak ground acceleration at the sites (predicted based on the Youngs et al. (1997) model) and the damage level based on Modified Mercalli Intensity (Wood and Neumann 1931) are presented in Fig. 9. As presented in Fig. 9a, PGA at Mukomuko site

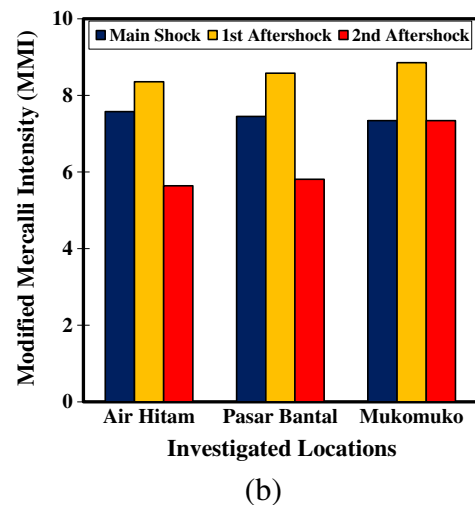
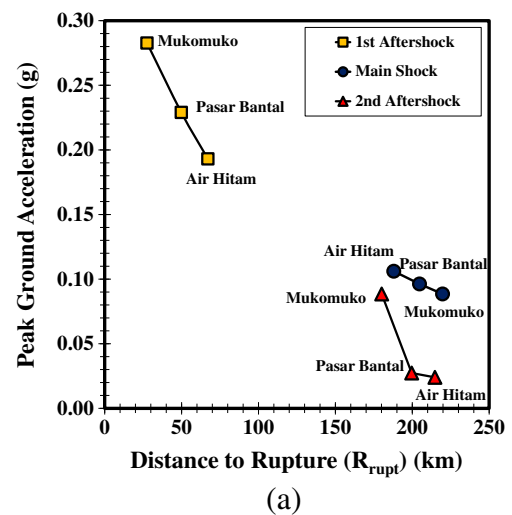
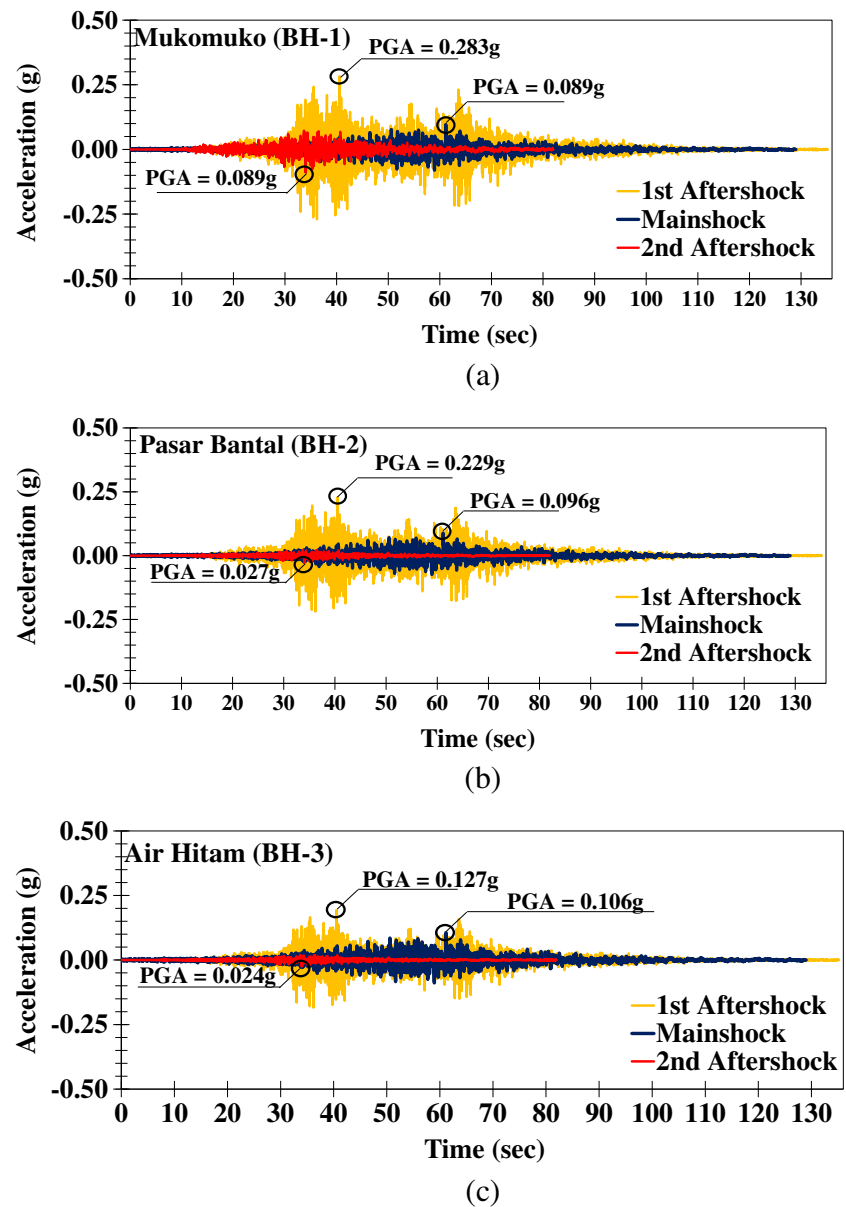


