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LIQUEFACTION POTENTIAL ANALYSIS USING VARIOUS METHODS (CASE STUDY OF RAILWAY BRIDGE IN SINTUK TOBOH GADANG DISTRICT, PADANG PARIAMAN REGENCY, WEST SUMATERA)

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ABSTRACT
The earthquake that rocked West Sumatra with a magnitude of 7.9 SR, a depth of 71 km, and an epicenter of 0.84 LS - 99.65 BT around 57 km Southwest of Pariaman on 30 September 2009 has caused damage to infrastructure and buildings and caused 383 fatalities. One of the problems caused by the earthquake is the liquefaction phenomenon. Liquefaction was reported to have occurred in Padang in the form of sand ejection coming out of cracks in the ground after the 7.9 SR earthquake in 2009. This study aims to determine the liquefaction potential of the Sintuk Toboh Gadang railway, Pariaman, using various liquefaction potential analysis methods so that the most practical and convincing method is obtained among these methods. In this study, the methods used to predict liquefaction are the Tsuchida (1970), Seed & Idriss (1971), Shibata & Teparaksa (1988), and Hakam (2020) methods. Field testing was conducted at four CPT test points, four NSPT test points, and machine drilling tests. The results showed that using the Tsuchida (1970) method, soil deposits at the four points tended to have liquefaction potential. The Seed & Idriss (1971) method showed that points 3, with depths of 8m and 14m, and point 4, with a depth of 8m, had liquefaction potential, while the Shibata & Teparaksa (1988) method using CPT data showed that at depths <10 meters there was a tendency for liquefaction to occur at the four points reviewed. The study's results using the Hakam (2020) method resemble the method proposed by Seed & Idriss (1971). It can be concluded that among the four methods, the most practical and convincing method is the Hakam (2020) method.
Keywords: *Earthquake, Liquefaction, Liquefaction Potential Analysis Methods.*

1. Introduction

Liquefaction is an event where the condition of the soil changes from a solid to a liquid state. Liquefaction is often found in earthquakes where soil behavior occurs due to earthquake loads that occur in only a short time. Earthquake vibrations that propagate in soil deposits in a short time cause the soil mass to transition from a solid state (behavior) to a liquid state (fluid behavior) (Kramer, 1996; Das, 1989; Putra et al., 2009; Hakam, 2012; Yuliet et al., 2019; Hakam, 2020; Adji et al., 2021). Liquefaction can occur in sandy soil because cyclic loads are applied to the sandy soil, resulting in an increase in stress between soil elements followed by an increase in pore water pressure in the soil. At the same time, due to the cyclic load, the total stress in the soil mass increases. The increase in pore water pressure can equal the total stress that occurs so that the effective soil pressure is lost. The liquefaction behavior that occurs in sandy soil can flow and sink objects above it (Wang, 1979; Aydan et al., 2008; Kogai et al., 2000; Muntohar, 2009; Wang & Yanli, 2010).

Padang Pariaman Regency is an area located in West Sumatra Province, where the regency is surrounded by two active plates, namely the Asian plate and the Indian plate, making Padang Pariaman Regency as regency that is prone to earthquakes. The earthquake that hit West Sumatra with a strength of 7.9 SR and a depth of 71 km and the epicenter at 0.84 LS - 99.65 BT approximately 57 km Southwest of Pariaman on September 30, 2009 has caused damage to infrastructure and buildings and caused 383 fatalities. One of the problems caused by the earthquake is the liquefaction phenomenon.

