LOCAL GEOLOGY CONDITION OF BENGKULU CITY BASED ON SEISMIC VULNERABILITY INDEX ($K_g$)

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ABSTRACT
Local geology condition has become one of the most parameters which affected damage level of earthquake. Local geology condition can be analysed based on the value of Seismic Vulnerability Index ($K_g$). The areas with high vulnerability index is estimated to have high probability of deformation an earthquake happened. Seismic vulnerability index of Bengkulu City has obtained by horizontal vertical spectral ratio (HVSR) analysis of sixty-seven micro-tremor recordings data that was installed on each geology formation types. Based on analysis result show that the seismic vulnerability index of Bengkulu city relatively heterogeneous in spite of on similar geology type. This variation was influenced by the thickness of sediment layer and the violence level of ground on the site. In general, the highest $K_g$ value is on the alluvium terraces ($Qat$) about 0.01-10.26 and the lowest $K_g$ value is on Reef Limestone ($Ql$) about 0.05-0.35. Distribution of seismic vulnerability index has compatibility with the soil surface condition visually. The highest $K_g$ value of Bengkulu city was only obtained on alluvium terraces which was estimated to have softer structure (visual observation showed the former swamp), and it had thicker sediment layer (based on $f_0$ value) than the other type of geology. This result showed that alluvium terraces has higher probability of deformation when an earthquake than others, such as the occurrence of high resonance effect, the strengthening of earthquake vibration and liquefaction. The safest area in Bengkulu city was identified on Andesit (Tpan) geology formation type.

Keywords: local geology condition, HVSR analysis, seismic vulnerability index.

INTRODUCTION
The level of risk due to the earthquake generally affected by magnitude of an earthquake, epicentre distance and local geology condition of the region. Some research suggests that the level distribution of earthquake hazard in Bengkulu city was varied despite on the earthquake epicentre and magnitude are similar relatively. It proves that the influence of geology condition of Bengkulu city should be considered carefully because it is believed that geology types have different characteristics toward responses of natural phenomena such as earthquake. The differences of geology response could be affected by rock constituent materials, the level of rock solidity and the thickness of sediment rocks. Several researches have shown that the characteristic of seismogram record become different following the geological rock types.

Seismic vulnerability index ($K_g$) is one of the simplest physical parameter that could be used to analyse the local geology condition. Seismic vulnerability index was derived from mathematical relationship between the resonance frequency and amplification factor of the ground natural vibration that obtained in horizontal vertical spectral ratio (HVSR) curve analysis. Seismic vulnerability index is going to be a parameter which describe the structure condition of surface soil layer, material composition condition of rock surface, rock solidity level and the thickness of sediment layer. The result of this research would be considered by both civil society and Bengkulu city government to choose safe location toward earthquake effect.

GEOLOGY FORMATION OF BENGKULU CITY
The level of damaged caused by earthquake is not only depend on the magnitude and distance to epicentre, but it was influenced by local geology condition [12]. The characteristic of seismogram changed toward geology types [8, 17]. It becomes an evident that geology conditions have different responses to the presence of seismic wave [2]. Bengkulu city has six types of geology formation, including alluvium ($Qa$), Reef limestone ($Ql$), swamp deposits ($Qs$), Alluvium terraces ($Qat$), andesit (Tpan) and bintunan formation ($QTb$), as shown on Figure-1.

Figure-1. Geology and administration map of Bengkulu City, modified from [5]. The most people of Bengkulu city occupies an area of alluvium terraces (green part of map).
Administratively, Bengkulu city residents (civilians and regional offices) are the most on Alluvium and alluvium terraces. The most serious damaged due to earthquake last few years was widely identified in the western part of Bengkulu city which geology formation of alluvium terraces and in others were not. This phenomenon shows that physical condition on each geology type of Bengkulu city was different.

THEORY

The geological condition is associated with the physical properties of rock such as thickness of sediment layer, the structure of surface soil layer, level of rock solidity and composition of materials [2]. This phenomenon has known as the local site effect that occurs due to the impedance contrast material layers of fine sediments above the bedrock [20]. When an earthquake, the sediment layer would be through multi-reflection of seismic wave between the bedrock and the sediment layer [19], as shown on Figure-2.

Figure-2. Illustration of the seismic waves which trapped in the glittering layer (modified from [19]).

Seismic vulnerability index is a value which describes the vulnerability level of soil layer toward surface deformation during earthquake [2]. Seismic vulnerability index could be obtained by squaring the amplification factor $A_0$ divided with the resonant frequency $f_0$ [6, 13, 14, 15, 16], is given by equation 1.

$$P_{HF} = D N \times \eta \times N_{mirror} \times A \times (1 - L)$$

Resonance frequency ($f_0$) and the spectrum peak ($A_0$) are parameters that reflects the dynamic characteristics of the surface soil layer [13]. The magnitude of the natural frequency and amplification factor are local effects that can be induced the amount of damage caused by the earthquake [18]. A reliable method to estimate the amount of the resonant frequency and amplification factor of the surface soil layer is Horizontal Vertical Spectral Ratio (HVSR) [11, 9, 13]. HVSR analysis is one of an analysis that used to estimate the characteristics of the ground motion [7].