Fig. 9 Ground motion prediction on the investigated sites and prediction of damage intensity level based on MMI (Wood and Neumann 1931). **a** PGA vs distance to rupture and **b** the damage intensity level

is the highest one among all investigated sites, especially during the first and second aftershocks. This is because the Mukomuko site is the closest site to the epicentres of both earthquakes. The PGA values for Mukomuko site during both earthquakes are about 0.283g and 0.089g, respectively. For the mainshock, PGA at Mukomuko is the lowest one among other locations. This is due to the fact that the Mukomuko site is far enough from the epicentre of mainshock. During the mainshock, the Air Hitam site is the closest location, so that PGA during the mainshock for this location is the highest one. In Fig. 9b, the MMI level on the investigated areas ranges from 5 to 9. Generally, the first aftershock contributes significantly on the damage intensity. The mainshock is predicted to had resulted in the initial damage to the structures in Mukomuko regency. The mainshock also remains the light structural damage since the impact of earthquake is not significant. However, the mainshock is then followed by the first and the second aftershocks, which ruptured at close distance to the investigated sites.

Fig. 10 Scaled ground motion for site response analysis in the investigated site. **a** BH-1, **b** BH-2, and **c** BH-3



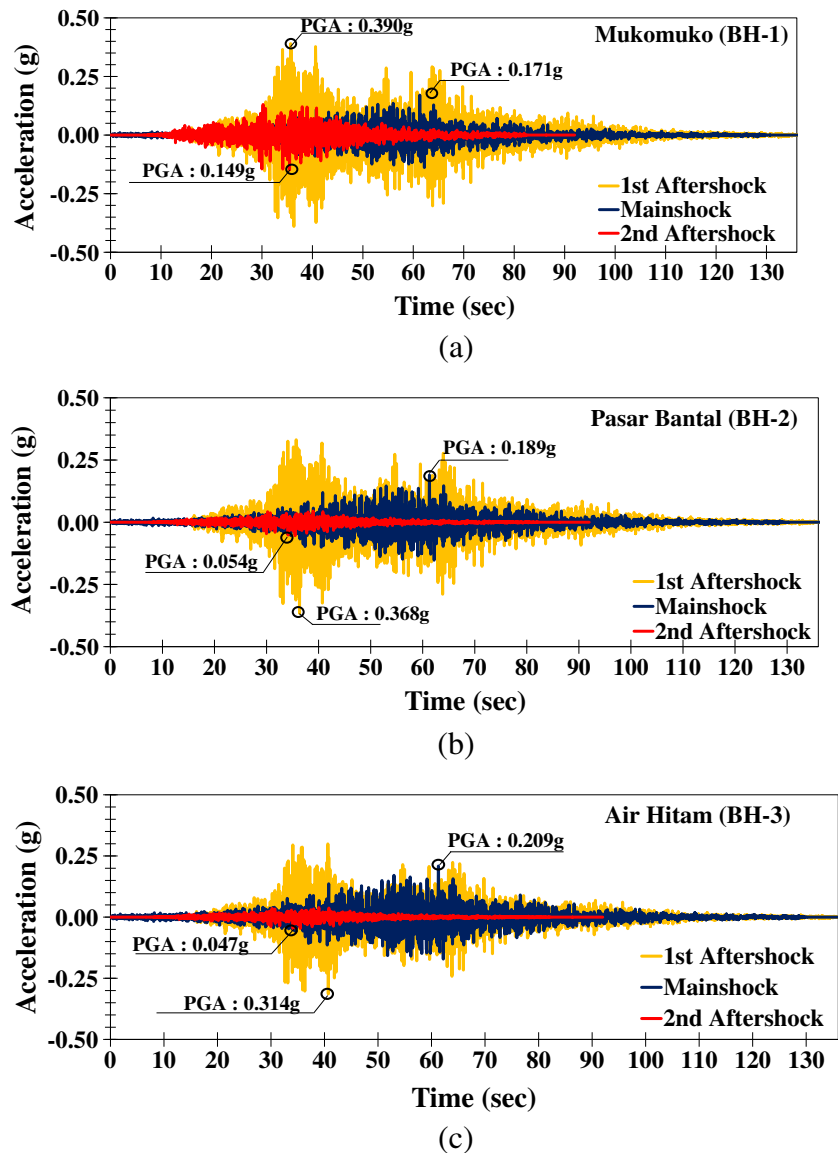
Both aftershocks are predicted to trigger more damage in the study area since the structures' strength had been decreased due to the mainshock. Accordingly, the damage due to aftershocks tends to be more significant. The results of this study are generally consistent with the report of Karnawati et al. (2007) and EERI (2007) which stated that the second strong earthquake (first aftershock) had yielded the huge damage in Mukomuko regency.

