Article

Vulnerability levels of liquefaction zones as a spatial planning concept based the disaster mitigation in Pariaman city – Indonesia

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Abstract: Knowledge about the liquefaction vulnerability in Pariaman city which is prone to an earthquake is very much needed in disaster mitigation based spatial planning. The liquefaction is an event of loss of the strength of the sandy soil layer caused by the vibration of the earthquake, where the liquefaction occurs in the sandy soil layer which has loose material in the form of sand that is not compact or not solid. This research was conducted by analyzing the potential of liquefaction vulnerability based on the *Conus penetration* to produce Microzonation of the susceptibility of subsidence due to liquefaction at 4 locations in Pariaman city, i.e Marunggi village, Taluak village, Pauh Timur village and Padang Birik-Birik village. The *Conus penetration* testing is carried out using the *piezocone* (CPTU) method and mechanical *Cunos penetration*, and approach using *Geographic Information System* (GIS). The results showed that the potential of liquefaction was found at the sandy soil layer of sand and a mixture of sand and silt, which is characterized by the value of *Cunos* resistance and local resistance each smaller than 15 MPa and 150 kPa at varying depths. Based on the results of the analysis using this method, the critical conditions of liquefaction found in the medium sandy soil to solid. The fine sand layer which has the potential for liquefaction is in sand units formed from coastal deposits, coastal ridges and riverbanks. This liquefaction vulnerability zones analysis is limited to a depth of 6.00 m due to the limitations of the equipment used. The results of the analysis show that the fine sand layer which has the potential for liquefaction occurs at a depth of> 1.00-6.00 m with the division of zones, i.e 1) High liquefaction in the sandy soil layer which has a critical acceleration (a) <0.10 g with shallow groundwater surface; 2) Medium liquefaction in the sandy soil layer which has a critical acceleration (a) between 0.10-0.20 g with shallow groundwater surface; and 3) Low and very low liquefaction in the sandy soil layer which has a critical acceleration (a) between 0.20-0.30 g with an average groundwater deep enough surface.

Keywords: liquefaction, vulnerability, earthquake, disaster mitigation, Pariaman.

1. Introduction

West Sumatra Province, especially the Pariaman city is an area that has enormous potential for earthquakes, where one of the problems caused by the earthquake hazard is the liquefaction. The liquefaction phenomenon due to an earthquake is the event of the loss of the strength of the layer of loose sand due to the increase in soil pore water pressure due to receiving earthquake vibrations [1]. Thus, liquefaction events will occur in areas prone to large earthquakes that are composed of sand deposits saturated with water with low density, and in areas with co-seismic surface movements exceeding the threshold value [2,3]. When liquefaction takes place, the strength of the soil decreases and the ability to deposit the soil to hold the load decreases. Soil effective voltage due

to cyclic load received by the soil with the characteristics of grained, saturated water and medium to loose density, where the soil undergoes a change in properties from solid to liquid. This thing causes damage to the building, such as the collapse. This liquefaction event has been proven through history that has occurred in the world, such as the earthquake in Niigata, Japan in 1964 [4,5], and the latest earthquake and tsunami in Donggala-Palu in Central Sulawesi Province 2018 with its trigger, one of which was of the Palu-Koro fault [6,7].

The liquefaction potential can be studied using three field testing methods, i.e 1) standard penetration test, 2) *Cunos penetration* test, and 3) shear speed measurement. Of the three methods, The Cunos penetration testing is often used because of its superiority in quality control, data repetition, and detecting variations in soil layer types [8,9]. Thus, the depth and thickness of the soil layer which has the potential for liquefaction can be known more accurately than other types of methods. Based on the research of [10] using the conus test method to predict liquefaction testing in Padang city region. Prediction results show the suitability with the phenomenon of liquefaction that occurred during the earthquake in 2009, Likewise the case of Pariaman city which has the characteristics of a coastal region and is densely populated the same as Padang city. The earthquake event in West Sumatra Province (Mw 7.6) off the coast of West Sumatra on September 30, 2009 also caused a phenomenon of liquefaction in several locations in the coastal region of Pariaman city [11-15]. The building and infrastructure damages that occur generally are due to loss of carrying capacity of the soil layer and spread on the alluvium plain around the coast and the estuary of the Sunua river which is precisely in the villages of Marunggi and Manggu Panjang in sub-district of South Pariaman, such as the decline of building foundations, roads and the decline in dikes/canals on the left-right of the Sunua river estuary.

