Analysis of potential soil fracture based on ground shear strain values in Solok, West Sumatra

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Abstract. Research has been carried out to the identify ground fracture-prone areas in Solok City using microtremor data. Data collection was carried out for 94 points using a seismometer. Microtremor data generated was processed by the HVSR method. The results of microtremor data analysis produce parameters of seismic vulnerability, peak ground acceleration, and ground shear strain. The parameter used in determining the fracture prone area is the ground shear strain value. The ground shear strain value was generated from the parameters of seismic vulnerability and peak ground acceleration. From the results of the study, the value of the ground shear strain in the study area is high in the northeast part of Tanjung Harapan sub-district with a ground shear strain value of 0.0032–0.0080. Whereas the area with a low value of ground shear strain distribution is in the middle of Solok City, precisely in Lubuk Sikarah District with a ground shear strain value of 0.0002–0.0018. Based on these data, the central area of the Solok City precisely Lubuk Sikarah District is an area prone to ground fracturing.

1. Introduction
Solok city is by passed by an active fault in Sumatra [1]. Around this city there are several active mountains such as Mount Marapi, Mount Singgalang, and Mount Talang. One of the earthquakes that caused quite severe damage in the Solok city was an earthquake with a magnitude of 6.4 Mw in 2007, this earthquake which will later be used as a source of earthquake in this study. One effort to reduce the risk of damage due to earthquakes is to examine in more detail the characteristics of soil dynamics with the microtremor method. Microtremor method has developed rapidly, this method is widely used in the study of soil dynamics characteristics, especially for the benefit of geotechnical purposes [2], besides the microtremor method is also used to identify site effects as mitigation of seismic vulnerability in an area [3]. Microtremor data analysis was performed using the Horizontal to Vertical Spectral Ratio (HVSR) method. Microtremor measurements will produce several parameters such as the value of the maximum ground vibration acceleration (PGA) and ground shear strain (GSS). Maximum soil acceleration and seismic vulnerability index are parameters that affect the GSS value. The maximum ground acceleration is the value of the largest ground vibration acceleration that has ever occurred in a place caused by an earthquake wave, while the seismic vulnerability index is a parameter that is closely related to the level of vulnerability of an area to an earthquake. Areas that have high GSS values have the potential to experience ground movement. One phenomenon that occurs is the fracture of the soil. The phenomenon of land fracture arises when earthquakes occur and can be one of the factors increasing damage caused by earthquakes. Soil fracture is a phenomenon of
loss of soil strength due to earthquake vibrations. Factors that cause soil movement (soil fracture) are
topography of slope, soil condition (texture, layer structure), rainfall, earthquake and state of forest
vegetation [4][5]. The natural conditions in the Solok City area vary between plains and hilly with an
altitude of 390 meters above sea level (m a.s.l). The Solok City region has a varied topography
between plains and hills [6]. During 2009 in the Solok City area, 121 days of rain occurred, with an
average rainfall of 131.02 mm/d. The phenomenon of landslides has occurred in Solok City on
December 11, 2015 in Tanah Garam Village due to continuous rain for 2 hours. Some previous
researchers such as [2][7][8] have conducted research related to ground motion using microtremor
data. Because rainfall can affect the slopes indirectly to the air-pore conditions in the slope forming
material so that the slope stability is low. When an earthquake occurs on a large scale it will cause
landslides to occur. Based on the above problems, the purpose of this study is to map areas with high
GSS values as a form of mitigation of areas prone to land fractures due to earthquakes.

2. Method

2.1. Geologycal Structure
The research location in the Solok City, West Sumatra province (latitude 0º32 ″ - 1º45 ″ S, longitude
100º27 ″ - 101º41 ″ E ) with an area of 57.64 km². Microtremor measurement data is 94 data taken
using Mark L4-3D type seismometer in April to May 2015 as shown in the Figure 1.

