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Liquefaction Vulnerability Analysis as a Coastal Spatial Planning Concept 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. 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. Based on the results of the analysis using this method, the critical conditions of liquefaction found in the intermediate 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) Intermediate 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.

***Index Terms*: Disaster mitigation, Earthquake, Liquefaction, Pariaman – Indonesia, Vulnerability.**

I. 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.

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Soil effective voltage due to cyclic load received by the soil with the characteristics of grained, saturated water and intermediate 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.

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

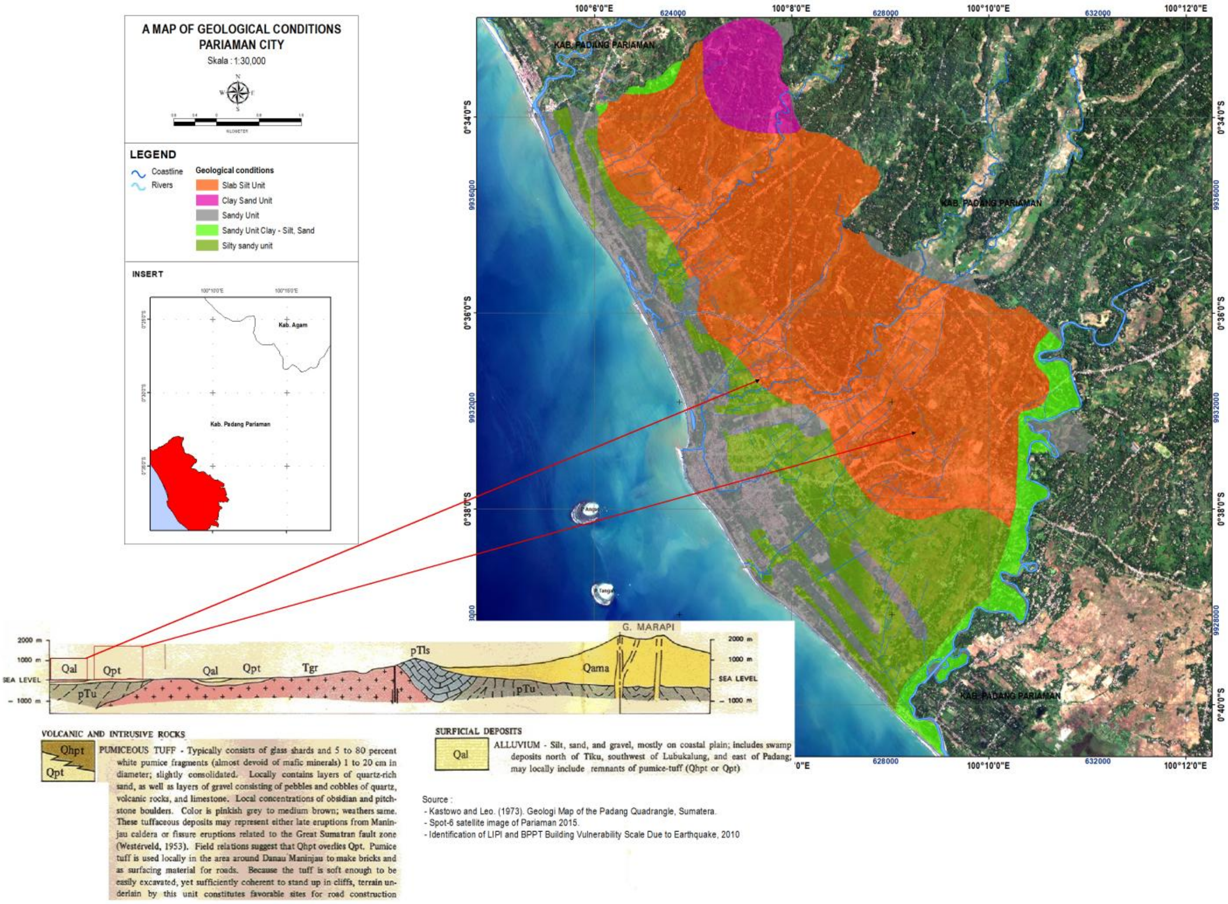

Figure 1. Map of the geological condition of Pariaman city.

III. RESEARCH METHODS

A. Evaluation of Liquefaction Potential

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

$$CSR = 0.65\,(a_{max}/g) \times (\sigma_{vo}/\sigma'_{vo})_{r_d}$$

Where a_{max} is horizontal acceleration maximum on the surface of the soil layer, g is the acceleration of gravity (9.81 m/sec^2), σ_{vo} is the total vertical load voltage, and σ'_{vo} is effective vertical load voltage, and r_d is a stress reduction factor according to [18]. Consider the maximum acceleration in the bedrock of 0.3g, and an amplification factor of 1.5 for soft soil layers in the Pariaman city region, then a_{max} of 0.45 will be used in CSR calculation. This maximum acceleration value is in accordance with [19]. Meanwhile, calculation of the ratio CRR based on CPT data using the procedure [20], as following:

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

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

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

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

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

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

B. The level of soil subsidence zones

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

Table 1. Classification of soil subsidence vulnerability zones

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

Source: Modified from [21].