The concept of this method is describes a local geological conditions which derived from the ratio of spectrum micro-tremor between horizontal components ($S_{H}$) and vertical component ($S_{V}$) to eliminate the effect of Rayleigh waves recorded at the surface [13]. Horizontal component consists North-South and East-West direction. The mathematical of this method shown on equation-2 and the curve of horizontal vertical spectral ratio shown on Figure-3.

$$m_{eff\_pebble} = \frac{Q}{c_{pebble} \cdot \Delta T}$$

![Figure-3. Illustration of micro-tremor spectrum that showed a peak of spectrum value and the resonance frequency.](image)

The resonant frequency was affected by the magnitude of the average velocity and thickness of the sediment layer, whereas the amplification factor was influenced by the surface area composed of soft sediments (peat and sand) [18]. The peak of micro-tremor spectrum increased on thick sediment layer and the soft material sediment [4]. In addition, the quarter sediments have a low level of solidity while tertiary aged rocks tend to be more solid and very stable against earthquake vibrations [1, 3, 10]. Relationship between resonance frequency and the thickness of the sediment layer ($H$), given by equation 3.

$$m_{pebble} = \frac{m_{eff\_pebble}}{R}$$

where, $V_{S30}$ is the average of seismic waves velocity on surface up to depth 30 meters. In shortly, the relationship between seismic vulnerability index, thickness of sediment layer, structure of the soil layer and rock solidity level to describe the physical condition of geological rocks, given by Table-1.
Table-1. Relationship seismic vulnerability index toward the thickness of sediments layer, the level of solidity and structure of a rock [2].

<table>
<thead>
<tr>
<th>$K_v$ Value</th>
<th>Thickness of sediment (H)</th>
<th>Solidity level</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>thick</td>
<td>Low</td>
<td>Soft</td>
</tr>
<tr>
<td>low</td>
<td>thin</td>
<td>High</td>
<td>Hard</td>
</tr>
</tbody>
</table>

Table-1 shows that the high index of seismic vulnerability value occur when the amplification factor is raise and the resonant frequency of the ground has narrowed. Amplification factor indicates lithological conditions such as the level of rock solidity, a rock solid increasingly greater amplification factor and vice versa. The thickness of the sediment layer has associated with the resonant frequency, the resonant frequency increased in a thin layer of sediment and resonance frequency decreases in the thick sediment layer.

RESULT AND DISCUSSIONS

Seismic vulnerability index ($K_v$) has been a parameter that describes the local geological conditions of Bengkulu city. The physical conditions of the rocks susceptible to deformation during an earthquake are characterized by high seismic vulnerability index at that point. The distribution of seismic vulnerability index Bengkulu is varied in spite of the same geology type. These variations show that the existence of irregularities in the geological conditions on each station, such as the material composition of the rock, the structure of surface soil layer, the thickness of sediment layers and rock solidity level. The measurement results have showed similar characteristics HVSR curve on the same geological rock types. The local geology condition of Bengkulu city based on seismic vulnerability index has shown on Table-2.

<table>
<thead>
<tr>
<th>Type of geology formation</th>
<th>Material compositions</th>
<th>Age</th>
<th>$H$ (in meter)</th>
<th>$A_0$</th>
<th>$f_0$</th>
<th>Site class / description</th>
<th>Probability of ground deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qa</td>
<td>Boulder, gravel, sand, silt, mud and clay</td>
<td>Quaternary</td>
<td>7.54&lt;H&lt;33</td>
<td>0.85-5.67</td>
<td>0.17-7.01</td>
<td>Partly soft soil, stiff soil and moderate soft soil</td>
<td>Medium to high</td>
</tr>
<tr>
<td>Ql</td>
<td>Reef limestone</td>
<td>Quaternary</td>
<td>9.19&lt;H&lt;19</td>
<td>0.35-1.45</td>
<td>0.05-0.35</td>
<td>Moderate soft soil</td>
<td>low</td>
</tr>
<tr>
<td>Qs</td>
<td>Sand, silt, mud, clay with plants remains</td>
<td>Quaternary</td>
<td>15.49&lt;H&lt;27.29</td>
<td>0.44-3.33</td>
<td>0.07-6.13</td>
<td>Partly soft soil and moderate soft soil</td>
<td>Medium</td>
</tr>
<tr>
<td>Qat</td>
<td>Sand, silt, clay and gravel</td>
<td>Quaternary</td>
<td>8.50&lt;H&lt;57.29</td>
<td>0.12-7.65</td>
<td>1.63-10.3</td>
<td>Majority soft soil</td>
<td>High</td>
</tr>
<tr>
<td>Tpan</td>
<td>Andesit</td>
<td>Tertiary</td>
<td>6.64&lt;H&lt;11</td>
<td>1.23-3.14</td>
<td>0.28-6.12</td>
<td>Hard soil</td>
<td>Low to medium</td>
</tr>
<tr>
<td>QTb</td>
<td>Polymict conglomerate breccia, reef limestone, pumiceous silicified wood</td>
<td>Quaternary</td>
<td>7.20&lt;H&lt;18.50</td>
<td>0.30-2.96</td>
<td>0.04-2.11</td>
<td>Partly hard soil, stiff soil and moderate soft soil</td>
<td>Low</td>
</tr>
</tbody>
</table>
Table-2 shows the physical properties of each geological formation types in Bengkulu city. Each type of geological formation has different material compositions thus it is affecting the amount of amplification factor when subjected to seismic vibrations. The magnitude of amplification factor describes the rock solidity level, hard or soft. Surface geological conditions of Bengkulu city have the conformity with the old of the rock (quaternary). High seismic vulnerability index was influenced by the high magnitude of amplification factor on a thick sediment layer. In Table-2, soft rock and thick sediment layer was identified on high seismic vulnerability index which is estimated to have a high probability of deformation when an earthquake happened.

