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Estimation of Strong Ground Motion along the Sagaing Fault Zone, Mandalay Region

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ABSTRACT. Over the past three decades, urbanization in Myanmar has been rapidly increasing. In most cities throughout the country, this urbanization took place with minimal consideration of building codes, sound construction and urban planning practices. In addition, the impact of potential future natural disaster events was never considered. As a result, many of Myanmar's urban cities developed in the proximity of active seismic sources and are at risk of experiencing earthquake events. These seismic sources include the Sagaing and Kyaukkyan faults, which are known to have produced significant earthquakes in the past. The Mandalay region lies very close to the dextral Sagaing fault. In the historical record, several earthquakes happened in and around the Mandalay region from the beginning of the year 1400. Among them, the most distinct event is the Sagaing earthquake that struck on July 16, 1956. This research was designed to identify possible seismic sources in the Mandalay region and then to develop a national seismic hazard map. These national seismic hazard maps would, in turn, identify an area or a city where a detailed seismic risk assessment study has been carried out. Mandalay region, a highly populated city and a commerce hub in the central region of Myanmar, was chosen as a pilot region for study because of its proximity to the Sagaing fault. This research mainly focuses on the results of the microtremor survey at 143 sites and 25 data points from the boreholes for the determination of sediment thickness characteristics and strong ground motion analysis in the Mandalay region. For the accurate prediction of earthquake ground motions, the investigation of three elements in its process, namely the source, path, and site effects, is crucial, and their accuracy and reliability should be evaluated. The subsurface profiles, predominant periods, shear wave velocity structures and information about sediment thickness or depth of engineering bedrock were evaluated based on data from boreholes, microtremor survey and laboratory results, combining with an inversion program. The shear wave velocity of the top layer is $Vs \leq 190$ m/s. The spectral amplitudes of the estimated strong ground motions were smaller at around 0.5 Hz and larger at around 8 Hz in the Mandalay region. The peak ground acceleration becomes more than 0.8 g in the Mandalay, Kyaukse, Meiktila, Myingyan, and Yamethin districts of the Mandalay Region along the Sagaing Fault Zone, which causes severe damage to buildings with high probability.

Keywords: Microtremor · Boreholes · Sagaing Fault.

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1 Introduction

This research was designed to identify possible seismic sources in the Mandalay region and then to develop a national seismic hazard map. These national seismic hazard maps would, in turn, identify an area or a city where a detailed seismic risk assessment study has been carried out. Mandalay region, a highly populated city and a commerce hub in the central region of Myanmar, was chosen as a pilot region for study because of its proximity to the Sagaing fault. The Sagaing fault is one of the strike-slip faults of Southeast Asia, bisecting Myanmar from north to south (Win, 1970). The fault is the principal right-lateral boundary between the Sunda and Burma plates (Myint *et al.*, 1991; Hla, 1987). Its southern terminus is at the Andaman Sea spreading system, and its northern end fans out towards the Eastern Himalayan syntaxis. The Nakamura technique (Nakamura, 1989), also known as the H/V ratio method, is a widely used passive seismic technique for obtaining overburden sedimentary layer thickness by researchers. In this technique, three-component microtremor recording is carried out at a given site. In this research, we have computed the shear wave velocity structure and seismic hazard assessment of the Mandalay region using empirical Green's function between standard penetration test blow counts (NSPT) and shear wave velocity. We have created a borehole log database, which provides information about the soil strata along with the NSPT value. At some of these borehole locations, we have also conducted microtremor data analysis of surface waves for obtaining shear wave velocity. We observed that the average shear wave velocity for overburden soil in the Mandalay region varies between 180 and 360 m/s. The main goal of the new measurements was the determination of the shear-wave velocities, fundamental frequencies, engineering bedrock, soil distribution, peak ground acceleration and strong ground motion throughout the Mandalay region, since they are very important parameters for site response analysis.

2 Base Map Development

Spatial databases have been developed for the Mandalay region in this research and used as base maps to assist the seismic risk assessments of the study area (Figure 1). Overall, important physical features of the Mandalay region were considered during the basement development with a digital elevation model. Base maps have been developed from existing maps, namely Myanmar Datum 2000 maps from the Survey Department. Quickbird Satellite images for the Mandalay region were collected and utilized to ensure the accuracy in basemap development. The following is the metadata of the Quickbird image used for the base map of the Mandalay region (Table 1).

3 Microtremor Survey and Data Collection

For obtaining the calibration relation between soil thickness and its resonant frequency, the following procedures were adopted:

a. Recording microtremor data and obtaining the frequency of the H/V spectral peak.
b. Finding the bedrock depth or soil thickness from the borehole log (Kramer, 1996).

A three-component accelerometer with data logger, SMAR 6A3P, produced by the Mitsutoyo Co. Ltd., was used. Observations were done in the daytime at places away from noise sources such as vehicle traffic. In this research, 143 microtremor surveys were performed that sampled every district of the Mandalay region (Figure 2). These observations were carried out from 28th July 2019 to 20th March 2020. The two horizontal (NS and EW) and the vertical (UD) components were recorded simultaneously for 20 minutes with a 100 Hz sampling frequency. With the complement of the pre-existing borehole data, microtremor records and the seismic hazard assessment of the Mandalay region is developed by using the current measured microtremor analysis.

