Liquefaction potential analysis using the Tsuchida method and correlation of Relative Density (Dr) − D_{50} at Padang Beach

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Abstract. Indonesia's seismic activity necessitates careful consideration of earthquake risks in construction projects, as seen in the 2009 Padang's Earthquake with high sand content and water table near the coast. The test was carried out based on the gradation of soil grains through sieve analysis testing using the Tsuchida boundary and relative density testing by analyzing the correlation value between Dr and D_{50}. The accelerations used in this test are 0.3g and 0.6g. Soil classification according to the AASHTO (American Association of State Highway and Transportation Officials) system, the type of sand on the beach is A-3 (fine sand), and according to the USCS (Unified Soil Classification System) system, all samples are classified as SP (Poorly-graded sand). With Cc (Coefficient Curvature) 2.436-1.975 and Cc (Coefficient Uniformity) 1.106-0.939. 0.3g Relative density ranges between 7-59%, and 0.6g ranges between 5-41%. Diameter passes 50% ranges between 0.187-0.408 mm. The Tsuchida boundary analysis and the Dr-D_{50} correlation retrieved similar results. Tsuchida analyses grain gradation, while Dr-D_{50} examines cyclic load and settlement for specific grain size, affecting liquefaction potential. One sample liquefied at 0.3g, while all samples liquefied at 0.6g. Due to a smaller diameter at 50% pass, it was indicating higher liquefaction potential.

1 Introduction

Indonesia has a high level of seismic activity because of its geographically location at the intersection of four major tectonic plates: Pacific, Philippine, Eurasian, and Indo-Australian, as seen in Fig. 1.

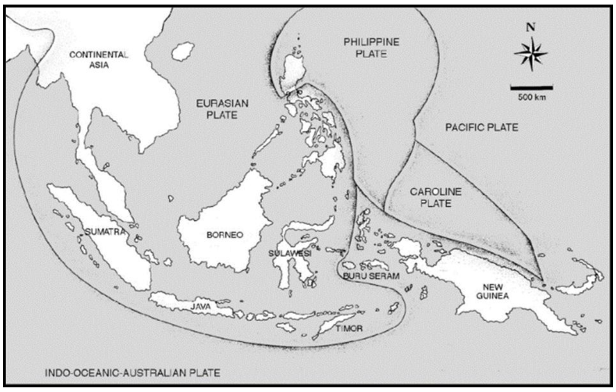

Fig. 1. Tectonic plate boundaries in South and South East Asia [1].

West Sumatra is one of the areas in Indonesia that is very prone to earthquakes. Located along the subduction zone between the Indo-Australian and Eurasian Plates, this region often experiences significant seismic activity. The earthquake that occurred in 2009 (Mw7.6) had its epicenter near Padang, which is the largest city in western Sumatra, Indonesia [2]. The tremors were so intense that they could be felt as far as Singapore, which is approximately 460 km away. This devastating earthquake resulted in the tragic loss of 1,117 lives [3].

The results of the investigation conducted on the 2009 earthquake caused sand to boil in several sites in Padang, as shown in Fig. 2. Liquefaction is a phenomenon in which initially solid soil turns into liquid due to strong vibrations, such as earthquakes. This process occurs when pore water pressure increases in fine-grained soil (usually sand or silt), causing soil particles to lose contact with each other and the soil lose its strength and stability [4]. This phenomenon often results in severe structural damage to buildings, infrastructure, and the surrounding environment. Liquefaction can cause severe damage to buildings, roads, bridges, and other critical infrastructure [5].

The buildings were found to be tilted or collapsed, water and gas pipes were burst, and roads and bridges were damaged or cut off. These damages not only caused huge material losses but also disrupted the economic and social activities of the community [6].

Chian et al. [3] found that the liquefaction in Padang was caused by high sand content and high-water table along the coastal strip plane. The geological condition of Padang City consists of alluvial soil deposited from river and sea activities, which tends to be composed of sand and silt that may have triggered the root caused

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Fig. 2. Sand boils on the ground surface [4].