Padang City is a city located in the north of Padang Pariaman Regency or a city adjacent to Padang Pariaman Regency. This city is one of the cities in West Sumatra Province that was reported to have experienced liquefaction due to the earthquake on September 30, 2009. The phenomenon of liquefaction and land surface deformation caused by the earthquake occurred at several points around the river flow or in areas several kilometers from the coast. The liquefaction event can be observed by the presence of water seepage out of cracks in the ground during an earthquake. In addition, the occurrence of liquefaction can also be marked by the sinking and tilting of several buildings as well as horizontal movement on a large scale (Warman & Jumas, 2013). Liquefaction potential analysis is critical in seismic areas, especially for bridge and railway infrastructure, because this phenomenon can cause severe impacts on ground stability and infrastructure safety (Esmaeili & Noghabi, 2013; Tabatabaei et al., 2019). Liquefaction causes land subsidence, which affects severe damage to railway infrastructure such as shifting or bending of rail tracks, increasing the risk of accidents such as train derailments. Mitigation must be done to determine locations with potential for liquefaction, select suitable construction types, improve soil, and design liquefaction-resistant structures. Liquefaction analysis can help reduce the risk of infrastructure damage and post-disaster repair costs (Zhou & Chen, 2007; Lai et al., 2020; Ghani & Kumari, 2023). The Sintuk Toboh Gadang Railway Line, Pariaman city is a railway line that plays an important role in connecting areas in West Sumatra, including transporting goods and passengers to and from Padang. Analysis of liquefaction potential in Sintuk Toboh Gadang railway is fundamental because this area has a high risk of liquefaction due to seismic activity, soil type, and high groundwater level. Sintuk Toboh Gadang is an area with alluvial soil layers dominated by loose sand and fine-grained soil that tends to be saturated with water. This type of soil is susceptible to liquefaction when hit by earthquake shocks. This area has a shallow groundwater level because the area is a lowland area close to the coast. Intense and prolonged earthquake shocks can trigger liquefaction in saturated soil, damaging railway infrastructure. Soil that loses its bearing capacity can cause rail sleepers and other supporting structures to become unstable, increasing the risk of train accidents and disrupting train operations so that passenger mobility and distribution of goods in the area will be hampered.

On September 28, 2018, an earthquake in Central Sulawesi measuring 7.4 Mw caused several areas to experience disasters such as a tsunami on the coast of Donggala and Palu, a fire in Balaroa Village, and a liquefaction disaster in the Palu and Sigi areas (Setiawan & Kurniawan, 2021). Liquefaction in this earthquake caused massive landslides and caused damage to the Balaroa and Petobo areas with liquefied soil flows. Several studies have been conducted since ancient times to evaluate the potential for liquefaction in soil deposits. Engineers and researchers mostly conduct liquefaction potential studies based on soil testing in the field and in the laboratory. Day (2002) explains that there are at least 12 factors that affect the potential for liquefaction in a soil. These factors are earthquake intensity and duration, groundwater level, soil type, relative soil density, grain size gradation, soil layer placement conditions in the environment, drainage conditions, particle shape, age and cementation factors, past environmental conditions, and building loads ((Ishihara, 1985; Rahman & Sik-Cheung, 2008; Hakam & Ismail, 2016; Asema et al., 2022).

Liquefaction that has occurred in several areas in Indonesia has had varying effects on the surface soil layers, ranging from sand bursts on the surface of the soil, loss of water in dug wells, to a combination with surface soil movement. Figure 1 shows the distribution of liquefaction potential in the province of West Sumatra, the coastal areas have to liquefaction potential.

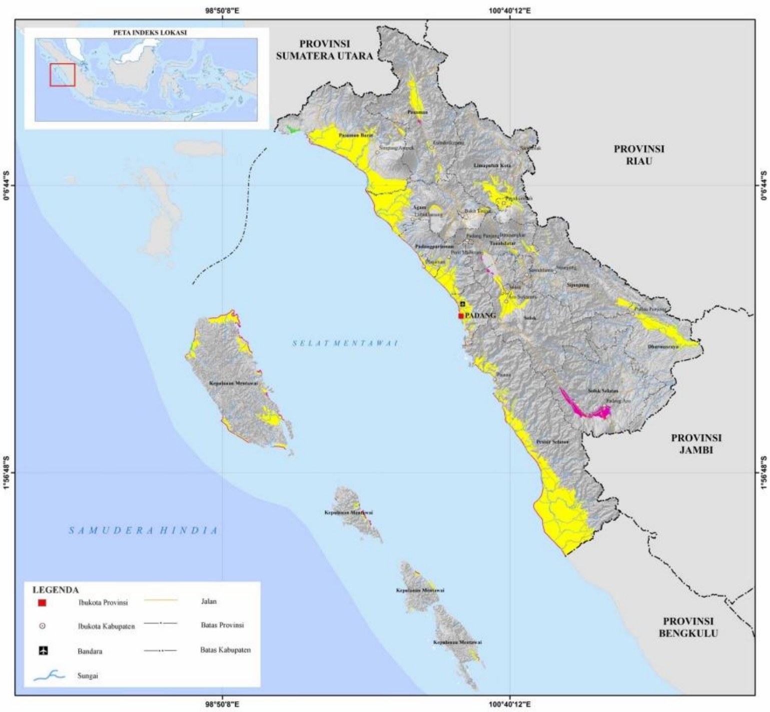

Fig. 1. Map of liquefaction vulnerability zones in West Sumatra Province (Ministry of Energy and Mineral Resources, 2019).

