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Site-specific ground response analysis at a site in the affected area of the 2016 Pidie Jaya earthquake

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Abstract. Analytical models have demonstrated that they are able to simulate reasonably well the seismic motions at the ground level. The most widely used model is the equivalent linear approach. This equivalent linear model was used to compute the free-field response of Meureudu-Pidie Jaya, Aceh Indonesia's soft soils during the 2016 Pidie Jaya earthquake. The model computes the ground response of horizontally layered soil deposits subjected to transient and vertically propagating shear waves through the one-dimensional soil column. Each soil layer is assumed to be homogeneous, visco-elastic and infinite in the horizontal extent. The equivalent linear estimation of soil properties is taken to express the nonlinearity of the soil's shear modulus and damping values. These values are assumed to be a function of shear strain amplitude and determined by an iterative process that must be consistent with the level of the effective strain induced in each sub-layer. Starting with the highest shear modulus and a low damping value, the shear modulus and the damping ratio of each sub-layer are modified. The modification is based on the applicable relationship between both properties and the shear strain. The calculation is repeated until strain-compatible modulus and damping values converge within a tolerance of 1%. This research reveals the ground motions of Pidie Jaya's soils. The results of the analysis are presented.

1. Introduction

A site-specific ground response analysis has to be taken into consideration for seismic hazard assessment. It has been well established that rock-based earthquake motions can be amplified on soft soil sites and cause structural damage, such as in the 1985 Mexico earthquake, the 1988 Armenian earthquake [1], the 1989 Loma Prieta earthquake in California [2], and the 1951 Adelaide earthquake [3,4]. Analytical models for a site-specific ground response analysis demonstrated that they are able to simulate reasonably well the soil behaviour due to dynamic loading. The widely used approaches are the equivalent linear technique which is included the EERA computer program [5]. The EERA (Equivalent-linear Earthquake Response Analysis) program was developed from the basic principles of the SHAKE program [6] which has been one of the most commonly used computer programs in geotechnical earthquake engineering since it became available in 1972. EERA was selected for this study because the program takes full advantage of the latest development of FORTRAN 90 and the Windows platform. EERA is not a stand-alone program. It is an add-on program embedded in

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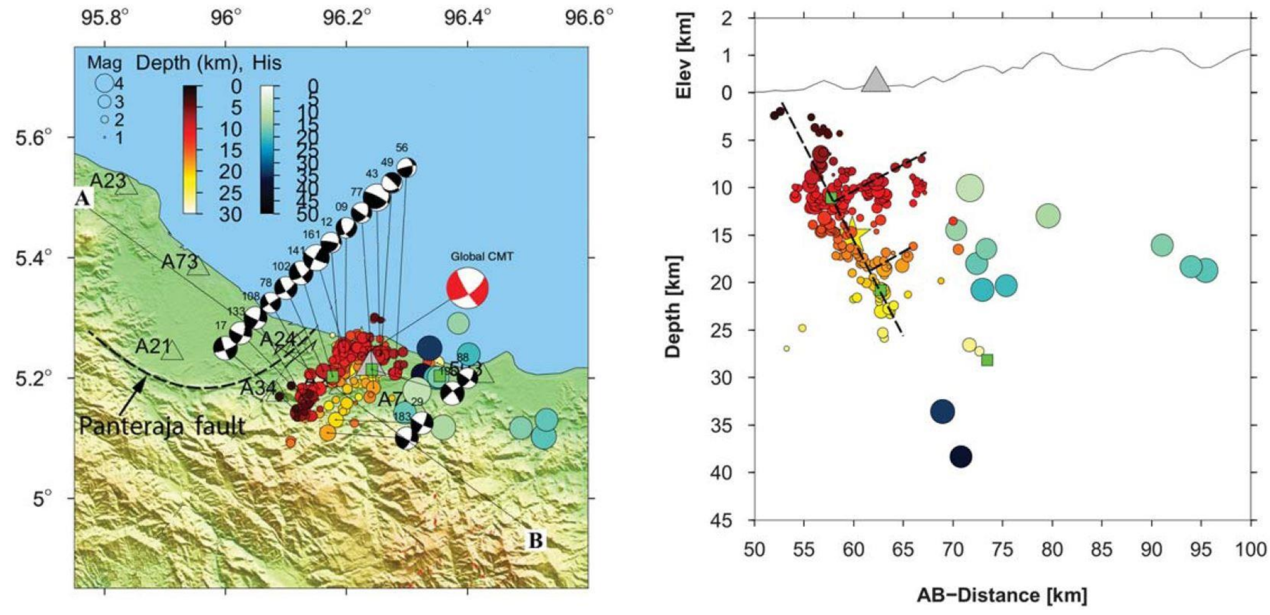
Microsoft Excel. The unavailability of the site-specific ground response analysis at a site in the affected area of the 2016 Pidie Jaya earthquake has become the motivation of this paper. A study by [7] found a greater seismic event than the 2016 Pidie Jaya earthquake at a deep potential seismogenic depth around the Pidie Jaya region. Furthermore, [7] suggested considering this potential larger event for seismic hazard evaluation of this region. Three actual seismic time histories and a synthetic of Pidie Jaya earthquake's time history were used. The equivalent linear approach was employed for this analysis. Several outcomes from these site-specific ground response analyses i.e. peak ground acceleration; stress and strain at each layer; amplification at the ground surface or the surface of each layer; Fourier amplitude; and the response spectrum of the soil are presented.