Figure 3 shows the tension cracks on the road at Padang city which this indicating as a result of lateral spreading. Earthquake shaking triggers significant ground movement, especially in weak or unstable soil layers. This shaking causes the road above it to experience excessive pressure, resulting in cracks. Repeated and high-intensity vibrations can cause road materials such as asphalt and concrete degradation. If there are already small cracks or problems with the road structure, an earthquake can worsen the cracks. Roads built on unstable soil foundations are more susceptible to severe damage.

Fig. 3. Tensile cracks arising from lateral spread in the Siteba residential area [3].

Figure 4 shows the lifting of floor slabs in the residential area of Perumdam Kota Padang. Floor lifting or shifting of house floors is an expected impact in earthquake-prone areas. Floor lifting in Padang can occur in areas prone to liquefaction, where the soil under the foundation suddenly loses its stability due to increased pore water pressure so that the effective soil stress decreases. Floor lifting is usually accompanied by other structural damage to the house, such as cracks in the walls, jammed doors and windows, and damage to the foundation. This can make the house unsafe to occupy without significant repairs.

Fig. 4. Uplifted floor slabs in the residential area of Perumdam, Padang City [3].

Research into liquefaction was initiated after earthquakes in Niigata, Japan, and Alaska in 1964 caused damage to superstructures due to the liquefaction of saturated sand layers. A combination of seismic vibrations, soil type and properties, groundwater conditions, geological structures, and human activities causes liquefaction. The main factor that triggers liquefaction is seismic vibrations, especially from earthquakes, which increase pore water pressures in fine-grained soils. Saturated soils with high porosity and not fully consolidated are particularly susceptible to this phenomenon. This led to numerous studies and the development of methods for assessing liquefaction potential, utilizing laboratory and field data. Soil parameters such as grain gradation and relative density (d5) significantly influence liquefaction potential and soil strength.

2009 Earthquake has caused liquefaction along Padang Beach. Due to this incidence, it is important to study their relationship. An analysis was carried out to find the influence of potential liquefaction with regard to relative density and grain degradation for the Padang Beach.

It was found that soils with low relative density (Dr) have high liquefaction potential due to their loose particle structure and significant instability to seismic vibrations. On the other hand, soil with high relative density (Dr) has low liquefaction potential because of its dense and stable structure [7-9]. Likewise, soil with uniform gradation has high liquefaction potential due to its low density and loose structure. In contrast, well-graded soil has low liquefaction potential due to its denser and more stable particle structure. Coarse and fine soils have varying liquefaction potentials depending on specific conditions such as saturation and seismic vibration intensity.

Research by Tohari [10] found that the depth of the groundwater table in Padang City ranges from 0.5 to 5.0 meters. Near the beach, the average depth is around 1.5 meters. These variations are due to the geological composition of Padang, which includes Tertiary volcanic rocks (Tomv), Plio-Plistocene volcanic rocks (QTv), and Quarternary alluvial deposits (Qa). Liquefaction typically occurs in areas with high groundwater levels, its effects are often observed in low-lying areas or nearby rivers, lakes, bays, and oceans [11, 12].

Liquefaction occurs because of reduction in effective stress due to an increase in pore water pressure so that the effective stress of the soil decreases to the point that the soil can lose its strength. This causes the soil to liquefy. When an earthquake or vibration occurs, if the soil particles are unable to maintain bonds, causing pore water to rise through the gaps between particles, then there is an increase in pore water pressure [13, 14]. The effect is that the Pore water pressure ($\bar{u}$) increases, but the total stress (σ) is still in the same condition as before the earthquake. If the pore water pressure increases over the total stress, effective stress (σ') will be smaller than zero ($\sigma' < 0$). This condition causes the soil to liquefy [15-18].