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, Padang Utara, Padang Timur, and Padang Selatan subdistricts where sand boiling, settlement, and lateral movement in high vulnerability zones (Tohari, 2020). Liquefaction vulnerability information is very important in increasing government and community preparedness in facing the possibility of liquefaction phenomena in the future. Easy-to-read and understand information is needed for the dissemination of liquefaction hazard information among stakeholders and the wider community. With the mapping of liquefaction potential, strategic steps can be taken to reduce the impacts that occur (Hakam & Darjanto, 2013; Novasari et al., 2023; Sudondo et al., 2024).

Studies and methods for analyzing liquefaction potential challenges such as the diversity of soil conditions, limited data, and the lack of universal standards. However, technological developments and increasing awareness can help overcome these challenges. In addition, environmental changes in human activities, such as urbanization and infrastructure development, can change soil characteristics, affecting liquefaction potential (Youd & Idris, 2001; Prasad, et al., 2019; Abdulhakim & Phani, 2023). The limitations of the methods used to analyze liquefaction potential quickly, precisely, and accurately depend on historical data, so they are less accurate when applied to locations with different geological conditions (Subedi & Acharya, 2022; Sahua & Tiwari, 2023). Using computer simulations to predict soil behavior during earthquakes has limitations and requires complete and correct input data, such as soil parameters and earthquake recordings. It is highly dependent on model assumptions, which can affect the analysis results. While the laboratory test approach requires soil testing to determine soil behavior to earthquake shaking, the limitations are that soil samples often do not represent actual conditions in the field, and many areas at high risk of liquefaction do not have adequate geotechnical data due to budget constraints that require field surveys and laboratory testing.

The gap between this research and other studies is that this research uses not only one method to analyze the liquefaction potential of a soil deposit, but this research uses various methods so that the results obtained are expected to be more accurate by comparing these methods with liquefaction events that have been recorded in history. Based on the problems above, it is necessary to analyze liquefaction potential using a method that is fast, precise, simple, practical and produces accurate outputs. This study was carried out using four methods using field and laboratory data obtained on the railway bridge in Padang Pariaman.

2. Research Methods

The location of research was conducted in Nagari Sintuk, Sintuk Toboh Gadang District, Padang Pariaman Regency. Data were obtained by collecting secondary data where the sondir, machine drill and SPT tests. This study used 4 (four) test points and soil sampling. Sondir and SPT testing were carried out until hard soil was found, and soil samples were taken for laboratory testing using boring. Sondir/CPT testing is by SNI 2827 of 2008, SPT is by SNI 4153 of 2008, and boring testing is by SNI 2436 of 2008. Samples obtained in the field from machine drilling testing were then tested in the laboratory, including water content tests (SNI 1965 of 2019), volume weight (SNI 03 - 3637 of 1994), specific gravity (SNI 1964 of 2008), sieve analysis (SNI 3423-2008). Unconfined Compressive Strength Test (SNI 3638 in 2012), and direct shear (SNI 3420 in 2016). This test was conducted at the Soil Mechanics Laboratory, Civil Engineering Department, Andalas University.

Data was obtained, a liquefaction potential analysis was carried out using various methods. Various methods for liquefaction potential analysis are essential because liquefaction is a complex phenomenon influenced by many factors, such as soil properties, hydrogeological conditions, and earthquake intensity. The combination of methods allows for more accurate, comprehensive, and reliable results to mitigate risks to infrastructure. Each analysis method has its strengths and weaknesses. Using various methods helps minimize errors if only relying on one approach. Based on the results of previous researchers and current researchers, this study will compare 4 (four) types of methods, namely the Tsuchida method (1970), the Seed & Idriss method (1970), the Shibata & Teparaksa method (1988), and the Hakam method (2020) which aim to determine the research area that has the liquefaction potential or not, then the more practical and convincing method will be chosen among these methods.