4 Geophysical Approach

The spectral ratio of horizontal and vertical motion obtained by microtremor observations is called the H/V spectrum. The predominant period is defined as the period of vibration corresponding to the maximum value of the Fourier

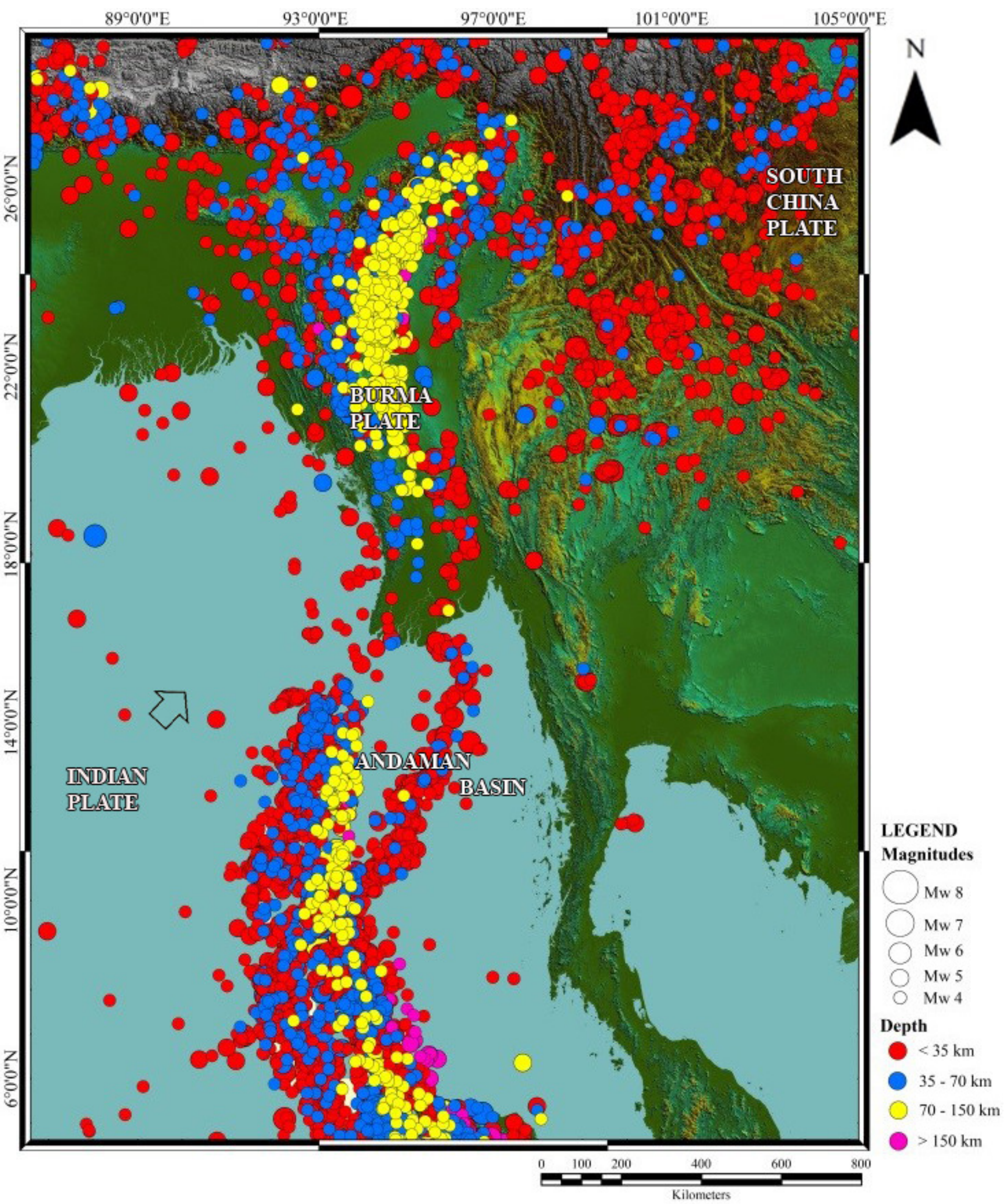

FIGURE 1. Seismicity map showing the distribution of the epicentres of the significant recorded earthquakes in Myanmar and the surrounding area (U.S. Geological Survey, 2023).

TABLE 1. Metadata of Satellite Images used for base map generation at Mandalay Region, Myanmar.

Satellite Image	Acquiring Date	Band & Resolution	Projection System & ellipsoid
Quickbird Image & DEM	1-3-2019	R/G/B (3 Band) - Resolution 0.6 m	UTM 47N, WGS 84

amplitude spectrum. It is a single parameter that provides a useful, although somewhat crude, representation of the frequency content of a ground motion. The predominant period is generally obtained from a smoothed spectrum so that the undue influence of individual spikes of the Fourier amplitude spectrum can be avoided. The predominant period of an H/V spectrum is thought to be equivalent to the predominant period of the ground directly beneath the site (Nakamura, 2000). H/V spectra at each site in the target area were calculated. The H/V spectra are classified into three types according to the shape of the spectra.

Type A: with a short period peak (Figure 3a)

Type B: with long period peak (Figure 3b)

Type C: those without clear peaks (Figure 3c)

Equation 1 shows the method used to calculate HVSR using the observed records.

