

IMPLEMENTATION OF SEISMIC HAZARD MITIGATION ON THE BASIS OF GROUND SHEAR STRAIN INDICATOR FOR SPATIAL PLAN OF BENGKULU CITY, INDONESIA

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ABSTRACT: Bengkulu, a city on west coast of Sumatra Island Indonesia, is very vulnerable to undergo earthquake and other natural hazards. A seismic hazard mitigation should be prioritised in this developing city. This paper presents the seismic hazard mapping on the basis of shear strain indicator for spatial plan in Bengkulu City, Indonesia. The values of ground shear strain can be the indicator for the possible damage that could occur in an area. This study was initiated by performing geophysical measurements using microtremor to obtain the geophysical description of study area. The analysis of horizontal to vertical spectral ratio (H/V) was further performed to determine peak amplitude (A_0) and predominant frequency (f_0). From those parameters, the empirical analyses of vulnerability indices (K_g) and ground shear strain (γ) were conducted. All results such as A_0 , f_0 , K_g , and γ were depicted in microzonation maps. The results showed that Bengkulu City was generally vulnerable to undergo seismic impact. The concern was focused along coastal area of Bengkulu City since the liquefaction damage could occur in this area. Results of this study could bring a recommendation to stakeholders to consider seismic hazard mitigation for Bengkulu City.

Keywords: *Earthquake, Mitigation, Shear strain, Spatial planning*

1. INTRODUCTION

The spatial plan for Bengkulu City has been composed in 2012. The spatial plan was designed for the next 20 years, i.e. up to 2032. During that period, the revision of spatial plan could be every single 5 years. Therefore, in accordance with the circumstances of significant developments in Bengkulu, the design should be revised in 2019. Another reason is because the intensity of natural disasters in Bengkulu City gradually increases every year, especially earthquakes. Seismologically, Bengkulu City is categorised as a high seismic intensity area in Indonesia [1 and 2]. Referring to this condition, the local government should be carefully considering the earthquake aspect for the spatial plan in Bengkulu City. The actions to define the spatial plan should cover safety, convenience, productivity on the basis of hazard mitigation are prioritized. Natural Disaster Agency of Bengkulu Province or BPBD [3] mentioned that the revised spatial plan is also destined to support Bengkulu City as the tourism and educating area and also as the trading area in the coastal area of Western Sumatra Island, nationally and regionally. Several studies [4, 5, and 6] suggested that the spatial plan is also able to reduce the potential risk when the hazards occurred. However, Those studies had not explained the specific natural hazards that should

be considered. In addition, those studies had not given the natural hazards indicator. Therefore, the spatial plan should consider the possible impacts of hazards.

Ishihara [7] suggested that the ground shear strain (γ) can be a parameter to determine the level of seismic vulnerability. A larger shear strain means a larger effect of earthquake and vice versa. The measurement of ground shear strain can give the interpretation for each area. It is also possible to reflect the potential damage during the earthquake [8].

This paper focuses on the possible impact of earthquake occurred in Bengkulu City. The measurements of microtremor in Bengkulu City had shown the area with the high vulnerability to earthquake [9]. The measurements had also exhibited descriptions of liquefaction potential and landslides in Bengkulu City. For Bengkulu City, the liquefaction potential was found on several areas, such as Muara Bangkahulu, Sungai Serut, and Ratu Agung Districts [10 and 11]. Nurohmah [12] and Mase and Fathona [13] also mentioned that Muara Bangkahulu, especially along Muara Bangkahulu River Watershed in Bengkulu City is very possible to undergo flooding. This area is dominated by alluvial deposit with low permeability characteristic. Considering the information of hazards vulnerable spots, BPBD of

Bengkulu City would perform the intensive study for the areas, such as housing, industry, market, governance centre. Those areas could be vulnerable to undergo seismic damage. However, the vulnerable areas would be useful to develop as the agriculture, farming, and forestry areas.