2.1. Tsuchida Method (1970)

In 1970, Tsuchida proposed a method to analyze the liquefaction potential based on soil grain size. This method uses a gradation curve to observe the liquefaction behavior of soil in several earthquakes that occurred in Japan and showed similar responses after laboratory tests using a shaking table test. Figure 2 shows the grain size limits of soil that are potentially liquefiable and non-liquefiable. Figure 2 of the Tsuchida Graph shows that fine-grained soils (silty and finer) with an average grain size D_{50} of 0.02 mm are considered liquefiable at an unspecified shaking level. Uniformly gradated soils have higher liquefaction potential than well-graded soils. The Tsuchida method is suitable for the initial evaluation (screening) of liquefaction potential, especially on sandy soils with simple gradation. This method is simple and fast because it only requires basic data such as grain size distribution and soil gradation and does not require complex field tests or laboratory tests so that it can be applied more quickly, and the costs used are cheaper. The Tsuchida method can be used as an initial screening of a location for liquefaction potential. However, the analysis of liquefaction potential with this method is not deep enough, especially if data is needed on the effects of earthquakes, hydrogeological conditions, or mechanical characteristics of the soil.

Ishihara et al. (1980) stated that Tsuchida's (1970) chart was based only on the performance of soils of native alluvial, dilluvial, or volcanic origin, and the boundaries of liquefaction-prone soils did not correspond to soils containing a low plasticity fraction of clay particles. Tokimatsu & Yoshimi (1983) collected field soil testing data from earthquake events in Japan that correlated observed soil behavior with local soil gradation characteristics. Soils containing up to 60 percent silt-size particles and 12 percent clay-size particles (i.e. particles smaller than 0,005 mm) showed moderate to extensive liquefaction (in terms of land area affected). Their compilation did not include indices of soil properties, such as the Atterberg Limit, which has been shown to influence cyclic strength.

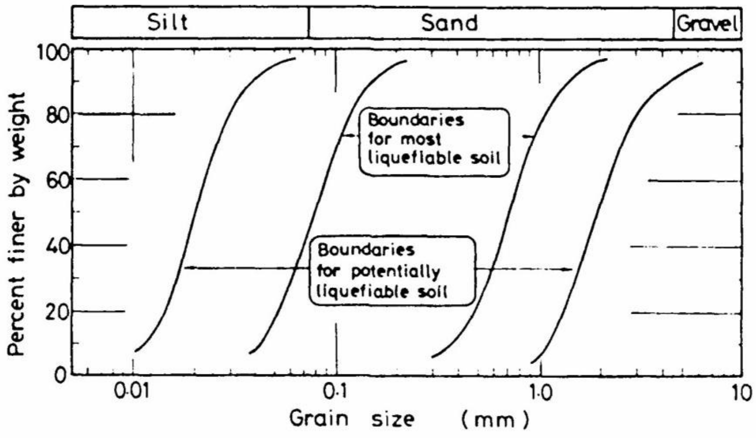

Fig. 2. Gradation of liquefiable soil according to Tsuchida (1970)

2.2. Seed & Idriss Method (1971)

The Seed & Idriss method (1971) is a practical and widely accepted approach to evaluate liquefaction potential. This method is flexible, has a strong empirical basis, and considers soil conditions, loads, and seismic parameters. The method's limitations include complex soil conditions, non-sandy soil, or earthquakes with non-homogeneous cyclic stress distributions. Therefore, although this method is suitable for initial evaluation, it is often necessary to combine it with other methods or more detailed numerical analysis for more complex soil conditions or high-risk areas to obtain more reliable results.

Another way to evaluate liquefaction potential is by testing the standard penetration resistance (N_{SPT}) in the field. The first step to evaluate liquefaction potential is by calculating the effective vertical stress with the following equation:

$$\sigma_{v'} = (\gamma \text{ x h}) - (\gamma_w \text{ x } h_w) \quad (1)$$

After that, the CN value is calculated using the following formula:

$$\text{CN} = 9{,}78\sqrt{\frac{1}{\sigma_{v'}}} \quad (2)$$

After the C $_{N\ value}$ is obtained, calculate the N' value (correction to the $_{SPT\ N\ value}$) with the following equation:

$$N' = C_N \text{ x } N_{SPT} \quad (3)$$

Next, the N' value obtained is used to obtain the field value $(\tau_h/\sigma_v)_{field}$ for an earthquake with a magnitude of 7.5 which is obtained from the image below.