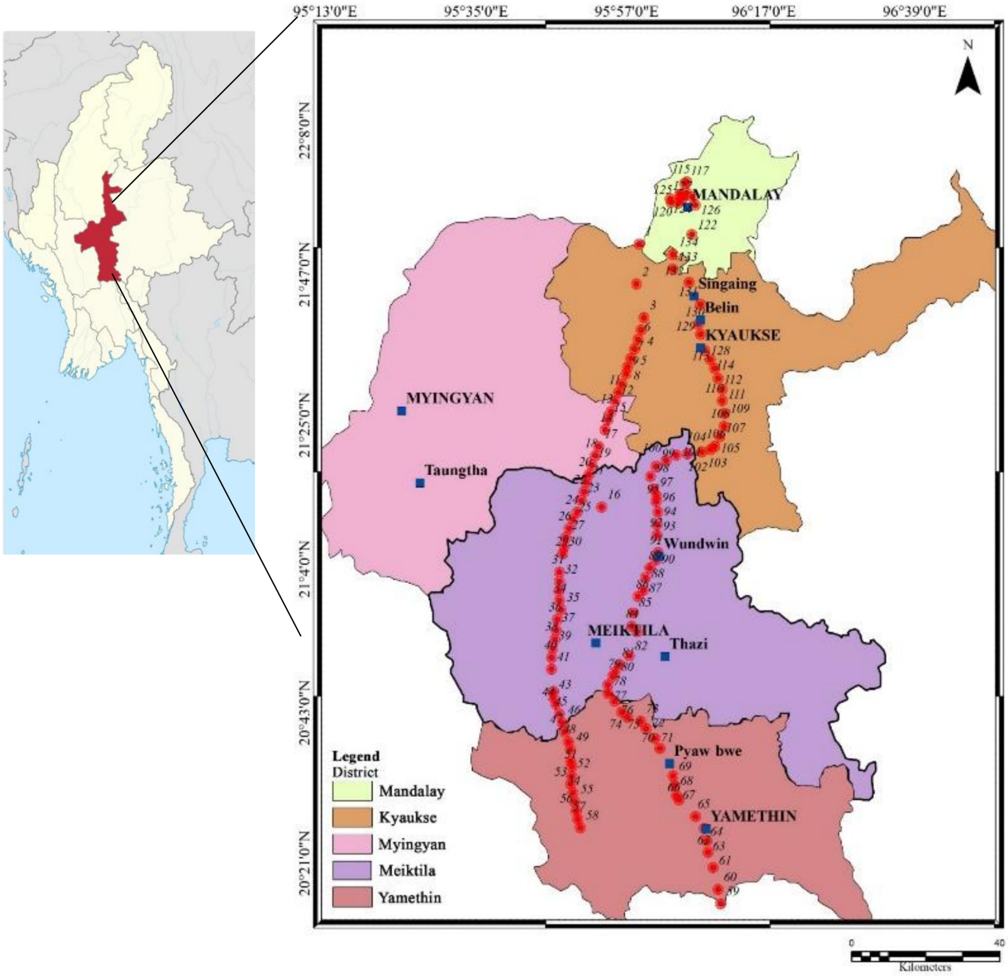

FIGURE 2. Location of microtremor survey sites in Mandalay Region, Myanmar.

$$HVSR = \frac{\sqrt{(F_{NSi}(\omega))^2 + (F_{EWi}(\omega))^2}}{F_{UDi}(\omega)} \quad (1)$$

Where $F_{NSi}(\omega)$ and $F_{UDi}(\omega)$ denote the Fourier amplitude of the NS, EW and UD components of each interval, respectively, and (ω) is the frequency.

Distinct peaks express the characteristics of the layers for which the shear wave velocity is quite different. The shorter and longer periods correspond to a shallow and a deep soil layer. Types A and B reflect the effect of the shallow and the deep soil layer, respectively. Type C is an observation site that has hard soil. Thus, it was established that the data for both long and short predominant periods was established. Although the predominant period does not always indicate the characteristics of an individual layer because typically the actual shaking mode of the ground is complex, it was assumed that the long and short periods reflected information from each layer (Pyi *et al.*, 2018 and Pyi *et al.*, 2013). Although there are 143 observation points, the points are not adequate to cover the target area. If each value of the predominant period obtained is considered to be a realization of a stochastic random field. Space interpolation is conducted by the ordinary kriging technique (Kiyono, 1996). The frequency of calculated peak H/V ratio at each site is in good agreement with observed microtremor results (Figure 4).

5 MODELLING OF SEDIMENTARY LAYERED MEDIA

The peaks in the short and long periods of the observed H/V spectrum could be explained by the estimated subsurface soil structure. In this research, it was used the two distinct peaks in the observed H/V spectra and Vs structure obtained by microtremor observation were

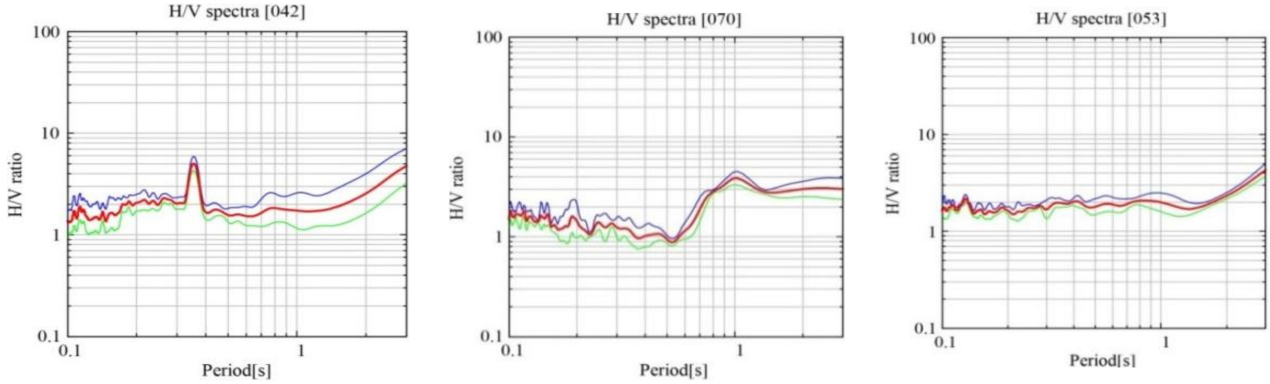

FIGURE 3. Example of the H/V Spectrum ratio (mean value and 1σ). (a) short period peak, (b) long period peak, (c) without a clear peak.