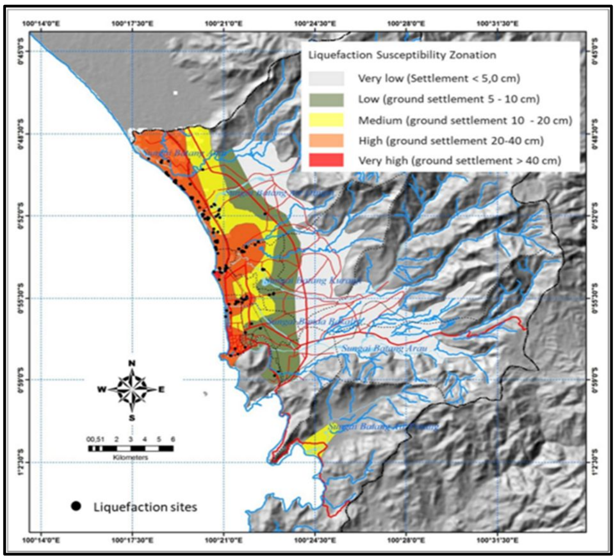

Fig. 5. Seismic microzonation of Padang City [10]

Figure 5 shows the seismic microzonation analysis of Padang City reveals that the regions with high to very high vulnerability to liquefaction are concentrated along the coastlines and river flows, areas in Koto Tangah, North Padang, East Padang, and South Padang subdistrict where sand boiling, settlement, and lateral movement in high vulnerability zones [10]. In addition to Adji et al. [19] reasearch in Air Tawar water areas such as Basko Mall, Alai area, Simpang Haru, Sungai Air and Kota Tua have liquefaction potential.

2 Methodology

Soil samples were taken at five locations along the beach of Padang, West Sumatra as shown in Fig. 6. The locations were selected based on potential liquefaction mapping from the Ministry of Energy and Mineral Resources [20] and seismic microzonation research on liquefaction [10]. Five of Sand cone tests were carried out on the sites along Padang Beach. The soil samples collected were taken to Andalas University's Soil Mechanics Lab for analysis. The disturbed soil samples were collected using a hoe (at 50 cm depth). The grain gradation tests and relative density were carried out using ASTM. Then the results were analysed using the Tsuchida method [21]. Then the Relative density Dr and D_{50} comparison charts by Hakam [22].

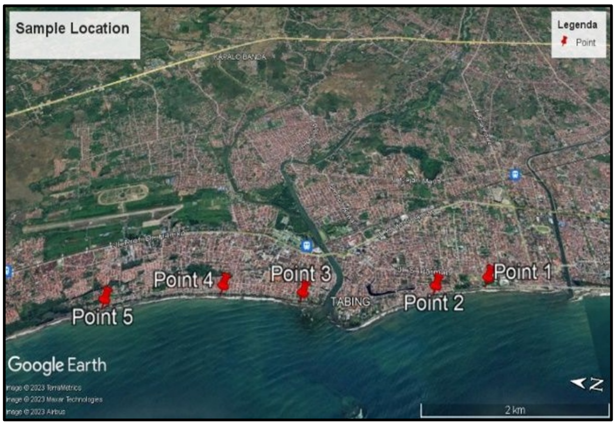

Fig. 6. Sampling locations.

Table 1 shows the sampling location for five (5) soil sampling points. The soil samples were disturbed samples soil and taken 50 cm below the ground surface. Laboratory testing was conducted to obtain the physical properties of the soil. The soil parameters obtained were soil grain analysis graphs, volume, weight, and other physical properties.