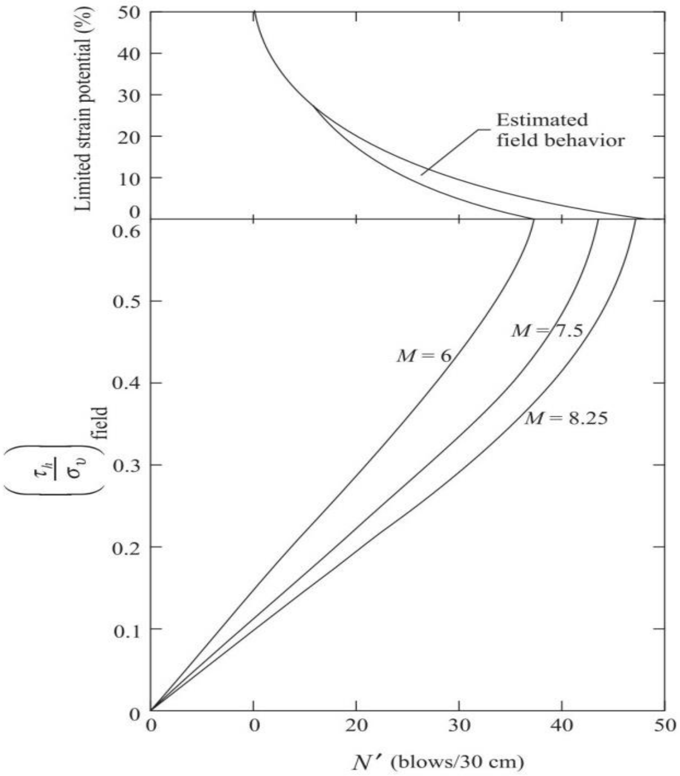

Fig. 3. The values of $(\tau_h/\sigma_v)_{field}$ with N' (after Seed, 1979).

Then calculate the value τ_h (force that resists liquefaction) with the following equation:

$$\tau_h = \left(\frac{\tau_h}{\sigma_v}\right)_{field} x\ \sigma_{v'} \tag{4}$$

Then determine the value of C_D (correction factor per depth reviewed) from the image below.

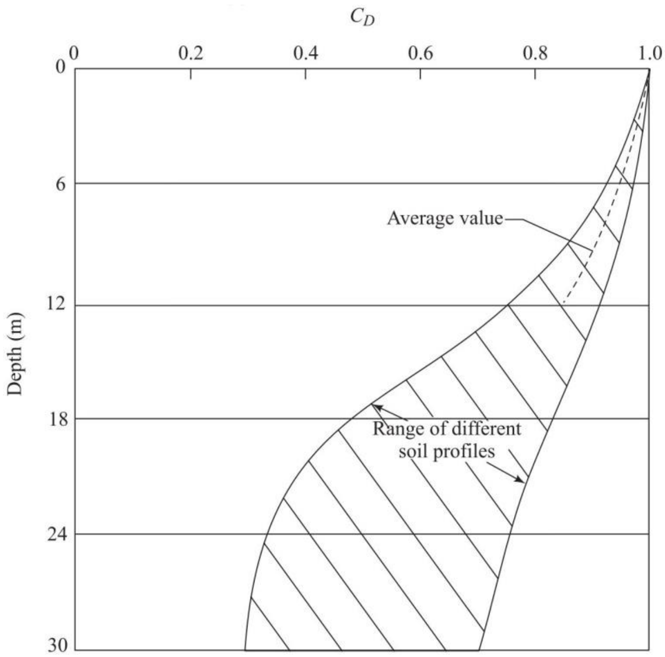

Fig. 4. C_D value against depth (Seed & Idriss, 1971)

The final step is to determine the value τ_{av} using the following equation:

$$\tau_{av} = 0{,}65\ C_D\ \left[\left(\frac{\gamma\ x\ h}{g}\right) a_{max}\right] \tag{5}$$

Check if the value $\tau_{av} \geq \sigma_h$ then sand deposits at that depth have the potential for liquefaction.