On June 4, 2000, the earthquake with magnitude of 7.9 M_w had occurred in Bengkulu City. This earthquake was also known as Bengkulu-Enggano Earthquake. The earthquake had resulted in destructive damage, as collapse of strategical buildings. Most of them were suspected to stand on the large ground shear strain sites (especially along coastal area of Bengkulu City). Several locations with high earthquakes impact had been also indicated to have large ground shear strain. Haseeb et al. [14] mentioned that the Northern Pakistan Earthquake in 2005 had destructed the areas with high values of ground shear strain. Schulz et al. [15] revealed that the earthquake on the coastal area of Oregon, USA, had triggered the landslides. In line with those studies, Chung [16], Pathak and Dalvi [17 and 18] suggested that there is a correlation between ground shear strain, shaking effect, landslide, and liquefaction. Referring to the previous studies, Bengkulu as an area with high seismic activity, could be very vulnerable to the earthquake damage. During the earthquake, a stress release between sediment layers and bedrock occurs along the subduction zone. The stress release energy is also known as ground shear strain. By knowing the information of ground shear strain in an area, the possible impact of the seismic hazard could be estimated. Method of ground shear strain inspection had proposed by Nakamura [8]. This method is very important to reach the goal of seismic hazard mitigation. The method could give the benefit, especially related to the consideration in spatial plan in Bengkulu City.

2. LITERATURE REVIEW

The ambient noise measurement using microtremor, which is aimed to observe the geophysical characteristic, has been performed by several researchers, such as El-Hady et al. [19], Kanai and Tanaka [20], and Mase et al. [21]. The method implemented in this measurement is horizontal to vertical spectral ratio (H/V), as described in Fig. 2. This method was widely introduced by Kanai and Tanaka [20]. H/V values can be obtained using the following Eq. (1),

$$H/V = \sqrt{\frac{H_{(EW)}^2 + H_{(NS)}^2}{2V^2}} \quad (1)$$

where, $H_{(EW)}$ and $H_{(NS)}$ are the horizontal spectral values in the east-west (EW) and north-south (NS)

directions, respectively, and V is the vertical spectral value.

Based on H/V interpretation, the predominant frequency (f_0) can be easily obtained, as shown in Fig. 1. This geophysical information is possible to use in determining the vulnerability indices (K_g) in observed area [8]. K_g formulation is expressed in this following Eq. (2),

$$K_g = \frac{[(H/V)_{peak}]^2}{f_0} \quad (2)$$

where, K_g is vulnerability indices, H/V_{peak} is peak of H/V ratio, and f_0 is predominant frequency.

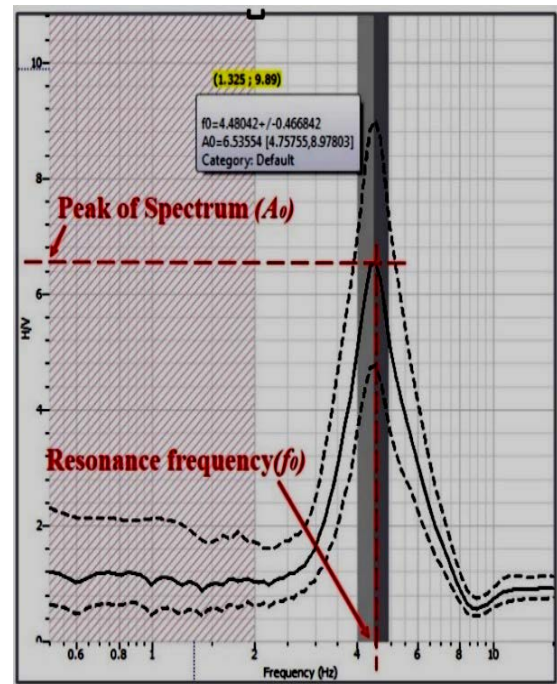


Fig. 1 The example of microtremor spectrum from H/V [22]

Nakamura [8] explained that ground shear strain is unique parameter. This parameter is strongly related to vulnerability indices. The ground shear strain values category and the possible ground failure phenomena were compiled by Ishihara [7] in Table 1. By following the ground strain dependences in Table 1, Nakamura [8] derived the formulation of γ , as shown in the following equations,

$$\gamma = \frac{K_g a_{max}}{\pi^2 V_b} \quad (3)$$

$$a_{max} (gal) = \frac{5}{\sqrt{T_0}} 10^{\left(0.61M_w - (1.66 + \frac{3.60}{R}) \log R + 0.167 - \frac{1.83}{R}\right)} \quad (4)$$

where, γ is ground shear strain of soil dynamic properties, K_g is vulnerability indices, $a_{\max}$ is acceleration of seismic wave at base rock (estimated by [23] in Equation 4), and V_b is shear wave velocity at base rock, T_0 is the predominant period (simply predicted by $1/f_0$), M_w is magnitude of earthquake, and R is the hypocentre of earthquake.