Ground response analysis during the earthquakes

The input motion of one-dimensional seismic ground response analysis on each investigated site is presented in

Fig. 10. Figure 11 presents the ground motion at the ground surface, which is resulted from one-dimensional seismic ground response analysis. As presented in Fig. 11, peak ground acceleration of ground response analysis at the Mukomuko site (BH-1) during the mainshock, first aftershock, and second aftershock is 0.171g, 0.390g, and 0.149g, respectively. For Pasar Bantal (BH-2), PGA values for each earthquake range from 0.054 to 0.368 g. PGA of the earthquakes at the Air Hitam site (BH-3) ranges from 0.047 to 0.314 g. The observed PGA values during the mainshock are less than 0.25g. The first aftershock yields a higher PGA than other earthquakes. Meanwhile, PGA resulted from the second aftershock is less than 0.15g. The PGA values of Bengkulu–Mentawai earthquakes are generally larger than

Fig. 11 The ground surface acceleration of ground response analysis for the investigated sites. **a** BH-1, **b** BH-2, and **c** BH-3



the 0.1g. Kramer (1996) mentioned that the minimum PGA of 0.1g could trigger liquefaction in a site. Therefore, for those investigated locations, the liquefaction possibly occurred during Bengkulu–Mentawai earthquakes. Based upon the study of Mase et al. (2017), several locations, such as Pasar Bantal (BH-2) and Mukomuko (BH-1), might be vulnerable to undergo liquefaction during the Bengkulu–Mentawai earthquakes in 2007.