The evidence of the liquefaction phenomenon shows that alluvial deposits layers in several areas of Pariaman city especially coastal regions and river estuaries have the potential to experience liquefaction. Given that information on potential liquefaction in the Pariaman city region is still very limited after the post-earthquake in 2009, then the regions vulnerable to liquefaction cannot yet be mapped as a whole. In writing this manuscript from the results of the research that has been done is to present the results of the study of susceptibility to soil degradation due to liquefaction in the Pariaman city region based on the *Conus penetration* test methods and GIS approaches. While the objectives of this study were to 1) evaluate the potential of the sandy soil layer liquefaction based on the *Conus penetration* data; 2) determine the magnitude of soil degradation due to liquefaction; and 3) compile liquefaction susceptibility microzonation maps based on the amount of soil subsidence.

2. Geology condition of Pariaman city

The geological structure in the Pariaman city region is generally covered by quarter sediment which is quite thick. A large number of solids in Pre-Tertiary lithology shows the occurrence of intensive tectonic activities after the formation of these rocks and given the absence of geological structure outcrops on the surface of quarter deposits, then can it is ensured that the Pre-Tertiary and Tertiary geological structures are covered by quaternary deposits. However, there was also a geological structure observed in quarter-aged lithology. The coastal region of Pariaman city is quarterly sediment in the form of a quarterly coastal plain that faces open sea deposits. Characterized by quarter deposits which consist of alluvial deposits, swamps and coastal ridges.

85 The plains are separated by open sea and coastal ridges, which form coastal swamps as swamp
86 deposits. Based on the analysis of the Geological Map Kastowo and Leo (1973) [16] shows the
87 coastal geological picture is characterized by deposits of loose sand, gravel with the continuity of
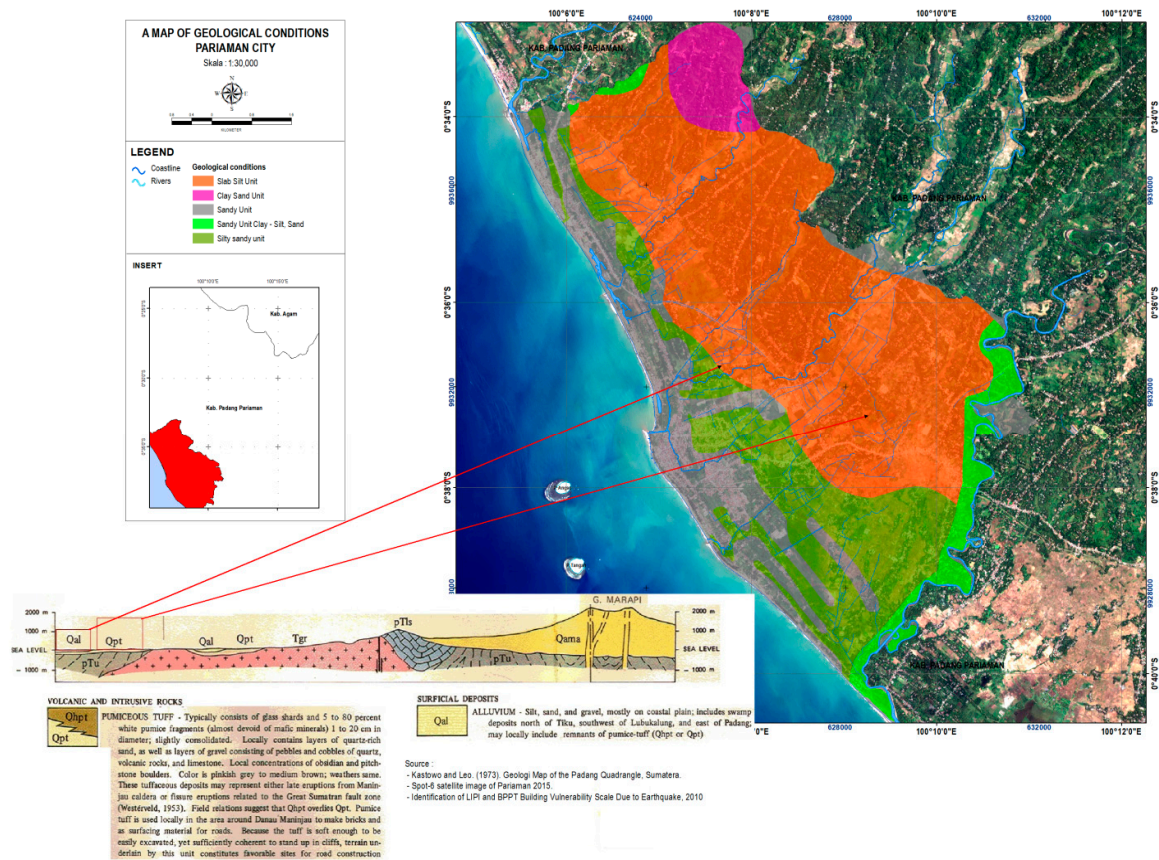88 silt and clay layers (Fig. 1).