2. The 2016 Pidie Jaya earthquake and site characteristics

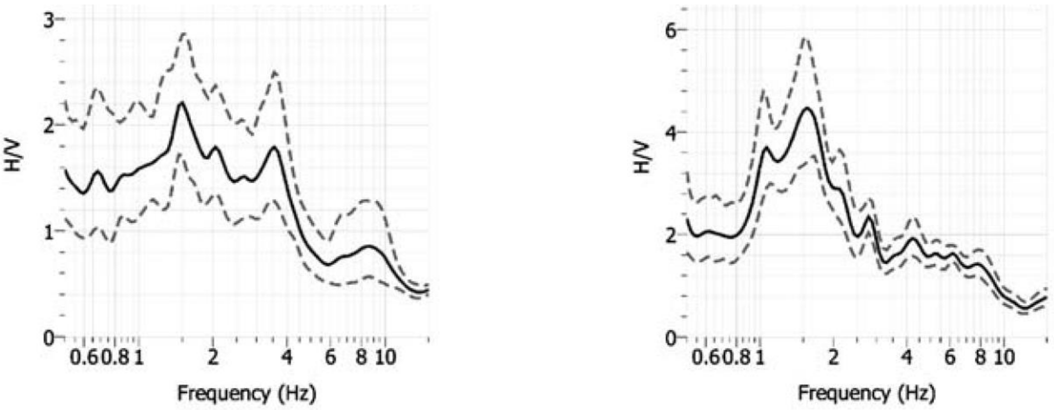
On 7 December 2016, 05:03:33 AM local time an Mw 6.5 earthquake shocked the northern coastal area of Aceh around the Pidie Jaya region (hereafter, Pidie Jaya earthquake). The Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) stated the epicenter of this seismic is at 5.29° S and 96.22° E and the depth of the event is 15 km. The earthquake caused heavy damage on structure and killed and injured many people within a radius of ~35 km from the epicenter. To justify the fault geometry and associated tectonics, [7] deployed many seismometers to locate the aftershocks of the event. More than 300 events with magnitudes larger than 0.50 were recorded. The results are shown in Figures 1a and 1b which was suggested that the seismic has re-activated a small fault of Panteraja fault.



(a) (b)

Figure 1. (a) Map of aftershocks distribution and focal mechanism of the 2016 Pidie Jaya earthquake, and (b) cross-section A-B [7].

The characteristics of the study site were developed based on the results of the site investigations up to 30.5 m depth at a site in the affected area of the 2016 Pidie Jaya earthquake. Additional study results by [7] were used to estimate the sub-surface profile at a greater depth than 30.5 m. The HVSR curves at two different sites in the affected area are illustrated in Figure 2. These HVSR analyses suggested a relatively shallow bedrock at the measured sites.



(a) (b)

Figure 2. HVSR analysis at two different sites at Pidie Jaya [7].

3. Methods

A sequence of steps (Figure 3) is followed to interpret the earthquake motions at the stable ground surface or bedrock to account for their effects on the soil profile at any specific site. There are three parameters to be defined, which are earthquake input motions, soil profile, and dynamic soil characteristics i.e. strain dependent modulus reduction and damping behaviour.