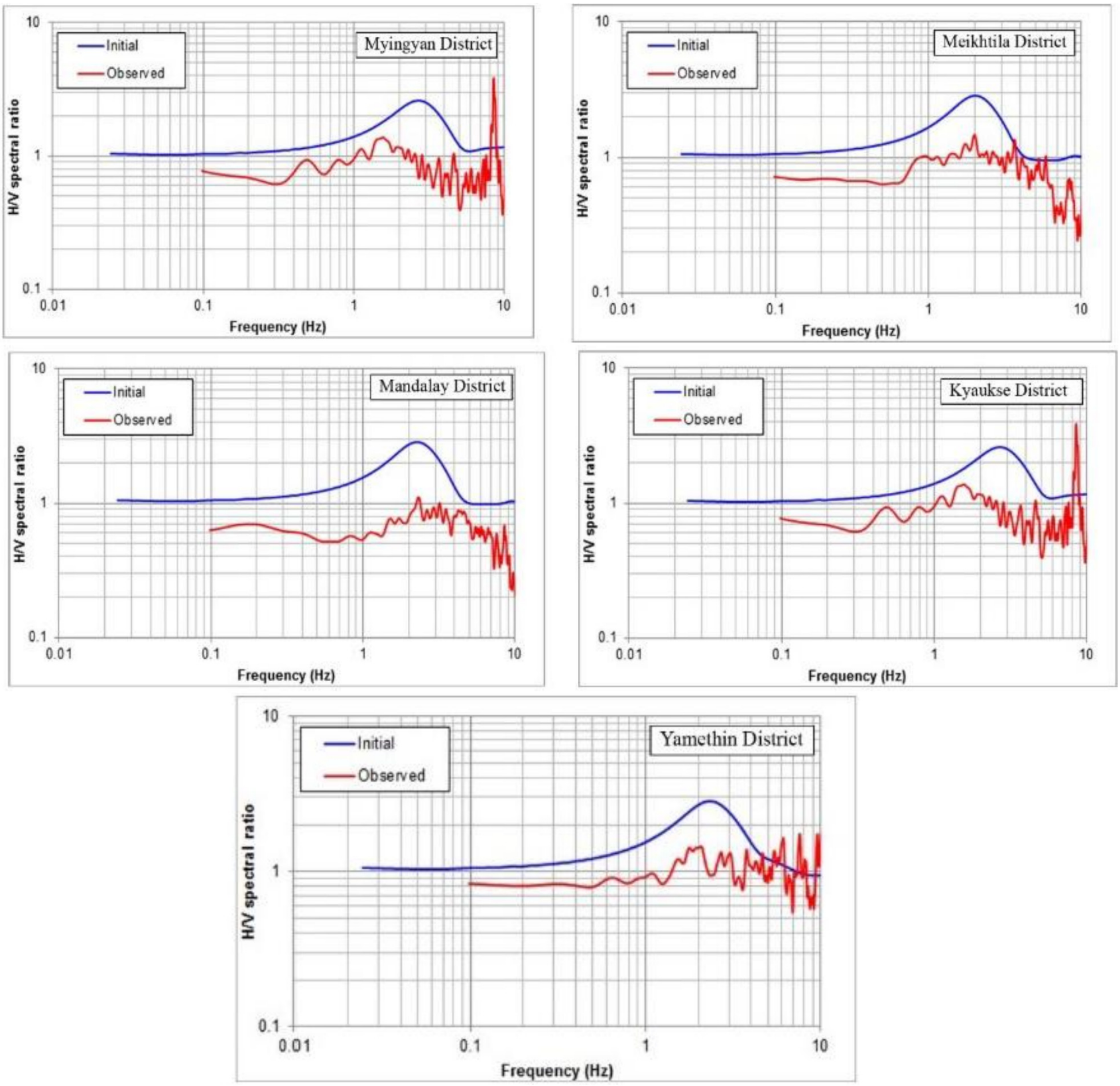

FIGURE 4. Modal HVSR and frequency response of the structure at various levels of the Mandalay Region, Myanmar (initial as blue line, observed as red line).

used. The technique used was the 1/4 wavelength principle, which can approximately be extended to multilayered media (Pyi *et al.*, 2021; Michael *et al.*, 2025).

$$H = \frac{1}{4} Vs \cdot T \qquad (2)$$

where H is the thickness of a layer. The ground was divided into three layers: the upper two layers and a base semi-infinite layer. The range of the shear wave velocity for the first, second and third layers is assumed (I) Vs $\leq$ 190 m/s, (II) 450 $\leq$ Vs $\geq$ 1300 m/s and (III) Vs $\geq$ 1300 m/s. According to the Kriging technique, the values of predominant periods, Ts, at the center of each mesh are interpolated by using a finite number of peak periods read from the observed H/V spectrum. The shear wave velocities, Vs, of layer-I and layer-II are calculated by the weighted average, for which the weight is the reciprocal of square of distance from the microtremor observation points (Bernard, 2012), Mandalay region, as where i defines the array site (i=1,2,. . . ,7), and xi indicates the distance between an microtremor observation site and the center of the mesh. The distribution of thickness for the first layer, for which Vs is $\leq$ 190 m/s in the Mandalay region, is shown in Figure 5, in which the rapidly varying area of the subsurface condition and dense observation area are enclosed. Since most of the boreholes were drilled for civil engineering purposes, they generally do not extend beyond the Quaternary deposits. Only a few penetrate deeper to reach the underlying Pliocene materials, which form the geotechnical substratum of the area.