![Figure 1. Geological map of the area and measurement points [9]]
The topographical conditions of Solok City are diverse, consisting of flat, wavy, steep, and hilly areas. To the north of the Solok City lies Singkarak Lake, to the east is bordered by the town of Sawah Lunto, to the south is bordered by the Solok district, and to the west is bordered by the Padang Pariaman district. Based on the geological map of Solok (Figure 1), then the order of the stratigraphy in Solok are shown in Table 1.

| Formation                  | Lithology                                           | Sediment                        |
|----------------------------|-----------------------------------------------------|---------------------------------|
| Alluvium (Qal)             | Clastic sedimentary (river alluvium: clay, sand, gravel, and igneous boulder) | Sedimentation / Holocene         |
| Volcanic rocks undifferentiated (QTau) | Extrusive: intermediates (lava, fanglomerate, and coluvium deposits, others) | Volcanism / Pliocene             |

2.2. Seismic Vulnerability index.

Seismic vulnerability index is a parameter that is highly related to the level of vulnerability of an area from earthquake risk threats. The seismic vulnerability and the level of earthquake risk for damage caused by an earthquake shows a linear relationship. If an area has a large seismic vulnerability index then the level of earthquake risk will also be high. In determining the value of a seismic vulnerability index of an area, the local-geological conditions level needs to be considered. The high seismic vulnerability index is usually found in areas with low dominant frequency. This means that the relatively thick sedimentary layer covering the bedrock has a high seismic susceptibility index. In thick sedimentary layers, if accompanied by a large seismic wave amplification (amplification factor), it will produce a large vulnerability index value as well. Mathematically, the relationship between seismic vulnerability index $K_g$, dominant frequency $f_o$ and amplification factor $A$ can be written as follows [10]:

$$K_g = \frac{A^2}{f_o}$$  \hspace{1cm} (1)

with $K_g$ is a seismic vulnerability index value, $A$ is amplification and $f_o$ is the dominant frequency.

2.3. Maximum Ground Vibration

Acceleration of ground vibrations is a disturbance that is examined for each earthquake, then the maximum ground acceleration or Peak Ground Acceleration (PGA) is mapped to provide an understanding of the most severe effects a location has ever experienced. The maximum ground vibration acceleration is the greatest value of ground vibration acceleration that has ever occurred in a place caused by an earthquake [11]. The greater the PGA value that has happened somewhere, the greater the danger and risk of an earthquake that might occur. Soil acceleration is the main factor affecting building construction and creates a moment of force that is distributed evenly at building points, so that ground acceleration is the starting point for calculating earthquake resistant buildings. [12] developed an empirical equation for calculating PGA in bedrock (under surface sediment layers) based on earthquake data in Japan for 30 years recorded using an accelerograph. The empirical equation is stated as follows [11]:

$$\log(a_b) = 1.3 + 0.41M - \log(R) - 0.3219M - 0.0034R$$ \hspace{1cm} (2)

where $a_b$ is the maximum ground vibration acceleration in the bedrock in gal, $M$ is the moment magnitude in Mw and $R$ respectively are the hypocenter distance with measurements in kilometers. This empirical equation only uses earthquake magnitude and hypocenter parameters with...
measurement points. This calculation does not consider soil / rock conditions at the measurement location. In fact, the damage caused by an earthquake is not only influenced by the magnitude of the earthquake and the hypocenter but also the geological conditions or structure of the surface soil layers. So that the PGA value on the surface layer alone is used in earthquake hazard analysis while the PGA value in bedrock is only used to calculate ground shear strain values such as the formulation of [10].

2.4. Ground Shear Strains

Ground shear strains describe the level of ability of the soil in an area to stretch and shift during an earthquake. Ground shear strain values can be calculated by multiplying the seismic vulnerability index value of the HVSR curve and acceleration in the bedrock. In each study of the vulnerability of an area to an earthquake the value of ground shear strain is important to assess the vulnerability of surface soil layers [13]. The large value of ground shear strain indicates that the soil layer is more easily deformed, such as soil fracture, liquefaction and landslide. While the value of a small ground shear strain indicates a stable soil layer that is not easily deformed. Formulation by [4] regarding ground shear strains is as the following:

$$\gamma = Kg \times (10^{-6}) \times a_p$$  \hspace{1cm} (3)

where $\gamma$ is the ground shear strain, $Kg$ is the seismic vulnerability index, $10^{-6}$ is set to estimate the strain value in units of $10^{-6}$ in the surface soil layer), and $a_p$ is the PGA value in the bedrock. [14] states the relationship of ground shear strain values to surface soil conditions in the Table 2.