High seismic vulnerability index of Bengkulu city has identified on Alluvium Terraces (Qat) formation, whereas in other types of geological formations is tend to be lower (Figure-4). These results were indicated that Qat formation more susceptible to deformation when an earthquake than others. Qat formation has a softer structure (based on the amplification factor value, and has a thick sediment layer, see Table-2). Based on visual observation, surface soil of Qat formation in generally is a swamp (see on outside of Figure-4). The high seismic vulnerability index on Qat formation has identified at a few points only, while the other point is low. This phenomenon illustrates that, there are some difference of geology condition such as the thickness of the sediment layer and the material composition on the same type of geology.

Figure-4. Distribution of vulnerability seismic index on each geology type in Bengkulu city. The left, top and bottom part of the map shows the results visual observation on each local geological conditions Bengkulu city. Index vulnerability index appropriate with actual field conditions. The high seismic vulnerability index value has identified at Alluvium Terraces (Qat) geology formation.
Figure-4 shows the distribution of the seismic vulnerability index on each geological type in Bengkulu city. The right part of the map shows several local geological conditions of Bengkulu city based on visual observation. Visually at the point which has high seismic vulnerability index, the structure of the surface soil tends to be soft rock and solidity levels tend to be low. Otherwise, at the point which has low seismic vulnerability index, the structure of surface soil tends to be hard and it tends to be more solid than others. High seismic vulnerability index was found majority at swamp, sand, silt and clay areas. The result of this visual observation was compatible with the calculation results as shown on Table-2 above.

Local geological formations of Bengkulu city generally in quarter except Andesite (Tpan) is a tertiary, so geologically explained that the local geological conditions of Bengkulu city have a low level of solidity. This condition has compatibility with the results of this research. Although in general Bengkulu city have a low level of solidity, the distribution of seismic vulnerability index still varied because it was affected by the thickness of the sediment layer (Figure- 5). Like as Figure-4, the formation of Qat has a relatively thick (the northern part of Bengkulu city) if it is compared to other formations. The variation of sediment layer thickness on the same geological rock types is expected effects of human activities such as soil heaping before building construction.

Figure-5. Depth of sediment layer map on each geology type in Bengkulu city. The others side of the map are visual appearances on some surface conditions on site. The deepest sediment layer has identified in the Northern of Bengkulu city, Qat formation (red color contour). While the others are shallow relatively. The thin sediment layer has spread evenly on Tpan formation, so this area is expected more safety than other formations area. The thickness of the sediment layer condition in Bengkulu city has suitability with seismic vulnerability index and the actual condition visually.
The results of this research show that Alluvium Terraces (Qat) formation has a high risk of deformation due to earthquakes such as the occurrence of high resonance, the strengthening of earthquake vibration and the occurrence of liquefaction. Another type of geological formation was estimated to relatively more secure against the risk of deformation of the surface of the soil because it has a thin coating thickness, structure of rock harder and relatively more solid than the alluvium terraces (Qat).

In this research have found that the seismic vulnerability index is able to describe the local geological conditions of the city of Bengkulu. These results have compatibility both lithology and distribution of the level of damage caused by the earthquake that occurred in recent years, namely the worst damage has occurred at the west of Bengkulu city and geological rock types of alluvium terraces (Qat).

CONCLUSIONS
Generally, Local geology old of Bengkulu city is quarter (rock solidity low level), so the variations of seismic vulnerability index were influenced by the thickness of sediment layer and the violence level of ground on the site. The distribution of seismic vulnerability index has compatibility with the soil surface conditions visually. Alluvium terraces (Qat) is a type of geology formation that estimated to have a high seismic vulnerability index in case compared to other types of formations. According the distribution of seismic vulnerability index map, the soil structure of Alluvium terraces (Qat) is expected soft relatively (based on the value A0 and visual observation) and has a thick of sediment layer, so this geology formation has a high risk probability of deformation in earthquake and the safest area in Bengkulu city was identified on Andesit (Tpan) geology formation type.

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