2.3. Shibata & Teparaksa Method (1988)

Several practical methods for evaluating the liquefaction potential of soil deposits subjected to earthquake loading have been developed using in-situ (field) testing techniques. Examples include the Standard Penetration Test (SPT), the Cone Penetration Test (CPT), and shear wave velocity measurements. SPT has been widely used for many years in Japan and North America, but SPT has now become more popular as an in-situ (field) test for site investigation and geotechnical design. The advantages of Cone Penetration Test (CPT) are its simplicity and continuous recording (Robertson & Campanella, 1983; Robertson & Campanella, 1986; Cetin et al., 2000). One disadvantage of CPT in predicting the liquefaction potential of a soil deposit is that CPT has limited data to make a correlation between the characteristics of the soil deposit that are likely to experience liquefaction. Another problem is the unavailability of samples, so the soil type must be inferred from the CPT data.

To evaluate liquefaction potential using CPT (Shibata & Teparaksa, 1988) proposed a practical method, namely the corrected cone resistance (q_{c1}), and the cyclic stress ratio (CSR) generated by the ground motion due to the earthquake. The cone resistance needs to be corrected with the following formula :

$$q_{c1} = C_1 \text{ x } q_c = \left(\frac{1{,}7}{\sigma_{0'} + 0{,}7}\right) q_c \qquad (kgf/cm^2) \tag{6}$$

$$q_{c1} = C_1 \text{ x } q_c = \left(\frac{0{,}17}{\sigma_{0'} + 0{,}07}\right) q_c \qquad (MPa) \tag{7}$$

Where C_1 is the correction factor for the effective vertical stress (overburden) ($\sigma_{0'}$) at the depth of the CPT test carried out (see figure below).

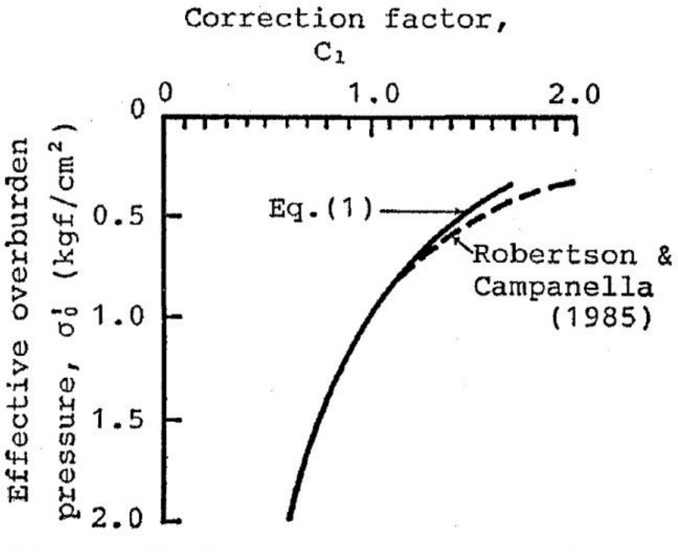

Fig. 5. C_1 value against σ_0'(Shibata & Teparaksa, 1988).

The CSR cyclic stress ratio that occurs in the field during an earthquake can be estimated using the following formula:

$$CSR = 0{,}1 \text{ x } (\text{M} - 1) \text{ x } \frac{a_{max}}{g} x \frac{\sigma_0}{\sigma_{0'}} x \, [1 - 0{,}015(z)] \tag{8}$$

Where :

M = magnitude of earthquake

σ_0 = total stress in the vertical direction

σ_0' = effective vertical stress (overburden)

a_{max} = maximum horizontal acceleration on the ground surface

Z = depth (m)

After the value q_{c1} and CSR value are obtained, they are plotted into the liquefaction potential graph proposed by (Shibata & Teparaksa, 1988) as shown below.

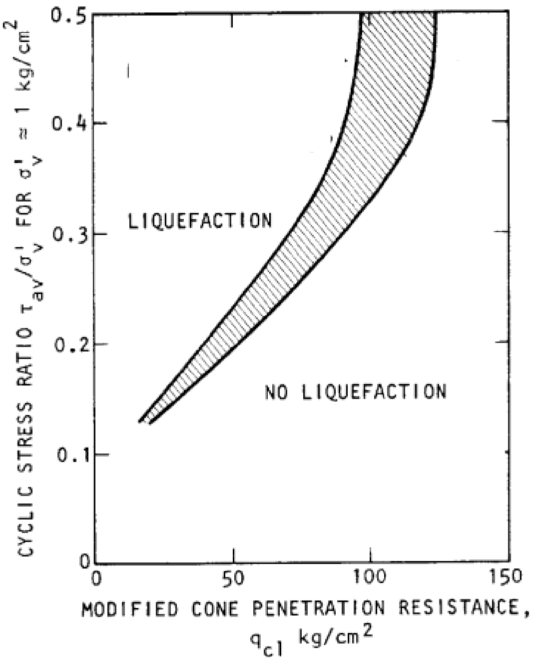

Fig. 6. Graph of Liquefaction Potential based on value q_{c1} vs CSR.