3.1. Acceleration time histories

In this study, four seismic motions were used. These four historical seismic events are outlined in Table 1. Three seismic motions are actual of historical seismic events of the 2012 Simeulue II earthquake, the 2013 Mane-Geumpang earthquake, and the 2013 Bener Meriah earthquake. The last seismic motions of the 2016 Pidie Jaya earthquake is synthetic time histories generated using EXSIM of [8]. All the acceleration time histories of the four past events are shown in Figure 4.

Table 1. Four seismic events used in this study.

Event	Epicentre coordinates	Magnitude (ML)	Depth & distance from Pidie Jaya (km)
7:43:11 on 11-04 2012 Simeulue II	N 0.82 – 92.42 E	8.1	24 & 600
05:22:42 on 22-01-2013 Mane-Gempang	N 5.49 – 95.21 E	6.0	11 & 70
14:37:03 on 02-07-2013 Bener Meriah	N 4.70 – 96.61 E	6.2	10 & 90
05:03:33 on 06-12-2016 Pidie Jaya	N 4.70 – 96.61 E	6.5	15 & 10

3.2. Soil profile

One-dimensional (1D) sub-surface profile is developed for the site response analysis. The developed 1D profile i.e. soil type, layer thickness, unit weight, shear wave velocity is shown in Table 2. This 1D profile was developed using a borehole sunk at a site in the affected area of the 2016 Pidie Jaya earthquake. The estimation of the shear wave velocity of the 1D was developed from the mechanical

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cone penetration test (CPT) and standard penetration test (SPT) ([9]-[18]). This detailed knowledge of the subsurface characteristics is important in the construction of the profile.

Table 2. Simplified soil profile input for ground response analysis

Note	Layer Number	Soil Material Type	The thickness of layer (m)	Total unit weight (kN/m^3)	Shear wave velocity (m/sec)
	1	Clay	4	21.31	120
	2	Sand	13	23.99	180
	3	Sand	13	23.48	220
	4	Sand	15	23.46	350
	5	Sand	10	23.26	500
Bedrock	6			22.80	800

3.3. Dynamic characteristics of shear modulus and damping curves

The default modulus reduction and damping curves provided by the EERA model have worked well in most applications [19]. The present study adopts these default curves to represent each typical material behaviour during strain since there was no laboratory testing to determine these curves.