| Table 2. The relationship of ground shear strain values to surface soil conditions [14] |
|---------------------------------|---|---|---|---|---|
| Ground Shear strain             | $10^{6}$ | $10^{5}$ | $10^{4}$ | $10^{3}$ | $10^{2}$ | $10^{1}$ |
| Soil conditions                 | Only fracture wave vibration propagation | reduction | landslide, compacting soil, liquefaction |
| Nature of soil dynamics         | Elastic | elastic-plastic | Collapse Collapses |
|                                |          | occurs quickly (accumulation effect) |

3. Results and Discussion

3.1. Seismic Vulnerability Index ($Kg$)

Seismic vulnerability index values calculated for the study area range from 4.5 to 42. The map shows that the area with the smallest seismic vulnerability index (green zone) is in the Lubuk Sikarah sub-district to the west. Whereas the high seismic vulnerability index value (red zone) is in the northeast area precisely in the Tanjung Harapan sub-district.
Figure 2. Map of the distribution of seismic vulnerability index values ($K_g$)

The high $K_g$ value in the study area is due to the geology of the area composed of a combination of the two type of sediment that is soft and thick such as colluvium, lava and fanglomerate rocks derived from alluvium fans, weathering land in the form of silt sandstone, dark brown-reddish brown. While other areas are located the green zone has a low $K_g$ value because this area has smaller amplification value so that the seismic wave amplitude is not undergoes enlargement and is not prone to deformation during the area experiencing an earthquake.

3.2. Maximum Soil Vibration Acceleration/ Peak Ground Acceleration (PGA)

The maximum ground vibration acceleration in bedrock is calculated using equation [12] with earthquake parameters that occurred on March 6, 2007, with a scale of 6.4 moment magnitude. The calculation results show that the study area are experiencing PGA values of 114 to 133 gal with a greater PGA value the closer the hypocenter. The result is consistent because the PGA value in the bedrock is only influenced by the hypocenter distance of the earthquake and the magnitude of the earthquake. The distribution of PGA values in bedrock in the study area can be seen in Figure 3. The PGA value in the bedrock will then be used in the analysis of the calculation of the ground shear strain value.
3.3. Ground shear strain (γ)

The value of the ground shear strain indicates the maximum strain experienced by the surface soil in the event of an earthquake. This ground shear strain value corresponds to the value of seismic vulnerability in the study area. The greater the ground shear strain value, the easier the surface sediment layer to stretch and shift so that deformation occurs like a landslide.

Figure 3. Map of the distribution of peak ground acceleration values

Figure 4. Map of the distribution of ground shear strain values
In this study the value of ground shear strain in the study area is between 0.00021 - 0.0080. Areas that have the highest ground shear strain values are in the northeast region precisely in the Tanjung Harapan sub-district with ground shear strain values of 0.0032 - 0.0080. While those with the lowest value are in the middle of Solok City and in the west of Lubuk Sikarah District with a ground shear strain value of 0.0002 - 0.0018. Based on the relationship of ground shear strain to the conditions and dynamics of surface soil, Tanjung Harapan District with the greatest ground shear strain value has the highest potential to experience soil fractures.

4. Conclusion
From our results the microzonation map of the study area, it can be concluded that the distribution of seismic vulnerability ($K_g$ values in the research area is the highest level at the northeast, precisely in Tanjung Harapan District and the lowest is in the middle of Solok City and west of Lubuk Singkarah District. Meanwhile, the distribution of ground shear strain values in the study area is high in the northeast part of Tanjung Harapan sub-district, and those that have low ground shear strain values are in the central area of Solok City, precisely in Lubuk Sikarah District. Areas with a high level of ground shear strain indicate that the area is likely to experience high level of fractures due to earthquakes.

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