3. METHOD

3.1. Study Area and Its Geological Condition

This study is focused in Bengkulu City, Indonesia. The geologic map of Bengkulu City [3] is presented in Fig. 2. In general, Bengkulu City is composed by several geological formations. The most dominant formation in Bengkulu City is alluvium terraces (Qat). This formation is generally found along coastal area of Bengkulu City. The formation is composed by sand, silt, clay, and gravel mixtures. Along coastal area of Bengkulu City, the small part of reef limestone (QI)

formation is also found. The alluvium deposit (Qa) is generally found in the central Bengkulu City. This formation is composed by boulder, gravel, sand, silt, mud, and clay. In western and northern parts of Bengkulu City, the swamp deposits (Qs) composed by sand, silt, mud, clay, with plant remains are found. Small parts of Andesite (Tpan) and Bintunan Formation (QTb) are also found. These formations are dominated by polymictic conglomerated and igneous rock. Considering the complex geological condition in Bengkulu City, the geophysical survey using microtremor was performed. The measurement was also addressed to study the seismic vulnerability index in Bengkulu City. Total of 446 sites (shown by black triangles in Fig. 2) had been investigated. The summary of several observed data is presented in Table 2. In Table 2, the locations of investigated sites are presented. The Bengkulu-Enggano Earthquake occurred in 2000, with magnitude of 7.9 M_w was considered in the analysis. The Peak Ground Acceleration (PGA) was estimated by using Kanai and Tanaka [23] equation, and K_g and γ values were estimated by using Nakamura [8] method.