89

90 **Figure 1.** Map of the geological condition of Pariaman city.

91 **3. Research methods**

92 3.1. Evaluation of Liquefaction Potential

93 The location of measurement activities for the *Cunos penetration* testing is carried out using the
94 *piezocone* (CPTU) method and mechanical *Cunos penetration* (CPT) in Fig. 2 presents location points
95 to obtain the Conus tip end profile (q_c), The local barriers (f_s) needed in evaluating the potential of
96 soil layer liquefaction at the research locations. The *Conus penetration* testing was carried out using
97 the CPTU method and CPT method at 4 village locations in Pariaman city, i.e Marunggi, Taluak,
98 Pauh Timur and Padang Birik-Birik (Fig. 2). Where evaluation of potential liquefaction with the
99 *Cunos penetration* test method is carried out with 3 (three) stages, i.e 1) calculation of the *cyclic stress*
100 *ratio* (CSR); 2) ratio calculation *cyclic resistance ratio* (CRR); and 3) evaluation of potential
101 liquefaction with calculating the soil layer *safety factor* (FK) granular to liquefaction. Calculation of
102 CSR uses the equation [2,17] as follows:

103 $$CSR = 0.65\,(a_{max}/g) \times (ó_{vo}/ó'_{vo})_{r_d}$$

104 Where a_{max} is horizontal acceleration maximum on the surface of the soil layer, g is the
105 acceleration of gravity (9.81 m/sec^2), σ_{vo} is the total vertical load voltage, and σ'_{vo} is effective
106 vertical load voltage, and r_d is a stress reduction factor according to [18]. Consider the maximum
107 acceleration in the bedrock of 0.3g, and an amplification factor of 1.5 for soft soil layers in the

108   Pariaman city region, then a_{max} of 0.45 will be used in CSR calculation. This maximum
109   acceleration value is in accordance with [19]. Meanwhile, calculation of the ratio CRR based on CPT
110   data using the procedure [20], as following:

111

$$CRR_{7,5} = \begin{cases} 0,833 \cdot \left[\dfrac{(q_{c1N})_{cs}}{1000}\right] + 0.05 & for \ (q_{c1N})_{cs} < 50 \\[2ex] 93 \cdot \left[\dfrac{(q_{c1N})_{cs}}{1000}\right]^3 + 0.08 & for \ 50 < (q_{c1N})_{cs} < 160 \end{cases}$$

112   where $CRR_{7,5}$ is the value of the ratio of cyclic resistance for earthquakes with magnitude Mw
113   of 7.5 and $CRR_{7,5}$ is the equivalent value of clean sandy for normalized *Conus penetration* resistance
114   (q_{c1N}), which is influenced by the soil behavior index. The calculation results CSR and $CRR_{7,5}$ will
115   used in calculating security factors (FK) soil layer against liquefaction with use the equation below:

116

$$FK = \left(\frac{CRR_{7,5}}{CSR}\right) . MSF$$

117   where MSF is a factor of multiples of the earthquake magnitude given by the following
118   equation [8,21]:

119

$$MSF = \frac{10^{2.24}}{M^{2.56}}$$

120   where M is the magnitude of the earthquake that is equal to 9.3. The limitation of the safety
121   factor (FK) used in this study is FK> 1.0 to indicate the soil layer is safe against liquefaction, and FK
122   <1.0 to indicate the soil layer is not safe against liquefaction.