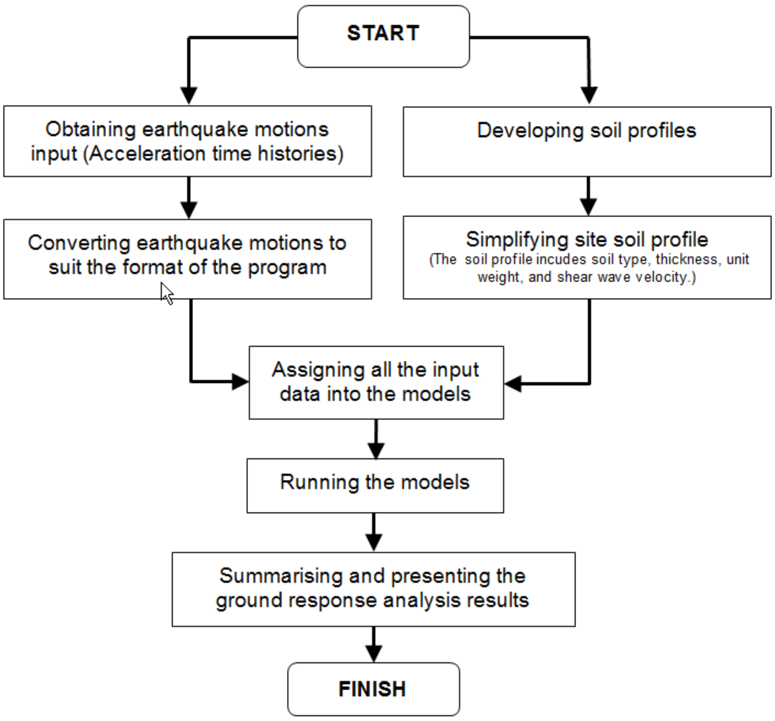


Figure 3. A sequence of steps for site-specific ground response analysis

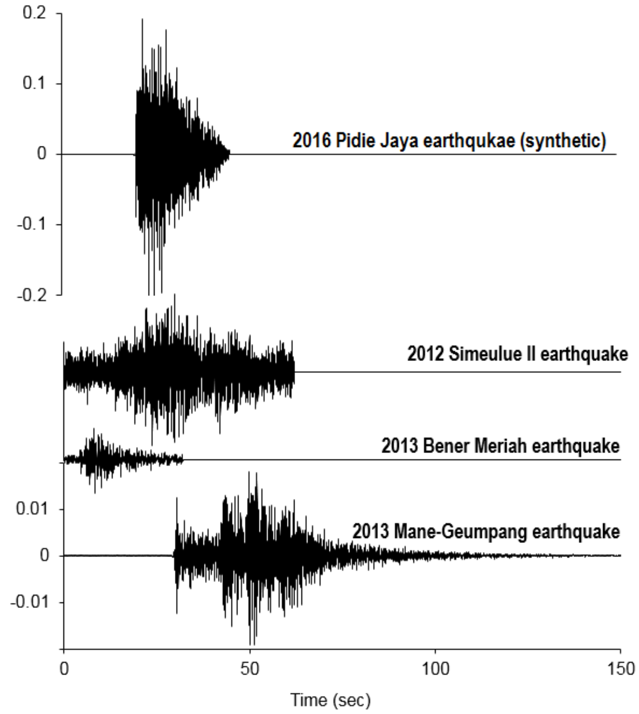


Figure 4. Time histories for ground response analysis

4. Results

The site-specific ground response analysis produces the following results: peak ground acceleration (PGA), response spectrum, fundamental site frequency, and site amplification. A summary of the site-response analysis outputs using the EERA is presented in Tables 3 and 4 below.

Table 3. PGA, maximum spectral acceleration and maximum spectral velocity results of site-specific ground response analysis

Parameters	Seismic event			
	2012 Simeulue II	**2013 Mane-Geumpang**	**2013 Bener Meriah**	**2016 Pidie Jaya**
PGA (g)	0.09	0.11	0.03	0.56
Max spectral acceleration (g)	0.35	0.51	0.10	1.95
Max spectral velocity (cm/s)	15.08	24.61	8.92	149.49

4.1. Peak ground acceleration (PGA), spectral ground acceleration and spectral velocity

The peak ground acceleration (PGA) results are 0.09g for 2012 Simeulue II earthquake, 0.11g for 2013 Mane-Geumpang earthquake, 0.03g for 2013 Bener Meriah seismic event, and 0.56g for the 2016 Pidie Jaya earthquake. As shown, the PGA varies across the seismic events. As expected, the highest PGA was caused by the 2016 Pidie Jaya seismic event (0.56g) and the lowest PGA of about 0.03g was triggered by the 2013 Bener Meriah earthquake. Similar results are shown in the max spectral acceleration and maximum spectral velocity. The highest spectral acceleration and velocity were caused by the 2016 Pidie Jaya seismic event of 1.95g and 149.49 cm/s, respectively. The lowest spectral acceleration and velocity were triggered by the 2013 Bener Meriah earthquake of 0.1g and 8.92 cm/s, consecutively. The spectral acceleration curves of all analyses are presented in Figure 5.