The spectral acceleration resulted from the ground response analysis is presented in Fig. 12. In general, the first aftershock spectral acceleration at each investigated site exceeds the designed spectral accelerations. For the mainshock and second aftershock, the designed spectral acceleration is still reliable since the spectral accelerations on each investigated site are still below the designed spectral acceleration. The spectral acceleration due to the first aftershock seems to yield the

serious impact to low-storey buildings (1- to 2-storey buildings) since the designed spectral accelerations are generally exceeded by spectral accelerations at a short period (0.1 to 0.2 s). Karnawati et al. (2007) and EERI (2007) also reported that the structural damage to low-storey building was massively found in Mukomuko regency after Bengkulu–Mentawai earthquakes.

The amplification factor on each investigated site is presented in Fig. 13. In Fig. 13, the input motions applied at the bottom of the investigated sites could amplify up to 1.5 to 2 times at the ground surface. The amplification factor values of the investigated sites are relatively consistent with each other. The first aftershock yields the lowest amplification factor, whereas the mainshock and the aftershock show the similar values of amplification factor on each investigated site, i.e. about 1.7 to 2. The amplification factors resulted from this

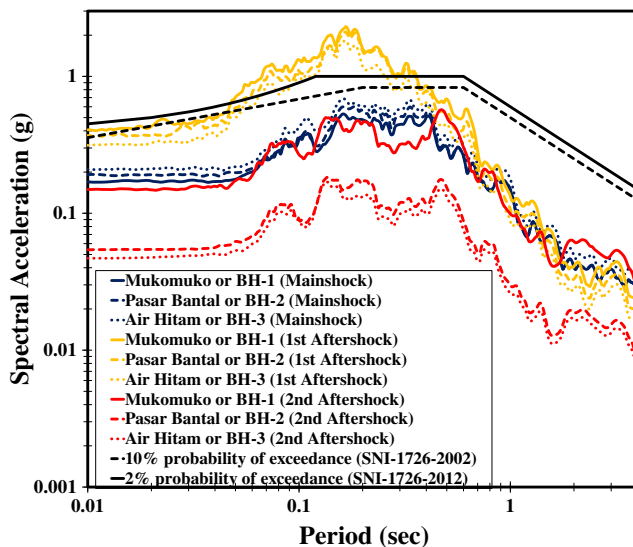


Fig. 12 The spectral acceleration of ground response analysis

study are generally consistent with the study of Mase et al. (2017).

Conclusion

This study is focused on analysis of ground motion parameters and analysis of ground response analysis during Bengkulu–Mentawai earthquakes in 2007. The first aftershock showed the highest amplitudes of the ground motion as well as the spectral acceleration. The first aftershock is also identified to yield the significant damage of low-storey buildings in the study area. During the earthquakes, ground motions of Bengkulu–Mentawai earthquakes could magnify two times at ground surface. The investigated sites also possibly undergo liquefaction during the earthquakes, especially during the first

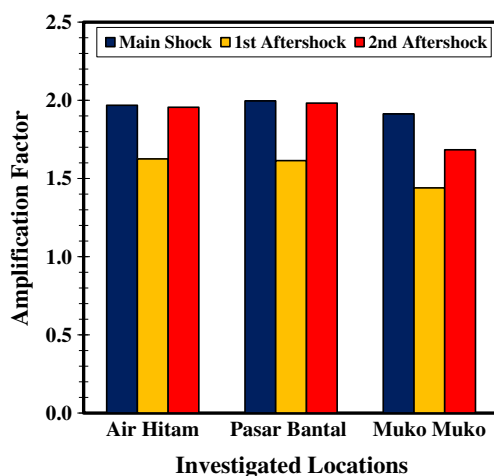


Fig. 13 Amplification factor of the sites

aftershock. Generally, the results of this study concluded that the first aftershock of Bengkulu–Mentawai earthquakes has played the key role to trigger the massive damage in Mukomuko regency, Bengkulu, Indonesia.