123   3.2. The level of *soil subsidence* zones

124   The level of *soil subsidence* susceptibility zones due to liquefaction was obtained by calculating
125   the total *soil subsidence* at each the *Conus penetration* test, using the "*Simplified Procedure*" method
126   [2,21,22] and approach using GIS. The results of the *soil subsidence* calculation are used to obtain the
127   *soil subsidence* vulnerability zones due to liquefaction based on the classification in Table 1 follows.

128   **Table 1.** This is a table. Tables should be placed in the main text near to the first time they are cited.

Soil subsidence s_{total}(cm)	liquefaction vulnerability zones
< 0,10	high
0,10 - 0,20	intermediate
0,20 - 0,30	low
>0,30	Very low

129   Source: Modified from [21].

130   **4. Results and Conclucion**

131   4.1. The level of *soil subsidence* zones

132   The location of sampling points can be seen in Fig. 2 which shows an analysis of potential
133   liquefaction based on the *Conus penetration* test data for several testing points. The soil layer that has
134   the potential for liquefaction is characterized by a CRR value smaller than the CSR value or a FK
135   value smaller than 1.0. Based on the graphs in Appendix Fig. 2 above, the potential for liquefaction
136   varies from one location to another. This is caused by differences in the profile of q_c and f_s that
137   control the type of soil layer in each location. Generally, liquefaction can occur in the sandy soil
138   layer to a depth of 25 m, which is characterized by q_c value of less than 15 MPa and f_s value of less

139   than 150 kPa. Because the potential for liquefaction is influenced by the a_{max} value, the lower the
140   a_{max} value, the lower the criteria for the q_c and f_s values for the passive soil layer that will
141   experience liquefaction. These graphs of liquefaction potential also show that the soil layer
142   characterized by q_c value smaller than 5 MPa and f_s smaller than 125 kPa tends to be unable to
143   experience liquefaction. According to the classification [23,24], the range of the q_c and f_s values
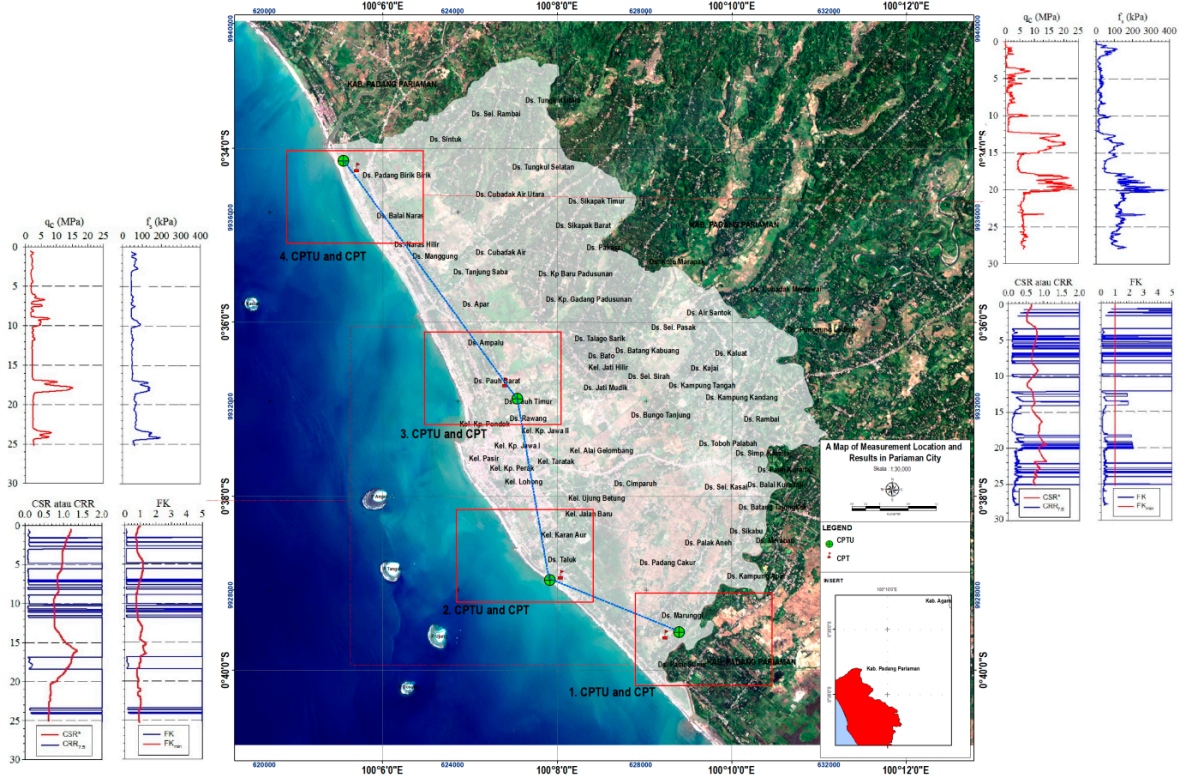144   characterizes clay behavior.