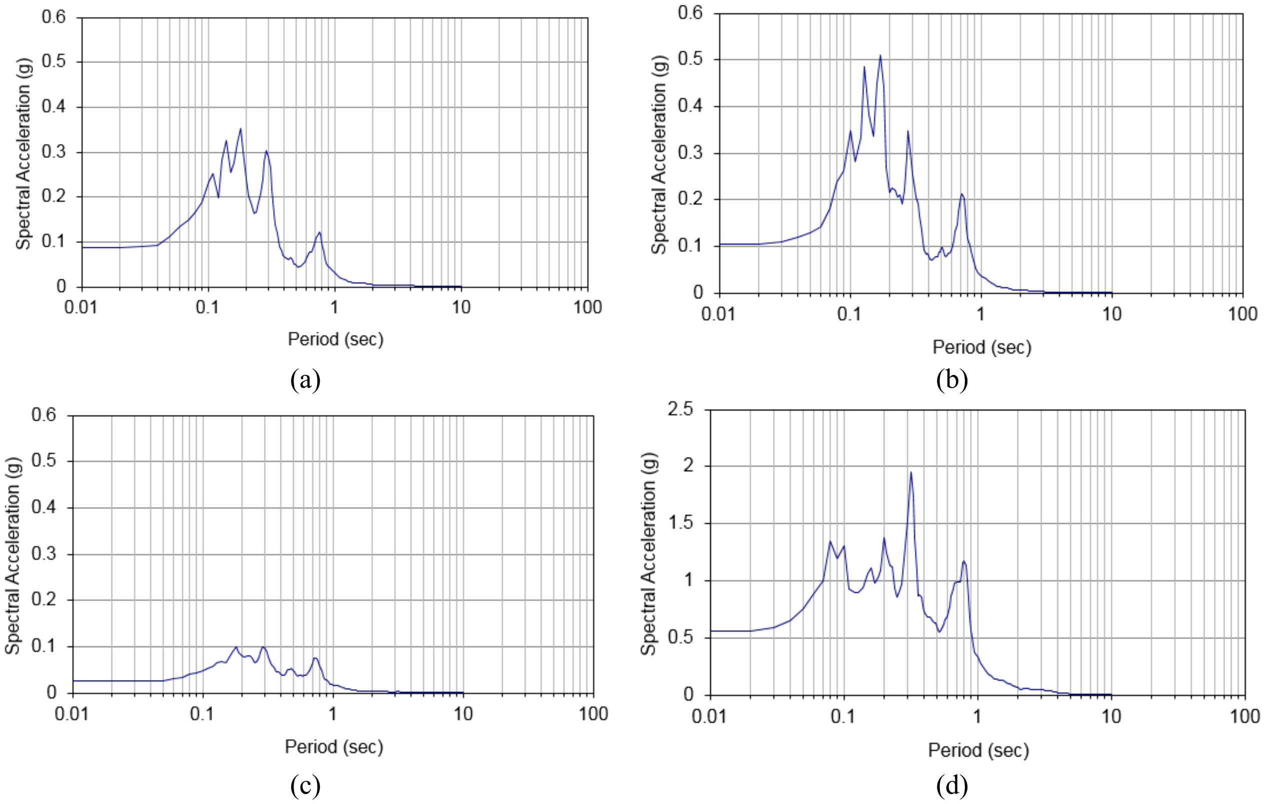


Figure 5. Spectral acceleration (a) 2012 Simuelue II, (b) 2013 Mane-Geumpang, (c) 2013 Bener Meriah, and (d) Pidie Jaya earthquakes

4.2. Site fundamental frequency and amplification

A summary of the site-response analysis outputs of the fundamental frequency and estimated amplification at ground level using the EERA is presented in Table 4. The estimated fundamental frequency of all studied sites is between 1.2 to 1.4 Hz. The typical estimated fundamental frequency is shown in Figure 6. The estimated amplification at the ground level at the investigated site is between 3.1 and 5.4. PGA profiles and amplification profiles of site response analysis are shown in Figure 7.

Table 4. Estimated fundamental frequency and amplification at ground level results of the site-specific ground response analysis

Parameters	**Seismic event**			
	2012 Simeulue II	**2013 Mane-Geumpang**	**2013 Bener Meriah**	**2016 Pidie Jaya**
Fundamental frequency (Hz)	1.4	1.4	1.4	1.2
Amplification at ground level	5.4	5.3	3.3	3.1

4.3. Discussion

In this study, the 2016 Pidie Jaya earthquake is estimated to produce PGA of 0.56g with a simplified average spectral acceleration (SA) of 1.0g at a period of 0.1 to 0.6s. These estimated PGA and simplified average SA of this study are in a reasonably well agreement with the USGS estimations [20] of 0.45g for PGA and ≈0.9g for peak SA, as shown in Figures 8a & 8b.

Another output of this study is estimated site fundamental frequency, which is important for building seismic resistant design [21]. Generally, the building fundamental frequency, f_B can be calculated using an Equation 1 [22].

$$f_B = \frac{10}{N} \qquad \text{Eq. 1}$$

Most buildings at the affected area of the 2016 Pidie Jaya earthquake area are single storey house and up to 3 storey shophouses, therefore the affected area of the Pidie Jaya earthquake's building frequency is estimated between 3.0 and 10 Hz (N is the number of building storey). In general, this study suggests a fundamental frequency of 1.2 to 1.4 Hz, which is only can significantly amplify the medium rise to high-rise buildings. However, detailed site fundamental frequency investigation using passive noise data, as shown in [25], is recommended as highly sub surface spatial variability around the study site is observed [7], [23], [24].