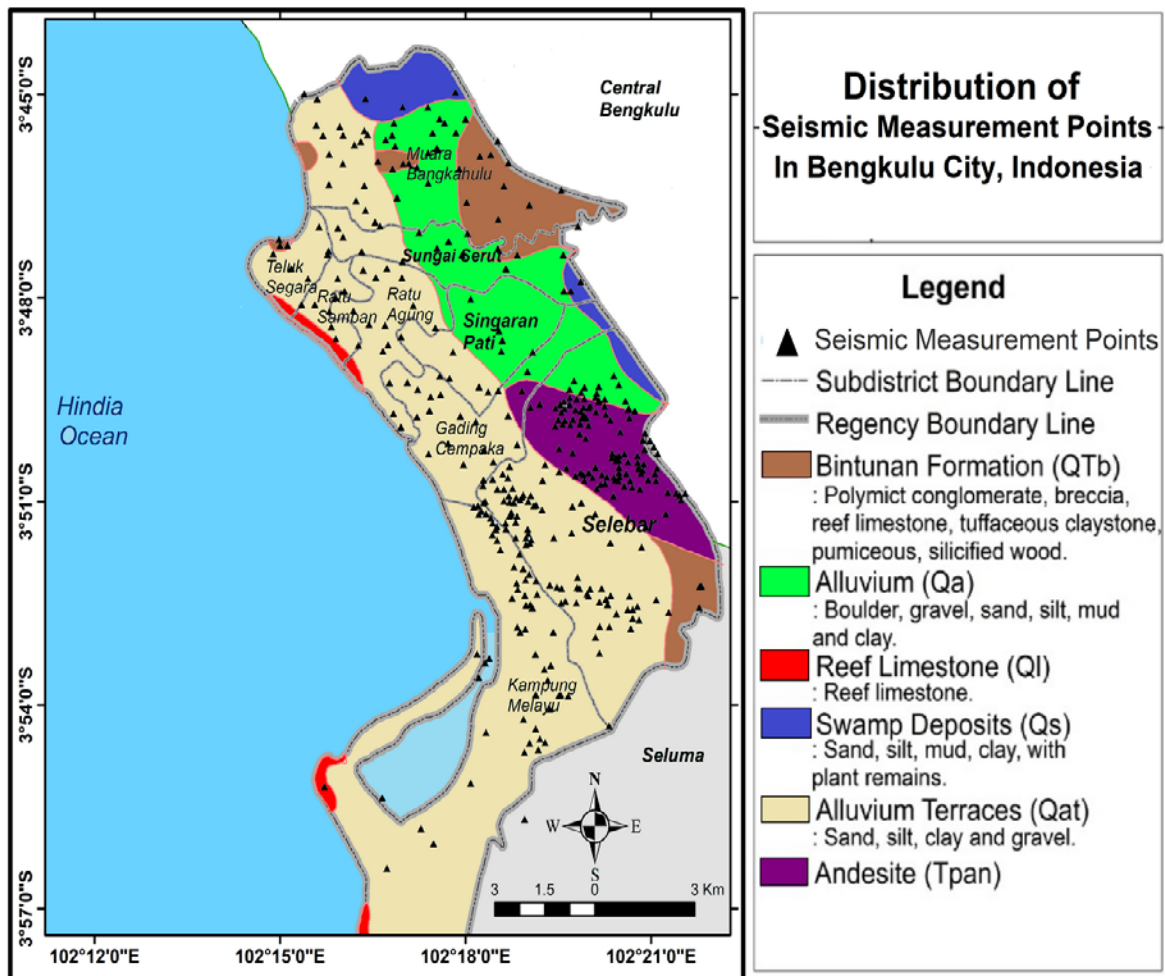


Fig. 2 Geological condition of study area [3] and distribution of seismic measurement points in this study

3.2. Analytical Procedure

A data collection, such as the geological information of Bengkulu City and the earthquake history in Bengkulu City is considered as the basis of seismic hazard study in Bengkulu City. This study was initiated by performing the microtremor measurement in the Bengkulu City. Microtremor measurements were performed by using a broad band seismometer called PASI Gemini (triaxial geophone) to record the ambient noise on the investigated sites. The measurement duration was about 30 minutes for each site. Furthermore, the ambient noise record was processed. The data processing of the microtremor analysis was performed to generate H/V by using Equation 1. From the interpretation of H/V , A_0 and f_0 values were determined. Those parameters were then analysed to obtain the vulnerability index (K_g) by using Equation 2 [8]. K_g which represented the level of vulnerability due to seismic hazard was further used to obtain ground shear strain (γ) (estimated by Equation 3). Before calculating the ground shear strain, the peak ground acceleration (PGA) on each investigated site was estimated by Equation 4. Ground shear strain parameter was then correlated by the potential hazard criteria. All results were afterwards presented in microzonation maps. In this study, four microzonation maps, i.e. microzonation map of A_0 , microzonation map of f_0 , microzonation map of K_g , and microzonation map of γ were presented. The results were elaborated with the geological condition of the study area and previous studies. In general, the results of this study could bring a recommendation for seismic hazard mitigation in Bengkulu City. The results would give information to the local people for the prospective hazards zones in Bengkulu City.

4. RESULT AND DISCUSSION

4.1. Spatial Plan Map of Bengkulu City

The spatial plan map of Bengkulu City is presented in Fig. 3. There are two major areas in Bengkulu City. They were protection area and cultivation area. For protection area, the spatial areas were utilised for natural reserved area, cultural heritage, open space for green zones, water infiltration, coastal area, and river watershed. In addition, the prone area to natural disaster was indicated on zones facing the ocean (along coastal area), while cultivating area, the priority was destined for housing area, trading area, office centre, industry, college, agricultural, informal sector, security, fisheries area, and evacuation area during the natural disaster. In general, the concentration of socio-economy in Bengkulu City was located along coastal area of Bengkulu City [1].

It implies that the local people inclined to live in the location where the local government had not recommended. During the Bengkulu-Mentawai Earthquake in 2000, the most impacted damage had been massively observed in this area, especially related to liquefaction and other geotechnical hazards, such as ground failures and ground subsidences [11]. Several conservation areas (river sub watershed) also became the most preference area in Bengkulu City [13], since the fast floods from the mountainous area also become the threat.

4.2. Microzonation Maps of A_0 , f_0 , and K_g

Fig. 4a presents the microzonation map of A_0 of Bengkulu City. In general, the amplification (A_0) of 2 to 5 were dominant in Bengkulu City, especially in the geological formations of alluvium terraces and swamp deposits found. Those materials are relatively loose. Several areas with lower amplification values were found on the formations of andesite, bintunan formation, and alluvium terraces. Those areas inclined to have the high soil density. Gosar [24] mentioned that a higher amplification means a larger impedance contrast between sediment and bedrock. This parameter could be related to the possibility of seismic wave amplification during the earthquake [1]. The microzonation of f_0 based on the geophysical survey is depicted in Fig. 4b. it can be observed that the predominant frequency (f_0) of investigated sites were generally ranging from 4 to more than 6 Hz, especially for the area located near coast line of Bengkulu City. Mase [1] and Gosar [25] stated that the relatively larger predominant frequency indicated thin sediment thickness. Refrizon et al. [26] and Mase [1] also reported that the engineering bedrock along coastal area of Bengkulu City was located at about 50 m depth below ground surface. The parameters of A_0 and f_0 were further analysed to generate the seismic vulnerability (K_g) map presented in Fig. 4c. As presented in Fig. 4c, Bengkulu City has the seismic vulnerability index up to 10. Several areas with seismic vulnerability index of about 10-20 were found on some parts of along coastal area of Bengkulu City. It indicated that this area could undergo more seismic impact during the Bengkulu-Enggano Earthquake in 2000. Generally, the results of this study is in line with Mase [1] study.