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References

- Abrahamson NA, Silva WJ, Kamai R (2014) Summary of the ASK14 ground motion relation for active crustal regions. *Earthquake Spectra* 30(3):1025–1055. <https://doi.org/10.1193/070913EQS198M>
- Adampira M, Alielahi H, Panji M, Koohsari H (2014) Comparison of equivalent linear and nonlinear methods in seismic analysis of liquefiable site response due to near-fault incident waves: a case study. *Arab J Geosci* 8(5):3103–3118. <https://doi.org/10.1007/s12517-014-1399-6>
- Ansal A, Tönük G, Kurtuluş A, Çetiner B (2012) Effect of spectra scaling on site specific design earthquake characteristics based on 1D site response analysis. In: *Proceedings of 15th World Conference on Earthquake Engineering*, Lisbon, Portugal, 24–28 October
- Arias A (1970) A measure of earthquake intensity. In: Hansen R (ed) *Seismic design for nuclear power plants*, Massachusetts Institute of Technology, Massachusetts, USA
- Bardet JP, Tobita T (2001) NERA: a computer program for nonlinear earthquake site response analyses of layered soil deposits. Department of Civil Engineering, University of Southern California, California, USA
- Bommer JJ, Martinez-Pereira A (1998) The effective duration of earthquake strong motion. *J Earthq Eng* 3(2):127–172
- Boore DM, Bommer JJ (2005) Processing of strong-motion accelerograms: needs, options and consequences. *Soil Dyn Earthq Eng* 25(2):93–115. <https://doi.org/10.1016/j.soildyn.2004.10.007>
- Centre of Earthquake Strong Motion Data (CESMD) (2017) Earthquake data of the 2007 Sumatra earthquake for Sikuai Island data. CESMD. <https://www.strongmotioncenter.org>. Accessed on 13 April 2017
- Chung DH, Bernreuter DL (1981) Regional relationships among earthquake magnitude scales. *Rev Geophys* 19(4):649–663. <https://doi.org/10.1029/RG019i004p00649>
- Douglas J, Aochi H (2008) A survey of techniques for predicting earthquake ground motions for engineering purposes. *Surv Geophys* 29(3):187–220. <https://doi.org/10.1007/s10712-008-9046-y>
- Earthquake Engineering Research Institute (EERI) (2007) Learning from earthquakes observation on the southern Sumatra earthquakes of September 12–13, 2007, EERI Special Report, Earthquake Engineering Research Institute, California, USA. https://eeri.org/lfe/pdf/indonesia_south_sumatra_eeri_report.pdf. Accessed 2 January 2019
- Elgamal A, Yang Z, Lu J (2015) Cyclic1D: a computer program for seismic ground response. Technical Report, TR-No. SSRP-06/05, University of California at San Diego, California, USA
- Elia G, di Lernia A, Rouainia M (2019) Ground motion scaling for the assessment of the seismic response of a diaphragm wall. In: Silvestri F, Moraci N (eds) *Earthquake geotechnical engineering for protection and development of environment and constructions*