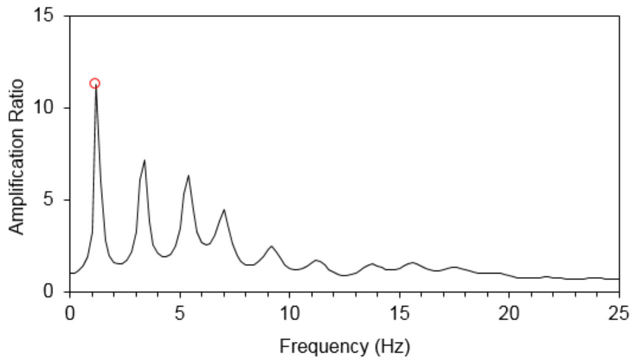


Figure 6. Typical estimated site fundamental frequency.

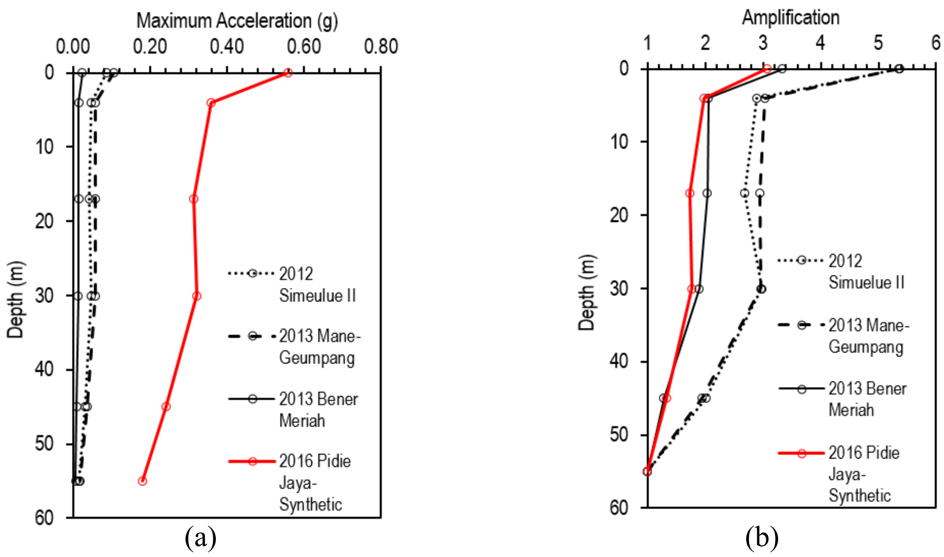
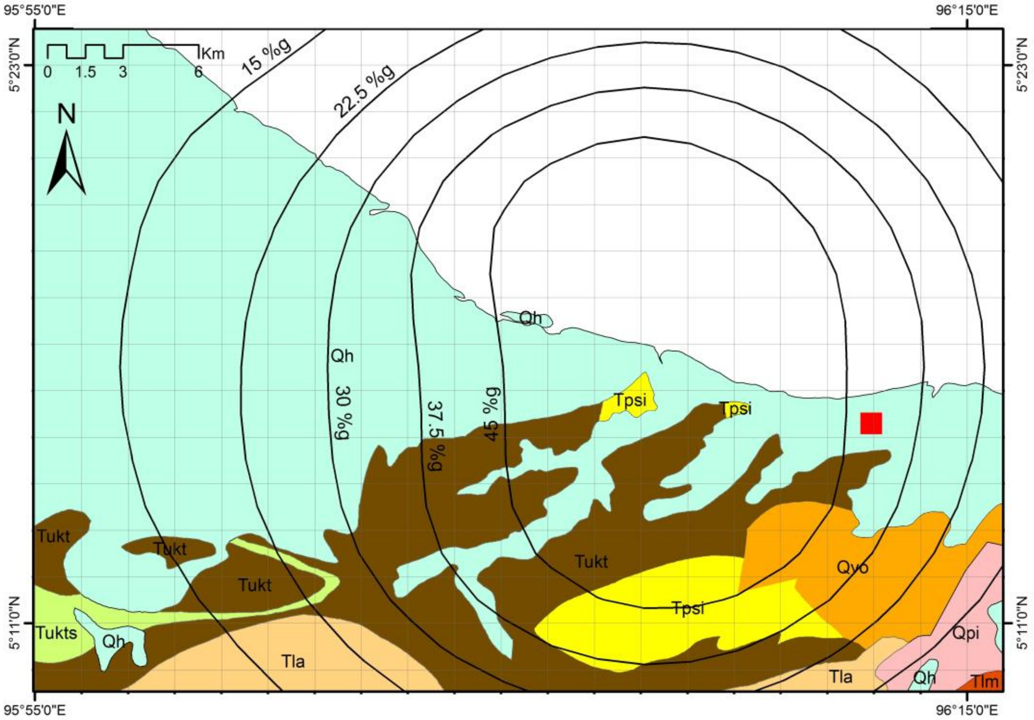
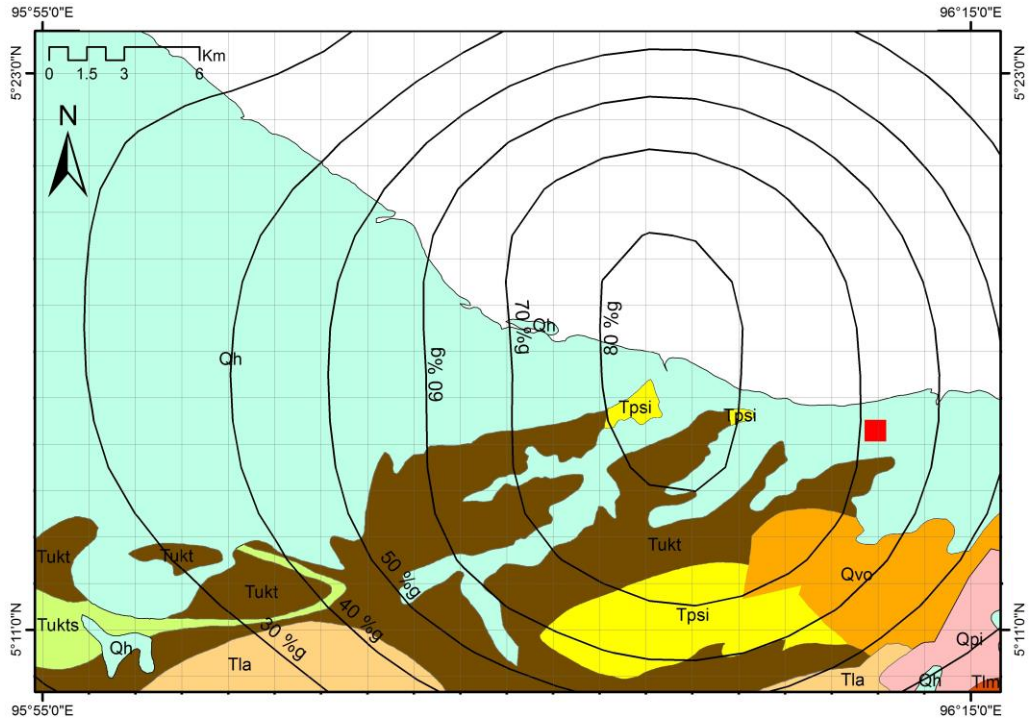


Figure 7. (a) PGA profiles of site response analysis, and (b) Amplification profiles of site response analysis.



(a)



(b)

Figure 8. Estimated (a) PGA and (b) peak spectral acceleration (PSA) of Pidie Jaya earthquake by USGS [20] incorporated geological characteristics [23] and [24]. The red box is the location of the investigated site.

5. Conclusion

A case study involving ground response analysis at the affected area of the 2016 Pidie Jaya earthquake was presented. This site response analysis involved the input parameters of four earthquake motions, a 1D developed soil profile and three types of modulus and damping curves. The results of these ground response analyses show that the PGA is up to 0.56g. The estimated PGA amplification at the ground level is up to 5.4. Average spectral acceleration with a 5% ratio of critical damping in the range of period from 0.1 and 0.60s is about 1.0g. A comparison of PGA and peak spectral acceleration of this study with USGS estimation confirms the reasonably good agreement.

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