4.3. Microzonation Map of γ

The microzonation map of γ overlaid by the spatial plan map is presented in Fig. 5. Three areas classifications which represented the γ range of $10^{-6} - 10^{-4}$, γ range of $10^{-4} - 10^{-2}$, $\gamma > 10^{-2}$ were presented. Those ranges were related to the soil damage phenomenon listed in Table 1. It can be

seen that the potential hazard of wave vibration could be felt by the western part area of Bengkulu City during the Bengkulu-Enggano Earthquake.

Several areas in the middle part of Bengkulu City could be possible to undergo crack and settlement during the Bengkulu-Enggano Earthquake.

Table 1 Strain Dependence of Soil Dynamic Properties [7]

Size of Strain (γ)	10^{-6} 10^{-5}	10^{-4} 10^{-3}	10^{-2}	10^{-1}
Phenomena	Wave, Vibration	Crack, Settlement	Landslide, Soil Compaction	Liquefaction
Dynamic Properties	Elasticity	Elasto-plasticity	Repeated-Effect, Speed Effect of Loading	

Table 2 Summary of Several Observed Data

Number	Station ID	Lat (°)	Long (°)	A_0	f_0 (Hz)	Magnitude (M_w)	PGA (gal)	K_g	γ
1	ST148	-3.787	102.250	5.0	9.64	7.9	691	2.6	0.00179
2	ST121	-3.767	102.267	2.3	9.60	7.9	675	0.6	0.00037
3	ST80	-3.823	102.306	3.5	9.53	7.9	703	1.3	0.00088
4	ST170	-3.758	102.316	2.8	9.40	7.9	657	0.8	0.00055
5	ST188	-3.821	102.284	4.7	9.10	7.9	688	2.4	0.00167
6	ST44	-3.812	102.271	4.3	8.95	7.9	679	2.1	0.00139
7	ST45	-3.803	102.263	2.3	8.84	7.9	670	0.6	0.00039
8	ST21	-3.798	102.267	0.3	8.75	7.9	663	0.0	0.00000
9	ST161	-3.783	102.261	5.7	8.50	7.9	645	3.8	0.00244
10	ST60	-3.861	102.347	3.3	8.31	7.9	673	1.3	0.00086
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444	SKR13	-3.839	102.339	2.1	1.2	7.9	265	3.7	0.00099
445	SKR14	-3.851	102.329	3.1	9.4	7.9	746	1.0	0.00074
446	PGD34	-3.844	102.311	4.6	5.7	7.9	579	3.7	0.00214