In this study, the Tsuchida method and relative density (Dr) and D_{50} were used to predict liquefaction potential. The Tsuchida Method was chosen because it is simple, has a strong empirical basis, directly correlates with soil parameters, and has wide application in various geotechnical conditions. Likewise, the Dr and D_{50} methods were chosen to analyze liquefaction potential because they provide in-depth information about soil density and grain size distribution, critical factors in determining soil susceptibility to liquefaction. Dr indicates the level of soil density and stability, while D_{50} provides an overview of the characteristics of soil grain gradation. Combining these two parameters allows for a more accurate assessment of liquefaction risk and helps engineers plan effective mitigation strategies to reduce the impact of earthquakes. Thus, these two methods provide a practical and effective way to evaluate soil susceptibility to liquefaction to reduce the risk of infrastructure damage and impacts on communities in earthquake-prone areas.

Table 1. Sampling location coordinates

No	Coordinate	Location
1.	-0.92164;100.24908	Lolong Belanti, West Padang
2.	-0.91578;100.34711	Ulak Karang, North Padang
3.	-0.90123;100.34408	West Air Tawar, North Padang
4.	-0.89229;100.34336	West Air Tawar, North padang
5.	-0.8799;100.34004	Parupuk Tabing, Koto Tangah

The soil classification systems that will be used are the American Association of State Highway and Transportation (AASHTO) and the Unified Soil Classification System (USCS).

AASHTO using some indexes like Cum. Passing on sieve no.10, no.40, and no. 200 as seen in Table 2. Then USCS used the Cum. Passing No. 4, fine particles and values of Cu and Cc, as shown in Table 2.

Table 2. AASHTO soil requirements type

Group Classification	A-1		A-3
	A-1-a	A-1-b	
Sieve analysis % Passing			
No.10	50 max		
No. 40	30 max	50 max	51 min
No. 200	15 max	25 max	10 max

The data obtained during testing was processed using the formula below:
Determining Field density (γd) from sand cone test:

$$V = \frac{(\text{Dry weight } (Wd))}{(\text{Excavation Volume})} \quad (1)$$

Determining Cc (Coefficient Curvature) and Cu (Coefficient of Uniformity):

$$Cc = \frac{D_{60}}{D_{10}} \quad (2)$$

$$Cu = \frac{{D_{30}}^2}{D_{10}\ x\ D_{60}} \quad (3)$$

Determining Bulk density:

$$\gamma = \frac{W}{Mould\ Volume}\ x\ 100 \quad (4)$$

3 Results and discussion

3.1 Sieve test analysis

Based on direct observation of grain of soil, all of the soil types are sand. The results from the sieve analyses are as shown in Table 3. Sieve analysis results for 5 sampling points.

Table 3. Sieve analysis results

Sieve No.	Cum. Passing (%)				
	1	2	3	4	5
4	99.ysis47	100.00	100.00	100.00	100.00
10	99.30	100.00	100.00	99.87	100.00
20	99.03	82.33	99.33	98.00	99.93
40	95.10	50.90	89.10	76.63	95.07
60	77.50	16.70	66.83	39.17	62.40
100	33.50	4.07	25.03	11.03	15.07
200	5.83	2.33	2.17	2.20	0.07
PAN	0.00	0.00	0.00	0.00	0.00

The classification of soil using AASHTO by the particle size, the index used is Cumulative Passing (%) on the Sieve no. 10, no. 40, no. 200 as shown in Table 4.

Table 4. Soil classification based on AASHTO standard

POINT	Sieve Analysis Passing (%)			AASHTO Classification
	#10	#40	#200	
1	99.30	95.10	5.83	A-3 (fine sand)
2	100.00	50.90	2.33	A-3 (fine sand)
3	100.00	89.10	2.17	A-3 (fine sand)
4	99.87	76.63	2.20	A-3 (fine sand)
5	100.00	95.07	0.07	A-3 (fine sand)

The results of soil classification using the AASHTO method show that the soil in the 5 locations studied is A3 (fine sand). Fine sandy soil has a high liquefaction potential because it has a small grain size so that its smooth surface will reduce interlocking between particles, making the soil looser and susceptible to rapid compaction; loose structure and low density increase the risk of increasing pore water pressure during seismic vibrations; at high saturation conditions.

