The Estimation of Seismic Site Amplification of Bukittinggi City, West Sumatera, Indonesia

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Abstract
Bukittinggi city area is exposed substantial risk of both, close to seismic source line and site amplification due to soft surface sediment / soil layer. The Great Sumateran Fault (GSF) which is crossing this area, notorious as a very active seismic source. Its responsible to some major earthquake in the vicinity of the fault line. Generally, Bukittinggi area is covered by volcanic product as pumiceous tuff. We applied combined array and single station microtremor measurement to characterize near surface sediment in this area. Based on analysis microtremor single station and array using spatial autocorrelation (SPAC) method, weathered surface layer thickness is in the range of 0-108 m with shear wave velocity in the range of 62-190 m/s, while the fresh pumiceous tuff is in the range of 375-629 m/s. The estimation of site amplification in this area which is indicated by mean amplification is in the range of 1-1.95. The high amplification zone is occupies the northernmost area and some area locally in the southern part of Bukittinggi city.

1. Introduction
As a main tourism destination in Sumatera Island, Bukittinggi city is undergoing rapid development. The 25.239 km² of Bukittinggi area inhabited by 130.773 populations with annual growth rate 1.55 % [1]. Tectonically, this area is crossed by very active fault structure Sianok Segment of the Great Sumateran Fault (GSF). Some major earthquakes which were occurred due to the activity of the GSF in West Sumatera area in the last century; Padang Panjang (1926), Singkarak (1943), Pasaman (1977), Agam (2003) and Batusangkar Earthquake (2007). The last event was caused 70 casualties and more than 5 thousands building damaged.

The intensity of ground shaking during an earthquake at a specific site is affected not only by the magnitude of the earthquake and its distance to the hypocenter, but also by the local surface sediment. As compared to nearby hard rock sites, soft sediment / soil layers in the surface will amplify seismic waves and cause more ground shaking. Based on geological mapping [2], the surface lithology in this area dominated by pumiceous tuff which is predicted as product of Maninjau eruption. The fresh of this volcanic clastics is outcropped in the bottom of Sianok canyon as a massive ignimbrite tuff, while top layer in the research area generally are soil, weathered of the volcanic clastics. Physically, the soil is as soft layer, therefore its may amplify seismic wave during earthquake occurred. In order to provide the level of site amplification data for spatial planning of future urban growth, it is essential to characterize the surface soft sediment / soil in this region.
2. Data and Method

The site amplification is known as the amplitude peak of the spectrum ratio between the ground surface and the base layer, and it is influenced by several factors such as the shear wave velocity of the surface sediment and the base layer, the density of the sediment layer, and the internal damping of each sediment layer. According to Kokusho & Sato [3], the ratio of shear wave velocity between the base rock and the surface soft sediment layer is the most important influencing factor. Theoretically, the amplification in a multilayer sediment structure (figure 1) can be expressed as:

\[
A = \sum_{i=0}^{N} \left( \frac{\rho_i V_{Si}}{\rho_{i+1} V_{S(i+1)}} \right) \exp \left( -\frac{\pi f_0 h_i}{Q_i V_{Si}} \right)
\]

where

- \( \rho_i \): density of i-th sediment layer
- \( V_{Si} \): shear wave velocity of i-th sediment layer
- \( h_i \): thickness of i-th sediment layer
- \( f_0 \): resonant frequency of i-th sediment layer
- \( Q_i \): quality factor of i-th sediment layer

\[
A_2 = \left( \frac{\rho_b V_{sb}}{\rho_s V_{ss}} \right) \exp \left( -\frac{\pi f_0 h_s}{Q_s V_{ss}} \right)
\]

where

- \( \rho_b \): base layer density
- \( \rho_s \): surface soft sediment / soil density
- \( V_{sb} \): shear wave velocity of base layer
- \( V_{ss} \): shear wave velocity of surface sediment / soil layer
- \( h_s \): thickness of surface sediment / soil layer
- \( f_0 \): resonant frequency of surface sediment / soil layer
- \( Q_s \): quality factor of surface sediment / soil layer

Figure 1. Multilayer of subsurface model for site amplification calculation, the site amplification in the surface is superposition of all individual layer.