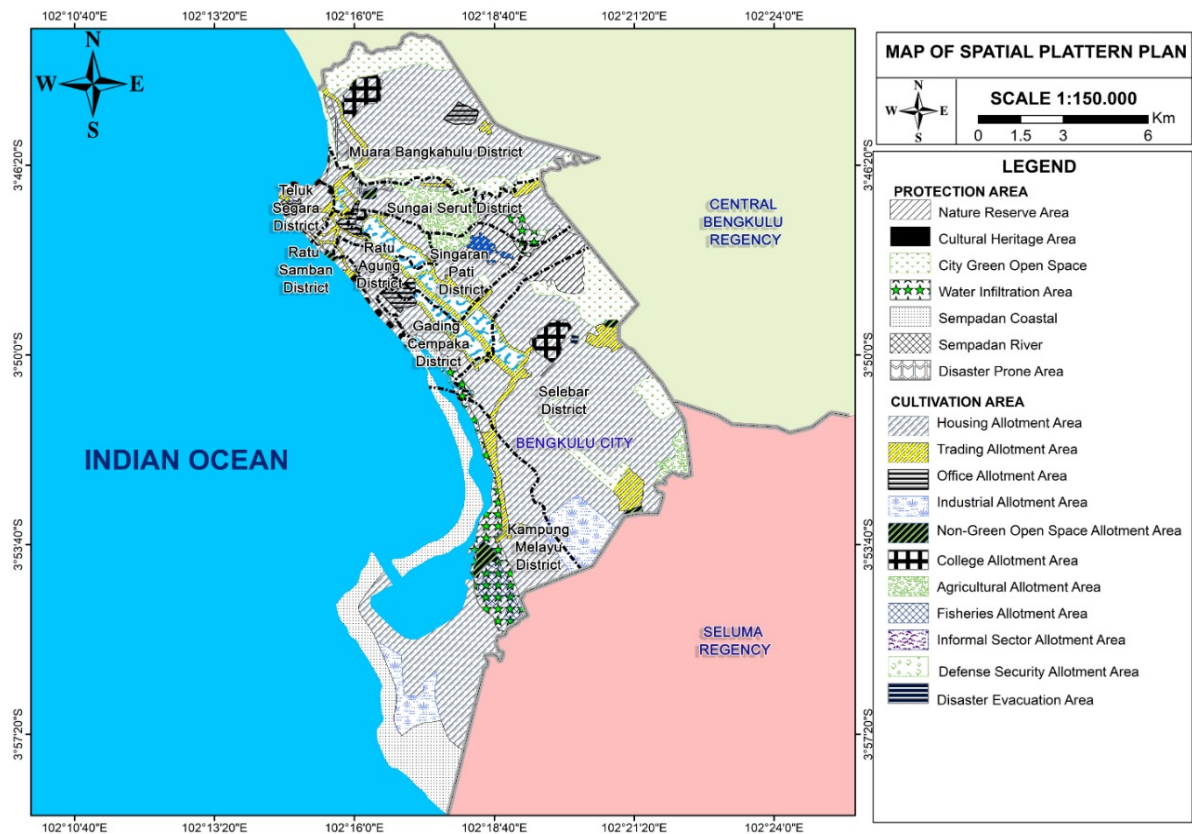


Fig. 3 Spatial plan of Bengkulu City (modified from [27])