- (Proceedings of the 7th International Conference on Geotechnical Engineering), 1st edn. CRC Press, New York, Italy, pp 2249–2257
- Finn WDL, Byrne PL, Martin GR (1976) Seismic response and liquefaction of sands. *J Geotech Eng Div* 102(GT8):841–856
- Finn WDL, Martin GR, Lee MKW (1978) Comparison of dynamic analyses for saturated sands. *Earthquake Engineering and Soil Dynamics*, ASCE, GT(S1): 472–491
- Hancock J, Watson-Lamprey J, Abrahamson NA, Bommer JJ, Markatis A, McCoy E, Mendis R (2006) An improved method of matching response spectra of recorded earthquake ground motion using wavelets. *J Earthq Eng* 10(Special issue 1):67–89. <https://doi.org/10.1080/13632460609350629>
- Hancock J, Bommer JJ, Stafford PJ (2008) Numbers of scaled and matched accelerograms required for inelastic dynamic analyses. *Earthq Eng Struct Dyn* 37(14):1585–1607. <https://doi.org/10.1002/eqe.827>
- Heo Y, Kunnath SK, Abrahamson N (2011) Amplitude-scaled versus spectrum-matched ground motions for seismic performance assessment. *J Struct Eng* 137(3):278–288. [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0000340](https://doi.org/10.1061/(ASCE)ST.1943-541X.0000340)
- Iai S, Matsunaga Y, Kameoka T (1992) Strain space plasticity model for cyclic mobility. *Soils Found* 32(2):1–15. https://doi.org/10.3208/sandf1972.32.2_1
- Idriss IM, Boulanger RW (2006) Semi-empirical procedures for evaluating liquefaction potential during earthquakes. *Soil Dyn Earthq Eng* 26(1):115–130. <https://doi.org/10.1016/j.soildyn.2004.11.023>
- Ishihara K, Tatsuoka F, Yasuda S (1975) Undrained deformation and liquefaction of and under cyclic stresses. *Soils Found* 15(1):29–44. <https://doi.org/10.3208/sandf1972.15.29>
- Karnawati D, Satyarno I, Pramumijoyo S (2007) Learning from Bengkulu Earthquake: preliminary observation on impacts of September 12, 2007 earthquake in Bengkulu, West Sumatra, Indonesia. EERI Special Report. Earthquake Engineering Research Institute, California, USA. https://www.eeri.org/lfe/pdf/indonesia_sept07_karnawati.pdf. Accessed 2 January 2019
- Kramer SL (1996) Geotechnical earthquake engineering. Prentice Hall, New Jersey
- Kurama YC, Farrow KT (2003) Ground motion scaling methods for different site conditions and structure characteristics. *Earthq Eng Struct Dyn* 32(15):2425–2450. <https://doi.org/10.1002/eqe.335>
- Ma J, Dong L, Zhao G, Li X (2019a) Focal mechanism of mining-induced seismicity in fault zones: a case study of Yongshaba mine in China. *Rock Mech Rock Eng* 52(9):3341–3352. <https://doi.org/10.1007/s00603-019-01761-4>
- Ma J, Dong L, Zhao G, Li X (2019b) Ground motions induced by mining seismic events with different focal mechanisms. *Int J Rock Mech Min Sci* 116:99–110. <https://doi.org/10.1016/j.ijrmms.2019.03.009>
- Mase LZ (2015) Earthquake characteristic in Bengkulu. *Teknosia* 2(15): 25–34 (in Indonesia)
- Mase LZ (2017) Liquefaction potential analysis along coastal area of Bengkulu Province due to the 2007 Mw 8.6 Bengkulu earthquake. *Journal of Engineering and Technological Sciences* 49(6):721–736. <https://doi.org/10.5614/j.eng.technol.sci.2017.49.6.2>
- Mase LZ (2018a) Reliability study of spectral acceleration designs against earthquakes in Bengkulu City, Indonesia. *International Journal of Technology* 9(5):910–924. <https://doi.org/10.14716/ijtech.v9i5.62>
- Mase LZ (2018b) One dimensional site response analysis of liquefaction potential along coastal area of Bengkulu City, Indonesia. *Civil Engineering Dimension* 20(2):57–69. <https://doi.org/10.9744/ced.20.2.57-69>
- Mase LZ (2018c) Performance comparison of liquefaction potential analysis methods using SPT due to the 12 September 2007 8.6 Mw earthquake along coastal area of Bengkulu. *Civil Engineering Journal* 25(1):53–59. <https://doi.org/10.5614/jts.2018.25.1.7> (In Indonesian)
- Mase LZ, Somantri AK (2016) Analysis of liquefaction potential in Lempuing sub-district, Bengkulu City using critical maximum acceleration. *Potensi* 25(1):1–11 (in Indonesian)