145

146   **Figure 2.** Location map of the measurements result points of CPTU-CPT in Pariaman city.

147   Fig 3 shows a description of the type, depth and thickness of the soil layer. The type of soil
148   layer in each soil profile is determined based on the soil behaviour index according to [25] The
149   depth and thickness of the soil layer experiencing liquefaction are indicated by a pink symbol.
150   Based on Fig 3, liquefaction generally occurs from the soil layer of sand and silt on surface to a
151   depth of 10 m, although liquefaction can still occur in layers of sand and silt at depths greater than
152   15 m. The thickness of the simulated soil tends to vary from one location to another because it is
153   associated with a factor of variation in soil density, which is controlled by the values of q_c and f_s.
154   In general, the sand layer that liquefaction can reach 4 m, while the silt soil layer can reach a
155   thickness of 3 m.
156   The potential for liquefaction tends not to occur in the surface layer of soil in areas that are
157   further away from the shore. This is caused by the presence of finer grained soil (clay silt to silt
158   clay) which dominates to a depth of 2 m above ground level. However, the presence of this soil
159   layer will not reduce the potential of the sand layer below to experience liquefaction. In other
160   words, the layer of loose sand until the medium below the thick clay layer can still experience
161   liquefaction. The potential for liquefaction tends to increase in the southern part of Pariaman city,
162   where the cross section is dominated by a layer of silt sand to the sand silt. Meanwhile, the soil
163   layer in the North and East part of Pariaman city tends not to experience liquefaction because it is
164   dominated by silty clay layers to organic material. Thus, the potential for liquefaction will be
165   reduced in region the East and North part of Pariaman city which are composed of thick clay layers.

166   4.2. Vulnerability microzonation of *soil subsidence* due to liquefaction

167   Table 2 presents the results of the calculation of *soil subsidence* due to liquefaction, based on the
168   *Cunos penetration* test method. Based on the Table 2, the value of *soil subsidence* varies greatly from
169   10 to 21 cm, due to variations in soil type and density in each location. In other words, the condition
170   of the soil layer will control the amount of *soil subsidence* due to liquefaction in the Pariaman city
171   region.

172   **Table 2.** Value of the *soil subsidence* due to liquefaction for each point the *Conus penetration* test

Location	Code	s_{total}(cm)	Code	s_{total}(cm)
Marunggi	CPT-01	10.51	CPTU-01	13.17
Taluak	CPT-02	21.12	CPTU-02	20.31
Pasia Timur	CPT-03	10.12	CPTU-03	10.05
Padang Birik-Birik	CPT-04	10.07	CPTU-04	12.31