IV. RESULTS AND CONCLUCION

A. The level of *soil subsidence* zones

The location of sampling points can be seen in Fig. 2 which shows an analysis of potential liquefaction based on the *Conus penetration* test data for several testing points. The soil layer that has the potential for liquefaction is characterized by a CRR value smaller than the CSR value or a FK value smaller than 1.0.

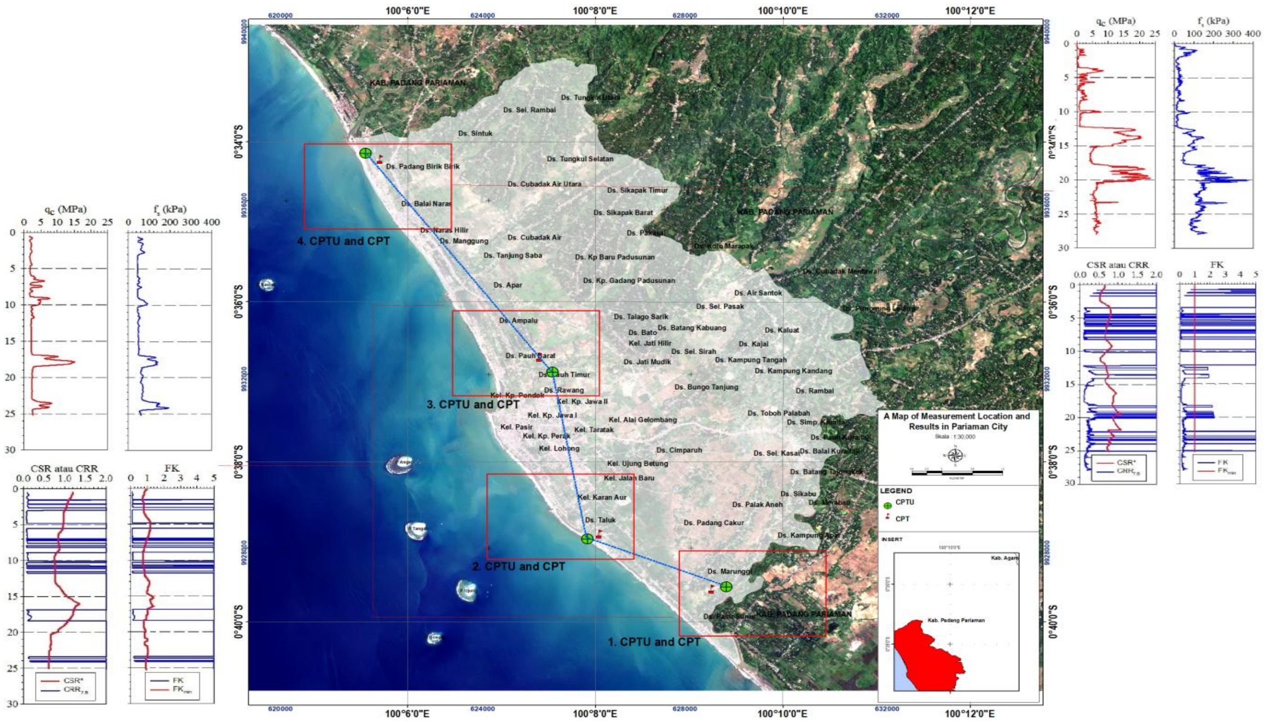

Figure 2. Location map of the measurements result points of CPTU-CPT in Pariaman city.

Based on the graphs in Appendix Fig. 2 above, the potential for liquefaction varies from one location to another. This is caused by differences in the profile of q_c and f_s that control the type of soil layer in each location. Generally, liquefaction can occur in the sandy soil 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 than 150 kPa. Because the potential for liquefaction is influenced by the a_{max} value, the lower the a_{max} value, the lower the criteria for the q_c and f_s values for the passive soil layer that will experience liquefaction. These graphs of liquefaction potential also show that the soil layer characterized by q_c value smaller than 5 MPa and f_s smaller than 125 kPa tends to be unable to experience liquefaction. According to the classification [23, 24], the range of the q_c and f_s values characterizes clay behavior.

Fig 3 shows a description of the type, depth and thickness of the soil layer. The type of soil layer in each soil profile is determined based on the soil behavior index according to [25] The depth and thickness of the soil layer experiencing liquefaction are indicated by a pink symbol. Based on Fig 3, liquefaction generally occurs from the soil layer of sand and silt on surface to a depth of 10 m, although liquefaction can still occur in layers of sand and silt at depths greater than 15 m. The thickness of the simulated soil tends to vary from one location to another because it is associated with a factor of variation in soil density, which is controlled by the values of q_c and f_s. In general, the sand layer that liquefaction can reach 4 m, while silt soil layer can reach a thickness of 3 m.