6 SEISMIC MICROZONATION

The strong ground motion and amplification characteristics in the Mandalay region had been computed by using synthetic waveforms of the 1956 Sagaing earthquake as input bedrock motion below the alluvium sediments. This function accounts for a different travel path through the heterogeneous geology. The Irikura's computer code was used to generate synthetic waveforms, mainly based on epicentral distance, magnitude and focal depth of earthquake (Irikura *et al.*, 2001). The USGS epicentre, magnitude Mw 7.1 and focal depth 25 km are used

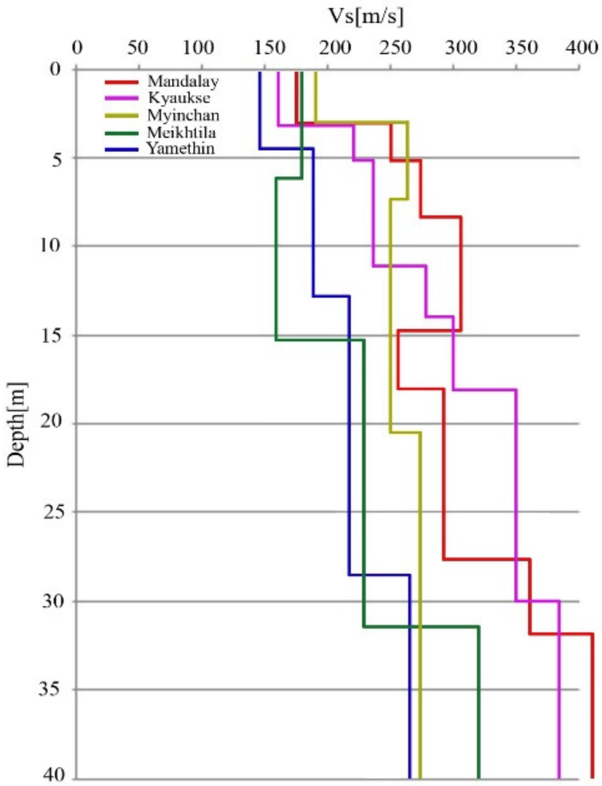

FIGURE 5. The evaluated Vs profiles at Mandalay Region, Myanmar.

for the calculation of synthetic accelerograms at 143 sites where microtremor measurements were conducted and interpolated kringing sites in the Mandalay region. In this study, a ground model is constructed by combining a layered model and an average seismic bedrock model used in Myanmar (Table 2). The Sagaing Fault is a major fault in Myanmar, a mainly continental right-lateral transform fault between the Indian Plate and Sunda Plate (Figure 6).

6.1 Peak ground acceleration at Mandalay District

A very strong seismic zone occupies the alluvial deposits and is close to the Irrawaddy River. This zone also sporadically occurred at the western most part of Mandalay City, showing very high PGA values greater than 0.8 g. The strong seismic zone is covered at the western part of Mandalay City shows high PGA values are 0.6 to 0.8 g. The moderate seismic zone, which covers the central part of the Mandalay district shows moderate PGA values are 0.3 to 0.5 g. The low seismic zone occurs at the northeastern part of Mandalay City, showing low

TABLE 2. Macroscopic source parameters for Mandalay Region, Myanmar.

Latitude (°)	96°	Moment magnitude	Mw = 7.1
Longitude (°)	22°	Fault area (km^2)	8000
Top depth d (km)	0	Shear wave velocity (km/s)	3
Bottom depth (km)	25	Mean density ρ (t/m^3)	2.9
Length L (km)	200	Modulus of rigidity mu μ (N/m^2)	2.39E+10
Width W (km)	40	Average slip (m)	0.46
Strike (°)	320.1°	Rupture velocity V_r (km/s)	3
Slope (°)	90	High-frequency limit (Hz)	20
Slip angle (°)	0°		

PGA values are 0.2 to 0.1. A very low seismic zone occurs at the north-eastern part of Mandalay City, showing low PGA values less than 0.1 g (Figure 7a).

6.2 Peak ground acceleration at Kyaukse District

A very strong seismic zone is mainly occupied by the alluvial deposits and is close to the Myitnge River. This zone also sporadically occurred at the western part of Kyaukse, showing very high PGA values greater than 0.8 g. The strong seismic zone is covered in the central portion of Singaing, Belin, and Kyaukse show high PGA values are 0.6 to 0.8 g. The moderate seismic zone, which covers at 7.5 km from the eastern part of Singaing, Belin and Kyaukse, shows moderate PGA values are 0.3 to 0.5 g. The low seismic zone occurs along 15 km from the eastern part of Singaing and Belin, showing low PGA values are 0.2 to 0.1. A very low seismic zone occurs along the north-eastern part of Kyaukse district, showing low PGA values are less than 0.1 g (Figure 7b).

6.3 Peak ground acceleration at Myingyan District

A very strong seismic zone is mainly occupied by the alluvial deposits and is close to the Sagaing Fault. This zone also sporadically occurred at the easternmost part of Myingyan district, showing very high PGA values greater than 0.8 g. The strong seismic zone is located 39 km from Myingyan, showing high PGA values are 0.6 to 0.8 g. The moderate seismic zone, which is located 26 km from the Taungtha, shows moderate PGA values are 0.3 to 0.5 g. The low seismic zone occurs along Taungtha and 7 km from the eastern part of Myingyan, showing low PGA values are 0.2 to 0.1 g. A very low seismic zone occurs along the western part of Myingyan, showing low PGA values are less than 0.1 g (Figure 8a).