173   Souce: Analysis of measurement data, 2018.

174   Based on the *soil subsidence* values in Table 2 and the classification of *soil subsidence*
175   susceptibility (Table 1), a microzonation levels map of s the *soil subsidence* susceptibility resulting
176   from liquefaction was produced as shown in Fig 3. Based on the microzonation map, the Pariaman
177   city is divided into 4 zones of *soil subsidence* vulnerability due to liquefaction, from the vulnerability
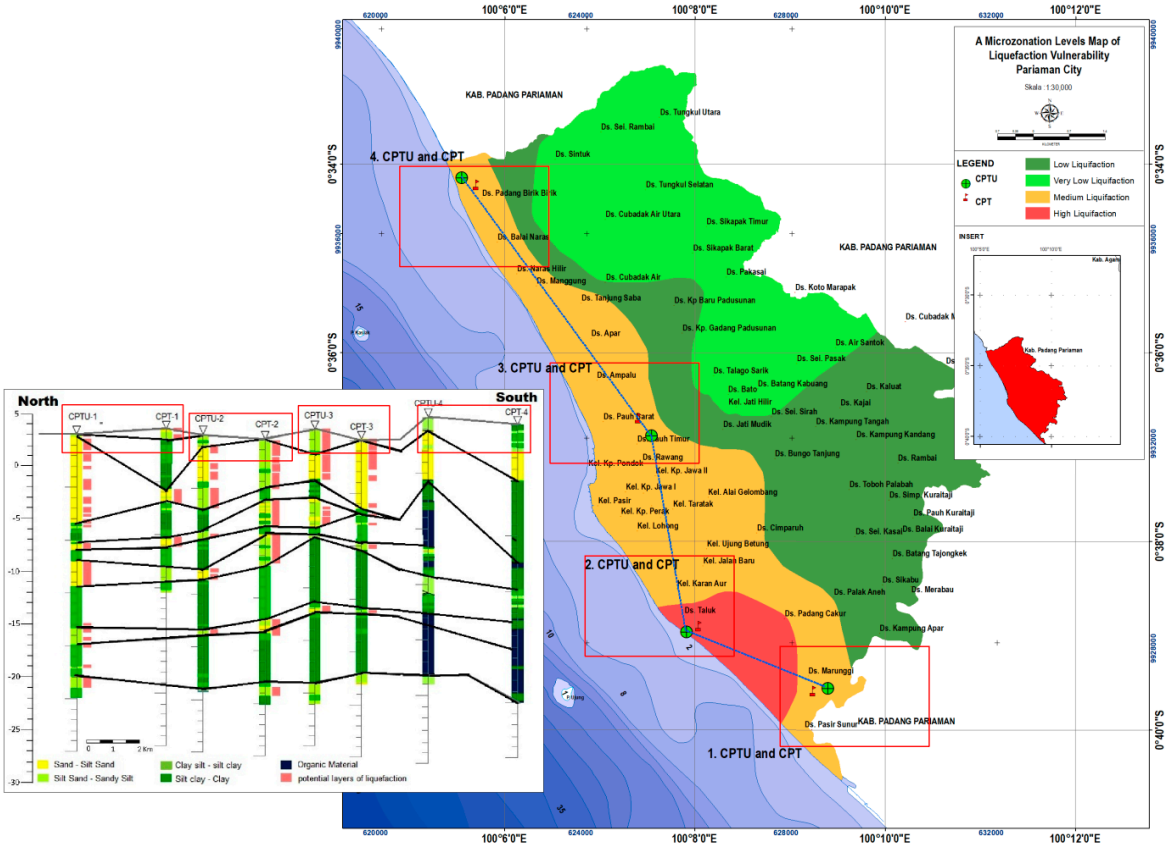178   zone of very low to high.

179

180   **Figure 3.** Microzonation levels map of   liquefaction vulnerability Pariaman city and cross section of soil the
181   potentially liquefaction at the sampling location of CPTU-CPT (black line: illustrates the correlation of the type
182   of soil layer).

183   The high vulnerability zones are found in the southern part of coastal areas of Pariaman city
184   (Taluak dan Marunggi), in this zone of vulnerability, *soil subsidence* that can occur is greater than 20
185   cm. Based on disaster mitigation-based spatial southern the Regional Spatial Planning (RTRW) of

186   Pariaman city 2010-2013, this vulnerability zone is very suitable for protected regions, green open
187   spaces, tourism regions and mangrove regions (7,26].