In this paper, we approach the estimation of amplification by simple 2 layer subsurface model, i.e. surface soft sediment / soil and a base layer, therefore equation (1) will be:

We applied array and single station microtremor measurement in Bukittinggi area. Array microtremor recording has been shown to provide a fair estimate of the shear wave velocity structure [4]. The spatial autocorrelation (SPAC) method was applied to array data of microtremors for determining shear wave velocity structures. This approach is one of the most effective for extracting surface wave phase velocities from ambient seismic noise [5]. To determine the geometry of the soil layer, it is important to combine the shear wave velocity profiles obtained by the SPAC method with observed resonance frequencies on horizontal to vertical spectral ratio (HVSR) results.
Array microtremor measurements were carried out in eight locations and its distributed evenly in order represent near surface properties in Bukittinggi area, generally. All of 1D velocity profiles which were inverted from the phase velocity dispersion of surface waves then interpolated to provide velocity structure, laterally.

Single station microtremor measurements were carried out in 96 points. The horizontal to vertical spectrum ratio (HVSR) is used to calculate the soft surface sediment layer's resonance frequency. Ibs-von Seht [6] found that the frequency of the main peak of the HVSR are well correlated to the sediment thickness at the site. According to another researcher, HVSR observations provide a reliable estimate of the fundamental frequency of soft sediments resonance over hard rock [7]. Mathematically, the relation between resonant frequency ($f_o$), the thickness of and the shear wave velocity ($V_{ss}$) soil layer can be expressed as:

$$\frac{1}{f_o} = \frac{4h_s}{V_{ss}}$$  \hspace{1cm} (3)

Based on resonant frequency data which is obtained from single station microtremor measurements and the shear velocity distribution the result of interpolation of shear wave velocity profiles from array microtremor measurements, then the thickness of soil layer can be mapped for all area. The combined-array and single station microtremor measurements allow to derive all parameter (Figure 2) which is needed for site amplification calculation.

**Figure 2.** The parameters for site amplification calculation of Bukittinggi area (a) resonant frequency, (b) soil thickness, (c) soil shear wave velocity and (d) base shear wave velocity. The yellow dot represents a single microtremor measurement station.
3. Result and Discussion

There is no doubt that the surface geology as one of dominant factor that effect to ground shacking intensity during an earthquake occurred. Therefore, characterization of surface sediment / soil is become a necessary requirement in seismic hazard reduction. Since the Bukittinggi region is located near the equator, the weathering intensity is high, and the weathered layer on the ground surface is thick enough. The shear wave velocity profiles in the eight sites indicate that the soil layer is relatively soft, with shear wave velocity values in the range of 61-191 m/s, and the base, which is estimated to be the fresh volcanic clastics layer, has shear wave velocity values in the range of 374-629 m/s (Figure 3). According to equation (2), the site amplification value is primarily a contribution of the impedance contrast between the base and the soil layer.

![Figure 3](image)

Figure 3. Ground profiles at the Bukittinggi area's eight sites. Soil is seen as the top layer.

The amplification value as a function of frequency in the site amplification spectrum. The maximum amplification value (peak) is correspond to resonant frequency. However, we will not use maximum amplification in this paper since maximum amplification is only valid in a narrow frequency range around the resonant frequency. Instead, we use mean amplification which is valid in the broader frequency range. The result of site amplification calculation shows that the mean amplification in Bukittinggi area is in the range of 1.0-1.91 (Figure 4). Generally, the high amplification zone is found in the northernmost part of Bukittinggi region, as well as in some areas in the southern part. This importance of site amplification indicates the level of vulnerability due to the possibility of ground shaking during an earthquake. The high amplification zone is not recommended for further development.
Figure 4. The distribution of mean amplification by soil layer of Bukittinggi area, the strong amplification zones are found in the northernmost with a few spot in the south area.

4. Conclusion
Bukittinggi area is covered by volcanic clastics, which is predicted as the product of Maninjau eruption. The result of shear wave velocity sounding by microtremor array measurements in eight sites in Bukittinggi area, its inferred that the surface ground layer are the weathered soil of volcanic clastics with shear wave velocity in the range of 61-191 m/s. The fresh volcanic clastics at the soil's base are expected to have shear wave velocity in the range of 374-629 m/s. The result of analysis shows that mean amplification value in Bukittinggi area is in the range of 1.0-1.91. The high amplification zones is in the northernmost and locally in some area in the southern part of Bukittinggi city. This site amplification data is expected used as consideration for further urban development and also for reevaluation of spatial planning.

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