The potential for liquefaction tends not to occur in the surface layer of soil in areas that are further away from the shore. This is caused by the presence of finer grained soil (clay silt to silt clay) which dominates to a depth of 2 m above ground level. However, the presence of this soil layer will not reduce the potential of the sand layer below to experience liquefaction. In other words, the layer of loose sand until the intermediate below the thick clay layer can still experience liquefaction. The potential for liquefaction tends to increase in the southern part of Pariaman city, where the cross section is dominated by a layer of silt sand to the sand silt. Meanwhile, the soil layer in the North and East part of Pariaman city tends not to experience liquefaction because it is dominated by silty clay layers to organic material. Thus, the potential for liquefaction will be reduced in region the East and North part of Pariaman city which are composed of thick clay layers.

B. Vulnerability microzonation of soil subsidence due to liquefaction

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

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

Souce: Analysis of measurement data, 2018.

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

The high vulnerability zones are found in the southern part of coastal areas of Pariaman city (Taluak dan Marunggi), in this zone of vulnerability, *soil subsidence* that can occur is greater than 20 cm. Based on disaster mitigation-based spatial southern the Regional Spatial Planning (RTRW) of Pariaman city 2010-2013, this vulnerability zone is very suitable for protected regions, green open spaces, tourism regions and mangrove regions [7, 26].

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

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

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

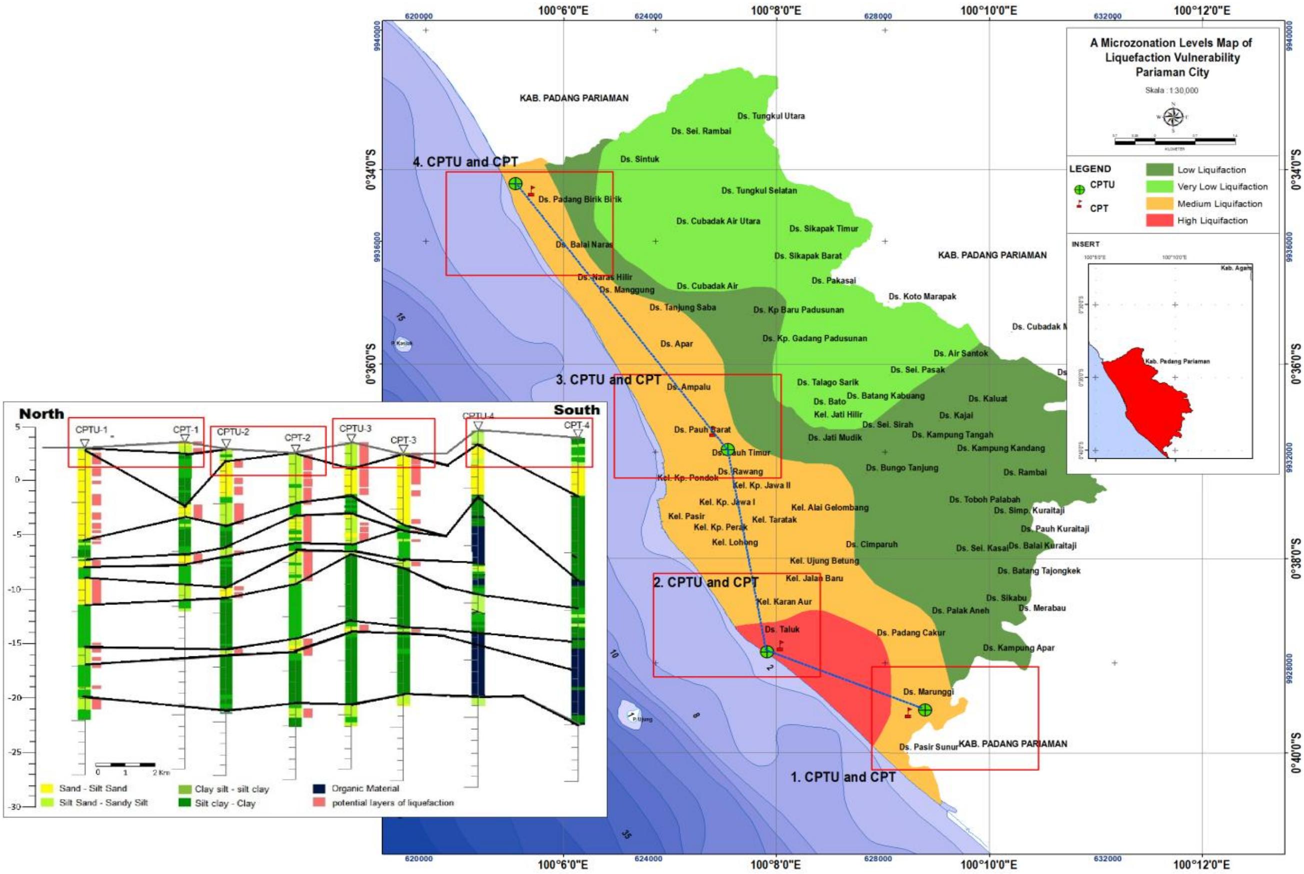

Figure 3. Microzonation levels map of liquefaction vulnerability Pariaman city and cross section of soil the potentially liquefaction at the sampling location of CPTU-CPT (black line: illustrates the correlation of the type of soil layer).

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

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

V.CONCLUSIONS

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

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