6.4 Peak ground acceleration at Meiktila District

A very strong seismic zone is mainly occupied by the alluvial deposits and close to the Thin bon Chaung. This zone also sporadically occurred at the Wundwin, Thazi and 3 km from the eastern part of Meiktila, showing very high PGA values greater than 0.8 g. The strong seismic zone is covered at Meiktila and 7 km from the eastern part of Wundwin and Thazi, showing high PGA values are 0.6 to 0.8 g. The moderate seismic zone, which covers at western part of Meiktila and 10 km from the eastern part of Wundwin and Thazi, shows moderate PGA values are 0.3 to 0.5 g. The low seismic zone occurs along 22 km from the eastern part of Thazi, showing low PGA values are 0.2 to 0.1 g. A very low seismic zone occurs along the eastern most part of Meiktila district, showing low PGA values are less than 0.1 g (Figure 8b).

6.5 Peak ground acceleration at Yamethin District

A very strong seismic zone is mainly occupied by the alluvial deposits and is close to the Sagaing Fault zone. This zone also sporadically occurred at Pyaw Bwe and Yamethin, showing very high PGA values greater than 0.8 g. The strong seismic zone is covered at 9 km from the west of Pyaw Bwe and 6 km from the east of Yamethin, showing high PGA values are 0.6 to 0.8 g. The moderate seismic zone, which covers at 14 km west of Pyaw Bwe and 12 km east of Yamethin, shows moderate PGA values are

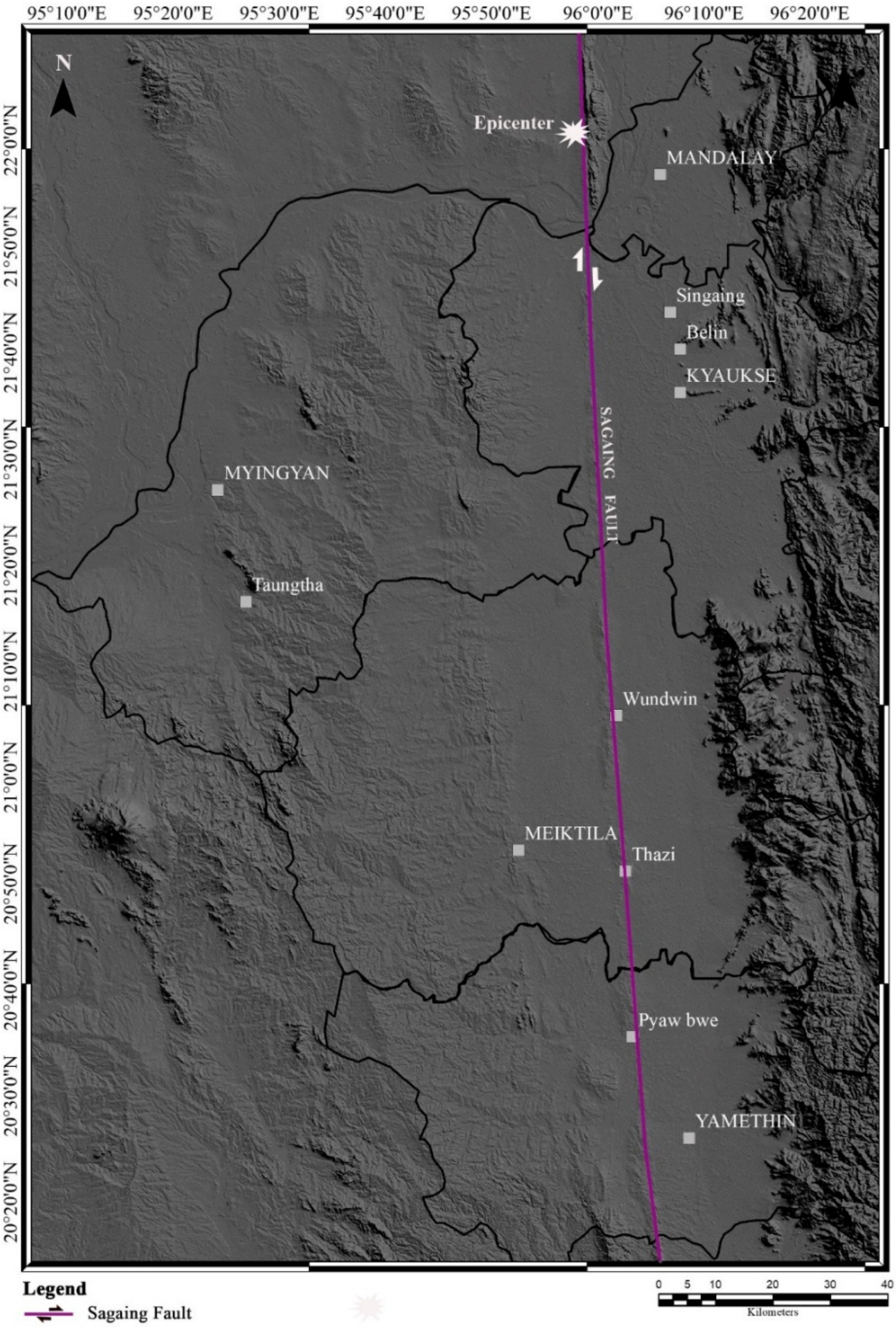

FIGURE 6. Map of the Sagaing Fault zone.

0.3 to 0.5 g. The low seismic zone occurs at 24 km west of Pyaw Bwe and 18 km east of Yamethin, showing low PGA values are 0.2 to 0.1 g. A very low seismic zone occurs along the eastern and western most part of Yamethin district, showing low PGA values are less than 0.1 g (Figure 9).