188   The areas with a high potential for liquefaction, because the sand layer in the zone has a critical
189   acceleration (a) <0.10 g with shallow groundwater, so if the sandy soil layer receives earthquake
190   vibrations with an acceleration (z) minimum of 0.10 g, in this zone there is the potential for
191   liquefaction. According to the current spatial pattern in the RTRW Pariaman city 2010-2030, some
192   areas of settlement, trading, services and public space are in the high vulnerability zone. In
193   addition, important infrastructure such as bridges and roads, are in this zone. Therefore, it is
194   necessary to re-evaluate the suitability of the foundation, especially in high buildings and bridge
195   infrastructure so that engineering efforts can be made to reduce the material loss potential based the
196   disaster mitigation.

197   The medium vulnerability zone is being found in most coastal regions and the central part of
198   the city in all sub-districts in Pariaman city. In this zone of vulnerability, *soil subsidence* which can
199   occur ranges from 10 to 20 cm. The areas with medium liquefaction potential, because the sand
200   layer in the zone has a critical acceleration (a) between 0.10 - 0.20 g with a shallow groundwater
201   level, so if the sandy soil layer receives earthquake vibrations with acceleration (z)> 0.10 g in the
202   zone has the potential for liquefaction.

203   Development in this zone can still be done by using liquefaction mitigation measures such as
204   soil compaction processes, vertical drainage applications, and selection of the appropriate type of
205   foundation. The medium vulnerability zone this can be allocated as a regions of cultivation, trading,
206   tourism, and public services. Based on the current spatial pattern in the RTRW Pariaman city
207   2010-2030, the areas of settlement and offices, and general services are generally in the medium
208   vulnerability zone. so that it is necessary to study the suitability of the foundations of important
209   buildings and infrastructure in the region.

210   Generally, half of the Pariaman city region is included in the vulnerability zone of the *soil*
211   *subsidence* from low to very low, especially in East Pariaman sub-district. The areas with low and
212   very low potential for liquefaction occur because the sandy soil layer of sand in the zone has a
213   critical acceleration (a) 0.20 - 0.30 g, besides that the average water table is quite deep. In this, the
214   vulnerability zone, *soil subsidence* that can occur is less than 10 cm. Damage to buildings and
215   infrastructure is very small, especially in buildings with deep foundations.

216   Based on the results of microzonation of *soil subsidence* susceptibility due to liquefaction,
217   spatial patterns in RTRW Pariaman city 2010-2030 require adjustments by paying attention to and
218   considering the potential for *soil subsidence* due to liquefaction in each region. Adjustment of this
219   spatial pattern can minimize the impact of liquefaction on damage to buildings and infrastructure
220   throughout the Pariaman city region. In addition, this microzonation vurnerability levels map is the
221   initial guideline to determine the level of vulnerability of a region to land subsidence due to
222   liquefaction. Therefore, investigations and studies of liquefaction potential in more detail are
223   needed especially in areas where there are strategic buildings and infrastructure as well as life
224   support networks (PDAM network, underground gas and electricity pipeline) that are in the
225   middle and high vulnerability zones.

226   **5. Conclusions**

227   The evaluation results of liquefaction potential based on data the *Cunos penetration* test, taking
228   into account earthquakes with magnitude ± Mw 8.0 and peak acceleration at the ground level of
229   0.45g provide information on the possible thickness of the liquefaction layer and the division of
230   zones of *soil subsidence* in Pariaman city. The layers of sandy soil and silt with *Conus* resistance
231   values of less than 15 MPa and local barriers of less than 150 kPa, potential to experience
232   liquefaction to a depth of 15 m, with variations in layer thickness which experienced liquefaction
233   reaching 4 m. Based on these data, the Pariaman city can be classified into 4 zoning vulnerability to
234   *soil subsidence*. In the high vulnerability zone, especially in the villages of Taluak and Marunggi, a
235   decrease in soil layer due to liquefaction can reach more than 20 cm. While the low vulnerability
236   zone is mainly found in the eastern part of Pariaman city. Most of the settlement, trade and service
237   areas, as well as public services, are in the medium to high land reduction vulnerability zone.
238   Therefore, investigation of detailed geotechnical and local microzonation studies in these regions
239   are important before building construction is carried out to reduce the risk of threat of the *soil
240   subsidence* due to liquefaction, as well as direction in spatial planning based the disaster mitigation
241   in Pariaman city.

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