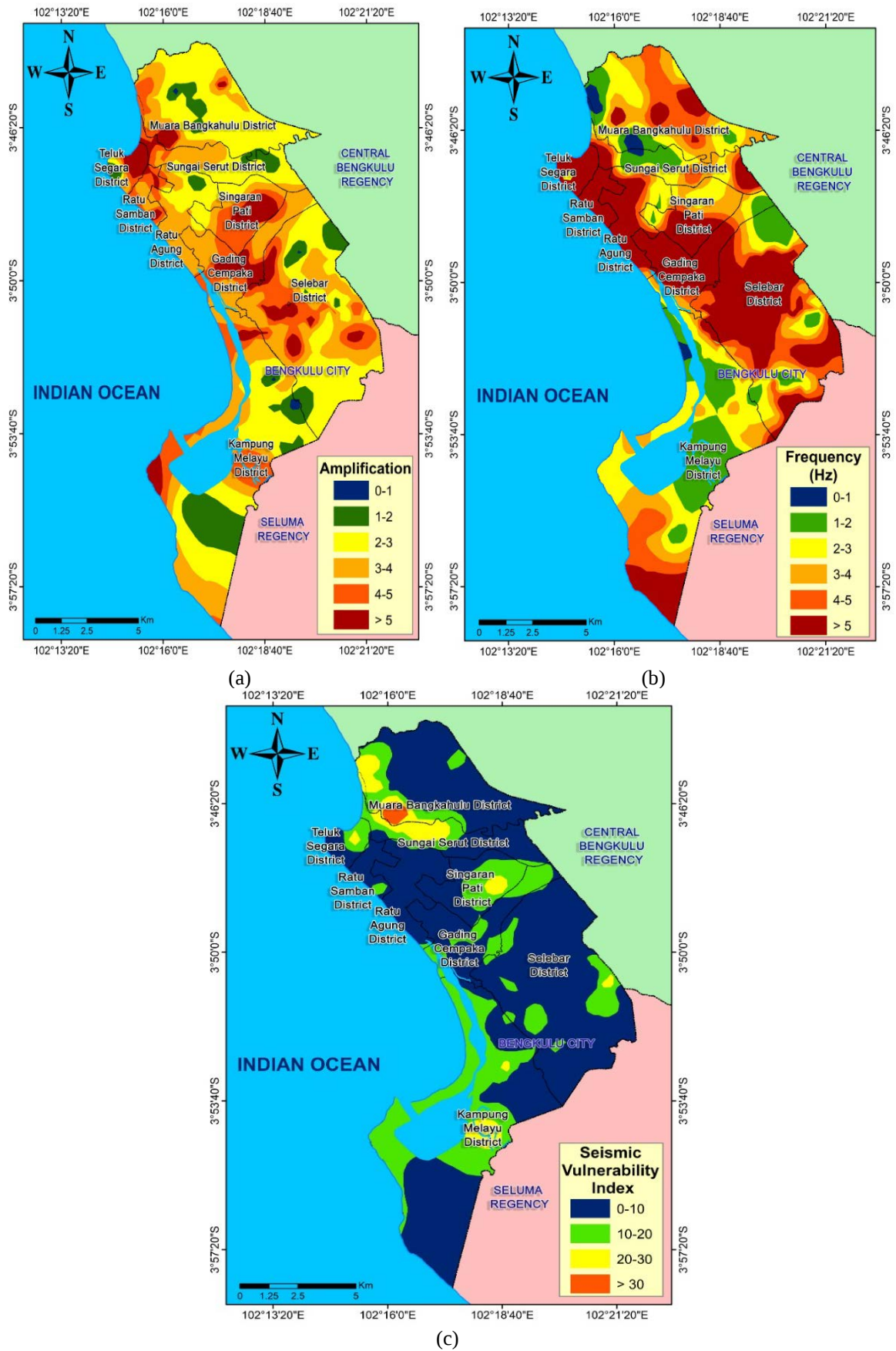


Fig. 4 Microzonation maps of Bengkulu City (a) A_0 (amplitude), (b) f_0 , and (c) K_g