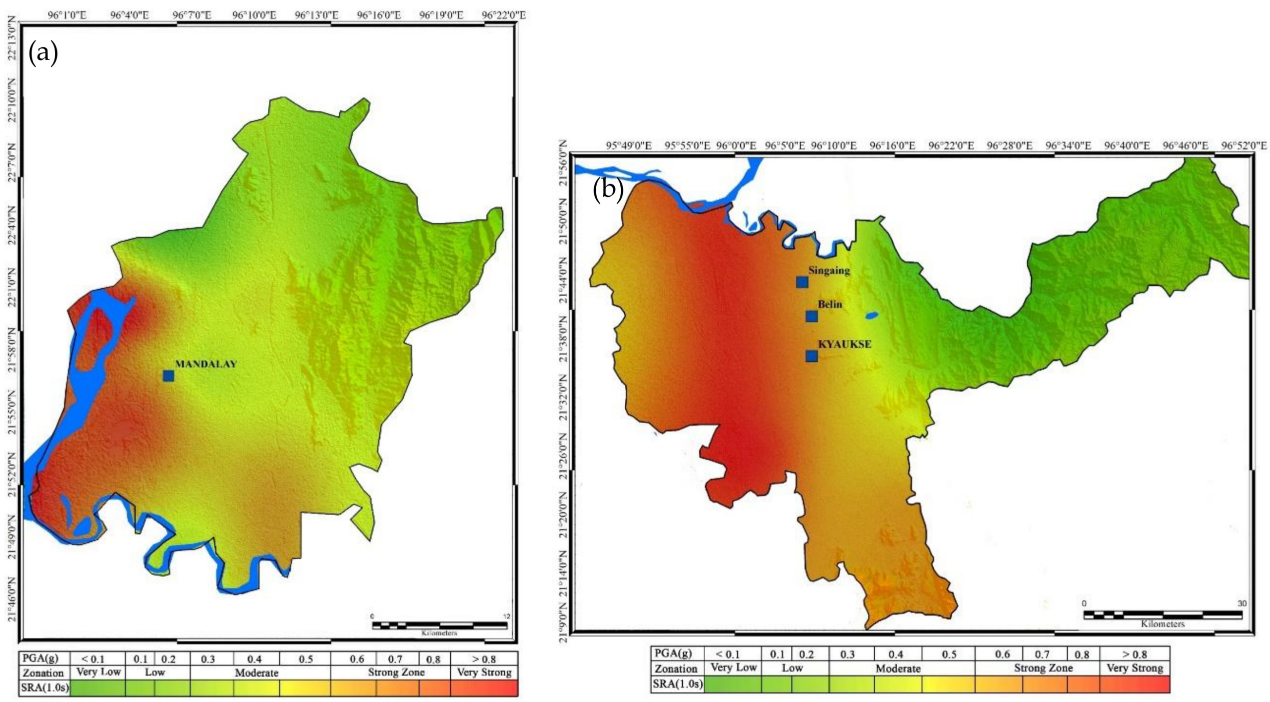

FIGURE 7. (a) Peak Ground Acceleration map at Mandalay district (b) Peak Ground Acceleration map at Kyaukse district.