Then, for the classification of soil using USCS, Coefficient Curvature (Cc) and Coefficient Uniformity (Cu) can be obtained from Sieve analysis test result.

Table 5. Soil classification based on USCS standard

POINT	Cu	Cc	USCS Classification
1	2.436	1.079	(SP) Poorly-Graded Sand
2	2.759	0.939	(SP) Poorly-Graded Sand
3	2.327	1.106	(SP) Poorly-Graded Sand
4	2.455	0.975	(SP) Poorly-Graded Sand
5	1.975	1.077	(SP) Poorly-Graded Sand

Based on Table 5, USCS classification shows that the soil in the Padang coastal area is SP (sand-poor). Poorly graded sand has unique characteristics that make it more susceptible to liquefaction than well-graded soil. Poor gradation means that this soil has particles that are uniform or nearly uniform in size, without significant size variations; because the size is uniform, the soil particles cannot interlock well (poor interlocking), so the soil tends to be looser and less stable; this soil usually has a lower relative density (Dr), which means the soil is more prone to compaction and volume reduction when subjected to loads or vibrations; increased pore water pressure causes a decrease in the shear strength of the soil, which is the primary condition that causes liquefaction.

3.2 Relative density analysis

Relative Density (Dr) has a direct relationship with liquefaction potential. Soils with low Dr are more susceptible to liquefaction due to their low density and poor interlocking ability, while soils with high relative density (Dr) tend to be more stable and have better shear strength. Understanding soil is critical in liquefaction risk evaluation and mitigation planning in earthquake-prone areas.

Table 6. Relative density calculation

g	γ	γ (g/cm3)				
		1	2	3	4	5
	γd	1.221	1.082	1.465	1.177	1.267
	γdmin	1.163	1.058	1.275	1.143	1.153
0.3	*γmdax*	1.440	1.515	1.631	1.412	1.421
0.6	*γmdax*	1.574	1.659	1.731	1.445	1.483

As in Table 6, sample 2 is the lowest field density (γd), and sample 3 is the highest field density (γd). The field Density (γd) of all samples ranges between 1-1.5 g/cm3. The minimal bulk density (γdmin) of all samples ranges between 1-1.3 g/cm3. Sample at points 1, 3 and 5 have no significantly different values of field density (γd). On 0.3g shaking vibration, which is relevant to the Earthquake that occurred in Padang in 2009, has a greater density than 0.6g. According to this result, the soil will become looser as the intensity of vibration increases.

Table 7. Relative density result

g	Point		1	2	3	4	5
0.3	Dr	%	24.61	7.19	59.50	15.30	47.56
	Cond.		L	VL	I	L	L
0.6	Dr	%	18.13	5.98	49.37	13.94	40.34
	Cond		L	VL	L	VL	L

Ex:

I = Intermediate
L = Loose
VL = Very Loose

As shown from the result seen on Table 7, value of Dr ranges between 7-59% (0.3g), and 0.6g ranges between 5-49%. It is clear to observe that on 0.3 g shaking vibration, the soil that will be loose is at points 1, 2, 3, 4, 5. Meanwhile, point 3 is an intermediate condition. However, at a vibration of 0.6g, all points are in a loose condition. Therefore, point 2 is the most influential if an earthquake occurs and can have an enormous liquefaction potential.

3.3 Liquefaction potential

Results from the sieve shaker analysis will be plotted to the Tsuchida Boundary, and then the Dr (%) will be checked by correlation between Dr and D_{50}.