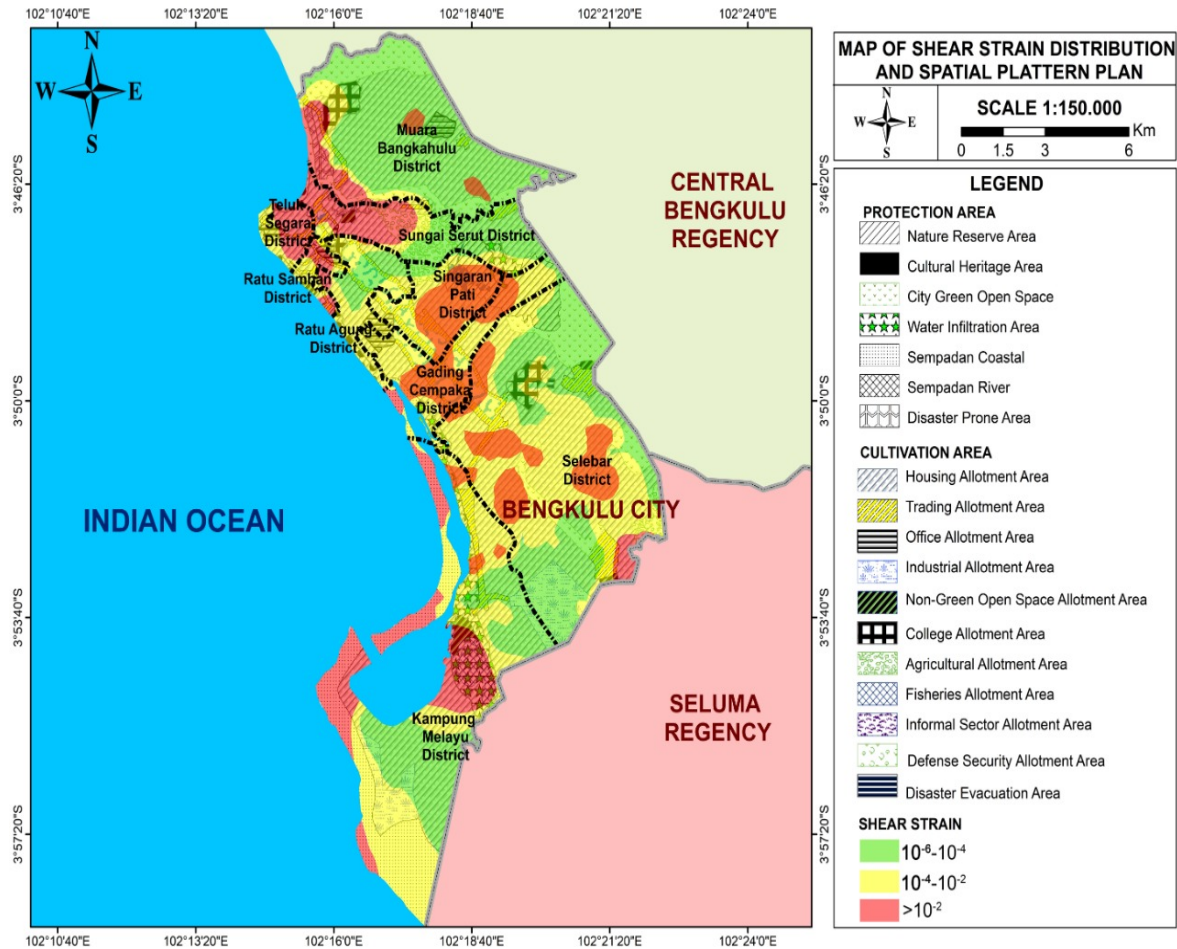


Fig. 5 The microzonation map of ground shear strain (γ)

The significant damage of liquefaction could be felt in several areas in Bengkulu City, especially along coastal area of Bengkulu City [1]. Related to map of spatial plan, housing area located in the western part of Bengkulu City is generally green zone. According to geological condition, the western part of Bengkulu City was dominated by alluvium, andesite and bintunan formations, which are also composed by the rock materials, boulders, and consolidated materials. In the middle part of Bengkulu City, the ground shear strain in this area was generally categorised as yellow zone.

According to geological condition, this area was dominated by alluvium terraces and swamp deposits, which were composed by coarse sands, silts, clays, and gravels. Those materials were found along the sub watershed of Muara Bangkahulu River. Those materials were consolidated by years [13]. However, shallow ground water level was commonly found in this location. During the earthquake, this area prone to undergo crack and settlement, but no liquefaction indication found in this area. The liquefaction hazard inclined to occur along coastal area of Bengkulu City [11]. This area was generally served

as nature reserve area, housing area, and fisheries allotment area. This area was also the socio-economy centre in Bengkulu City that the trading activity and the development of the city were centralised.

Linked to geological condition, along coastal area of Bengkulu City was dominated by alluvium terraces formation. This formation was dominated by sands, silts, clay, and gravel. Several researchers such as Mase [1 and 10] had confirmed that the subsoils along coastal area of Bengkulu City were dominated by loose sandy soils (SP) with shallow ground water level. These internal factors were indicated as the main factors of the liquefaction, during the earthquakes in Bengkulu. Those previous studies also suggested that liquefaction along coastal area of Bengkulu City could occur at shallow depth [10]. In general, the results of this study were relatively consistent as predicted by the previous studies [1 and 10]. The interpretation of microzonations based on the geophysical survey in Bengkulu City had shown that the vulnerable area to undergo seismic damage, such as liquefaction, was generally concentrated on the socio-economic centre. It indicates that the local people relatively

preferred staying in the strategic area to the relatively empty area, even if it is relatively safe from the disaster's threats. The typical of living pattern in Bengkulu City could be relatively different from other areas in Indonesia. In general, the local people were fishermen; therefore, the fishermen villages well established in this area. However, the educations of natural disasters impacts have not been fully achieved by the people. Hence, the local government should educate people living in those vulnerable areas step by step. The results of this study could be the first step to make a disaster mitigation preparedness for Bengkulu City.

5. CONCLUSIONS

This paper presented the implementation of seismic hazard mitigation on the basis of ground shear strain indicator for Spatial Plan of Bengkulu City, Indonesia. Hundreds of sites in Bengkulu City were studied. The geophysical characteristics, such as amplification (A_0), predominant frequency (f_0), and seismic vulnerability index (K_g) were presented. The ground shear strain (γ) was also analysed to measure the possible seismic impact during the strong earthquake in Bengkulu City. Generally, several areas in Bengkulu City had larger amplification, especially along coastal area of Bengkulu City. The sediment thickness of investigated area was relatively thin. It was indicated by the larger value of f_0 . The larger K_g values were found along coastal area of Bengkulu City. It indicated that the significant seismic effect could occur along coastal area of Bengkulu City. Along this vulnerable area, the high density of people concentration existed. The finding obtained from this study could bring a recommendation to the local government to consider the earthquake impact in Bengkulu City, especially along coastal area of Bengkulu City.

6. ACKNOWLEDGMENT

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