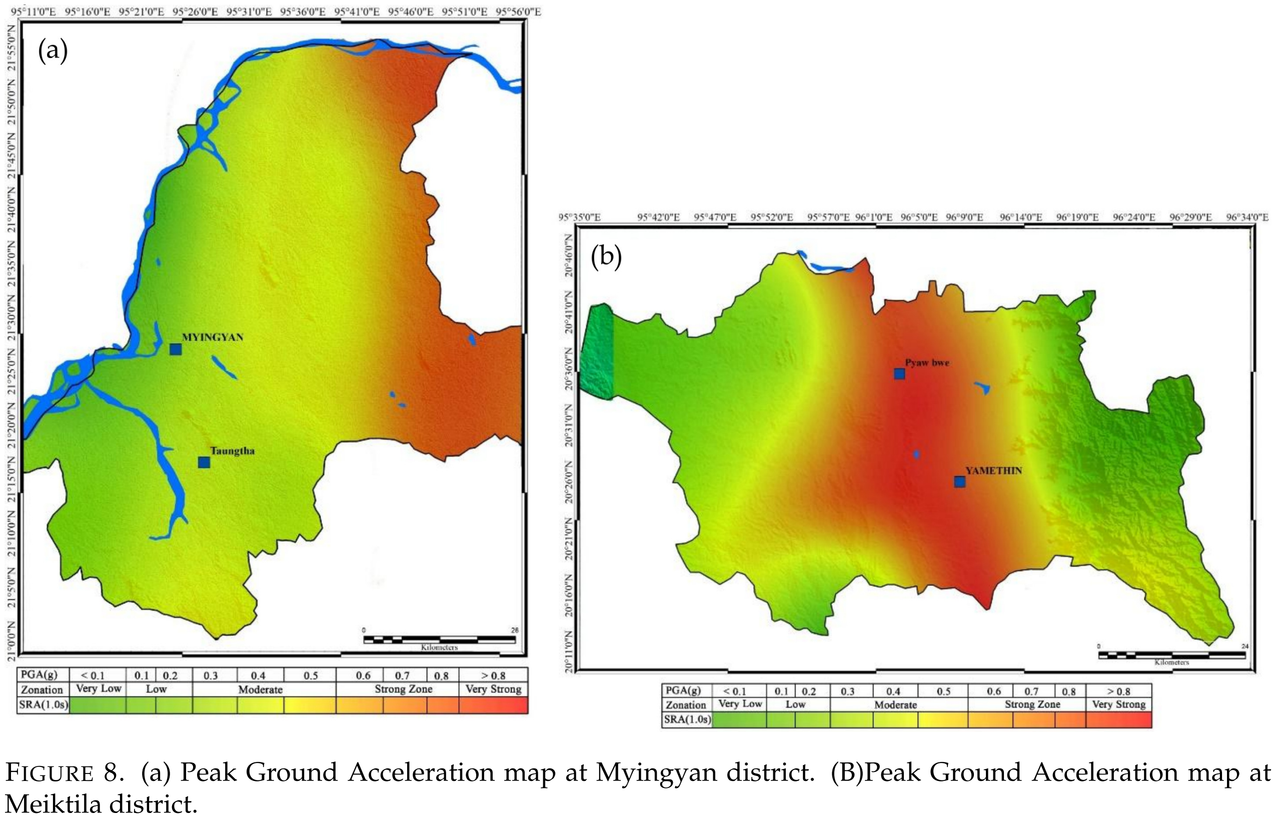

FIGURE 8. (a) Peak Ground Acceleration map at Myingyan district. (B)Peak Ground Acceleration map at Meiktila district.

7 CONCLUSION

This research mainly focuses on the results of strong ground motion analysis based on boreholes and microtremor data in the Mandalay region. Based on 25 drill core data and SPT results, the simplified subsurface soil layers were evaluated. A microtremor survey was conducted at 143 sites in the Mandalay region. A total of 25 boreholes were drilled in

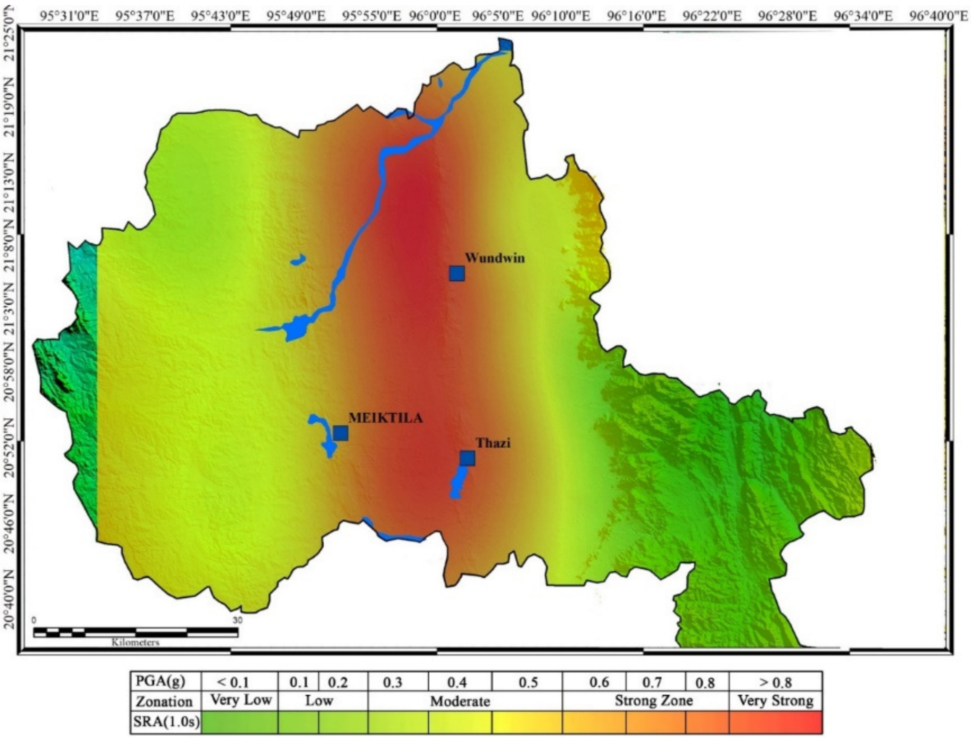

FIGURE 9. Peak Ground Acceleration map at Yamethin district.

the area for geotechnical and hydrological investigations. These boreholes provide valuable data on the thickness of Quaternary sediments, which varies from a few meters to about 80 meters near the Irrawaddy River of the Mandalay region. The inversion and H/V program were used for the determination of sediment thickness by microtremor observation. The H/V ratio, dispersion curve, and its phase velocity had been calculated by using preliminary S-wave velocity structure together with thickness, depth and unit weight of each soil layer in the Inversion Program. The observed results from microtremor are more reliable, and thus calculated results are calibrated to be equivalent (maximum 2% error) by changing the S-wave velocity structure proportionally in the Inversion Program. The Mandalay region is located very close to the seismically active Sagaing Fault, which is a right-lateral strike-slip fault. The Sagaing earthquake, 1956, Mw 7.1, was first chosen and used its waveform as input motion. The synthetic waveforms of the Sagaing 1956 earthquake were generated by Irikura's Empirical Stochastic Green's Function computer code based on focal depth, focal distance and epicentral distance and used as bedrock motions in response analysis. The outputs of this research would be applicable for both engineering purposes and to integrate into public education for earthquake hazard awareness and preparedness. The trench drilling survey should be performed along the Sagaing Fault Zone. It will help to understand the paleo-earthquake and seismicity in the Mandalay region. The drilling and resistivity survey should be more thorough in the study area, and future drilling programs should be performed in the Mandalay region. It will help to understand the information on underground structures, especially for soil types and sedimentary layers overlying bedrock, like in the Mandalay region. A future large array of microtremors and geoelectric surveys should be conducted around the Mandalay region. That kind of survey is needed to prepare adequate and satisfactory input data for future seismic hazard analysis in Mandalay region.

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