- Mase LZ, Tobita T, Likitlersuang S (2017) One-dimensional analysis of liquefaction potential: a case study in Chiang Rai Province, Northern Thailand. *Journal of Japanese Society of Civil Engineers, Ser A1 (Structural Engineering/Earthquake Engineering)* 73(4): I_135–I_147. https://doi.org/10.2208/jscejsee.73.I_135
- Mase LZ, Likitlersuang S, Tobita T (2018) Analysis of seismic ground response caused during strong earthquake in Northern Thailand. *Soil Dyn Earthq Eng* 114:113–126. <https://doi.org/10.1016/j.soildyn.2018.07.006>
- Miller RD, Xia J, Park CB, Ivanov J (1999) Using MASW to map bedrock in Olathe, Kansas (expanded abstract). *Journal of Society of Exploration Geophysics* 1:433–436. <https://doi.org/10.1190/1.1821045>
- Misliniyati R, Mawardi, Besperi, Razali MR, Muktadir R (2013) Mapping of liquefaction potential of coastal area using cone penetration test in Lempuing, Bengkulu City. *Inersia* 5(2):1–8 (in Indonesian)
- Misliniyati R, Mase LZ, Irsyam M, Hendriawan H, Sahadewa A (2019) Seismic response validation of simulated soil models to vertical array record during a strong earthquake. *Journal of Engineering and Technological Sciences* 51(6):772–790. <https://doi.org/10.5614/j.eng.technol.sci.2019.51.6.3>
- National Earthquake Hazard Reduction Program (NEHRP) (1998) Recommended provisions for seismic regulation for new buildings and other structures 1997 edition. Technical Report. FEMA 302, Federation Emergency Management Agency, Washington, USA
- Olafsson S, Remseth S, Sigbjornsson R (2001) Stochastic models for simulation of strong ground motion in Iceland. *Earthq Eng Struct Dyn* 30(9):1305–1331. <https://doi.org/10.1002/eqe.64>
- Parra E (1996) Numerical modelling of liquefaction and lateral ground deformation including cyclic mobility and dilative behaviour in soil systems. PhD Dissertation, Department of Civil Engineering, Rensselaer Polytechnic Institute, New York, USA
- Pender M, Orense R, Wotherspoon L, Storie L (2016) Effect of permeability on the cyclic generation and dissipation of pore pressures in saturated gravel layers. *Geotechnique* 66(4):313–322. <https://doi.org/10.1680/jgeot.SIP.15.P.024>
- Prevost JH (1985) A simple plasticity theory for frictional cohesionless soils. *Soil Dyn Earthq Eng* 4(1):9–17. [https://doi.org/10.1016/0261-7277\(85\)90030-0](https://doi.org/10.1016/0261-7277(85)90030-0)
- Schnabel PB, Lysmer J, Seed HB (1972) SHAKE: a computer program for earthquake response analysis of horizontally layered sites, Report No. EERC 72-12, University of California, Berkeley, California, USA
- Seed HB, Idriss IM (1971) Simplified procedure for evaluating soil liquefaction potential. *Soil Mechanics and Foundations Division ASCE* 97(SM9): 1249–273, September 1971
- SNI 03–1726-2002 (2002) Standard of earthquake resistance design for building. Ministry of Public Works, Jakarta, Indonesia [in Bahasa]
- SNI 03–1726-2012 (2012) Standard of earthquake resistance design for building. National Standardization Agency, Jakarta, Indonesia [in Bahasa]
- Streeter VL, Wylie EB, Richart FE (1974) Soil motion computations by characteristics methods. *J Geotech Geoenviron* 100(GT3):247–263
- Trifunac MD, Brady GA (1975) A study of the duration of strong earthquake ground motion. *Bull Seismol Soc Am* 65(3):581–626
- Vemuri J, Kolluru S (2020) Evaluation of ground motion scaling techniques. In: Prashant A, Sachan A, Desai C (eds) *Advances in*

- computer methods and geomechanics, Lecture notes in civil engineering, vol 55. Springer, Singapore, pp 525–535
- Wood HO, Neumann F (1931) Modified Mercalli Intensity scale of 1931. Bull Seismol Soc Am 21(4):277–283
- Yang Z (2000) Numerical modelling of earthquake site response including dilation and liquefaction. PhD Dissertation, Department of Civil Engineering and Engineering Mechanics, Columbia University, New York, USA
- Youngs RR, Chiou SJ, Silva WJ, Humprey JR (1997) Strong ground motion attenuation relationships for subduction zone earthquakes. Seismol Res Lett 68(1):58–73. <https://doi.org/10.1785/gssrl.68.1.58>