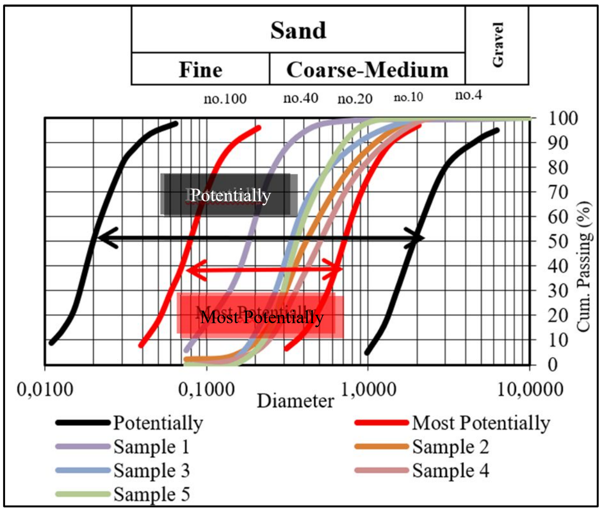

Fig. 7. Tsuchida boundaries liquefaction potential

Based on Figure 7, the results of the gradation of soil grains that have been tested in the previous sieve shaker analysis show that all samples have an enormous potential to liquefy. This is due to the uniformity of the size of the soil grains, causing a lack of binding force between each soil particle.

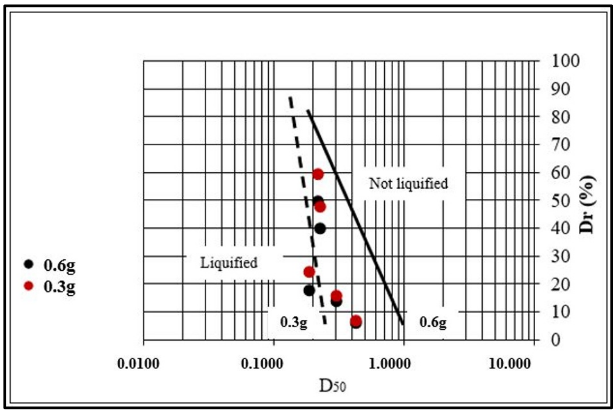

Fig. 8. Dr vs D_{50} liquefaction potential

As seen Fig. 8, at 0.6g vibration shaking, all of the samples potentially liquefy. However, on 0.3g vibration shaking, only one sample potentially liquefied at point 1 at Lolong Belanti, North Padang.

Although sample point 1 has a greater relative density, the D_{50} is smaller than the others. It causes 50% size passing on in a small particle size of 0.186 mm and is classified as fine sand.

Table 8 shows the relationship between Liquefaction Potential based on Dr vs D_{50}, the results show that the 5 (five) points located in the Padang coastal area have the potential for liquefaction at 0.6 g while at 0.3 g, the liquefaction potential only occurs at point 1. The magnitude of the earthquake acceleration also influences the liquefaction potential, as seen in Table 8.

Table 8. Liquefaction potential based on Dr vs D_{50}

Poin	0.3g	Liquefaction Potential	0.6g	Liquefaction Potential
1	24.61	Yes	18.13	Yes
2	7.19	No	5.98	Yes
3	59.50	No	49.37	Yes
4	15.30	No	13.94	Yes
5	47.56	No	40.34	Yes

4 Conclusion

Based on test results, the grain size along the Padang beach is classified as the same type. However, at point 3, the grain size is finer sand due to its location close to the estuary, which is influenced by sediment deposition. Using AASHTO standards, all samples tested were classified as A-3 (fine sand). Using USCS standards, all samples tested are included in poorly graded sand (SP).

Tsuchida analysis shows that the gradation of the samples tested, including into the range, has the potential to liquefy because the soil type is sand with high uniformity.

Based on the relative density value (Dr) of sand soil along Padang Beach, it can be said to be sandy soil with loose density because there are 3 of 5 samples that have a Dr value between 0-15% when 0.3g vibration occurs and all have a Dr value between 0-50% when 0.6g vibration occurs. This analysis shows the relative density of samples tested, including the range that has the potential of both 0.6g and 0.3g liquefy because this indicates that the density of the soil is still relatively low.

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