2.4. Hakam Method (2020)

Hakam (2020) stated that to analyze the potential for liquefaction at a location, the following steps can be taken. First, conduct a geotechnical investigation at the location to obtain the main soil parameters at a certain depth. The investigation was conducted using a machine drill so that it can reach a depth of up to 30 meters from the ground surface. In the investigation, disturbed and undisturbed soil samples were taken. Usually, the machine drill investigation will also be followed by a standard penetration test to obtain the value of N_{SPT}. Second, disturbed soil samples at a certain depth are tested in the laboratory using sieve analysis to obtain the distribution of soil grain size so that obtained the parameter of D_{50}.

Disturbed soil can also be used for maximum volumetric weight (γ_d) testing, and minimum volume weight $(\gamma_d)_{min}$ while the original soil sample tested its volume weight (γ) and water content (ω). Furthermore, the dry volume weight (γ_d) of the original soil can be calculated using the following equation :

$$\gamma_d = \frac{\gamma}{1 + \omega} \tag{9}$$

The relative density of the soil is calculated using the following equation:

$$Dr = \left(\frac{\gamma_d - (\gamma_d)_{min}}{(\gamma_d)_{\max} - (\gamma_d)_{min}}\right)\left(\frac{(\gamma_d)_{max}}{\gamma_d}\right) \tag{10}$$

If undisturbed soil sampling fails so that the original undisturbed sample is not obtained, the relative density value can be calculated using the following equation:

$$Dr = 0{,}0006\, N^3 - 0{,}075\, N^2 + 3{,}9\, N \tag{11}$$

Where: N = N_{SPT} (Gibbs & Holtz, 1957) or N_{60} (Terzaghi, 1996).

After the parameters D_{50} and Dr are obtained, both are plotted into a liquefaction diagram made from the results of laboratory testing and comparison of liquefaction data in the figure below. If the meeting point of D_{50} - Dr are on the left side of the acceleration boundary line, then the soil layer at that point has the potential to experience liquefaction if an earthquake occurs.

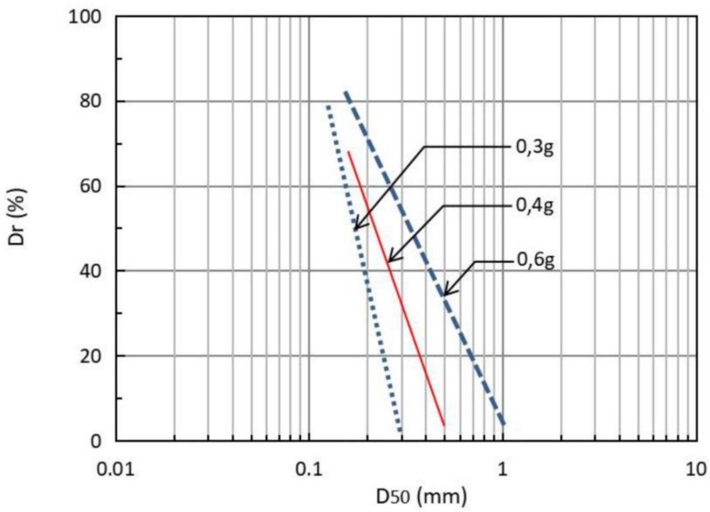

Fig. 7. Liquefaction Potential Diagram (Hakam, 2020)

2.5. Relevant Research

Andriani et al. (2025) conducted a study on the liquefaction potential around the Padang coast, West Sumatera Province. The study utilized the Tsuchida method and the Dr-D_{50} method. The results indicated that all tested samples from the five locations around the Padang coast exhibited liquefaction potential when analysed using the Tsuchida method with sieve analysis. This was due to the uniformity of soil grain size, which led to a lack of cohesive force between soil particles. Another method used was the Dr-D_{50} method. Their findings showed that all samples had the potential to liquefy under a vibration of 0.6g. However, at a vibration of 0.3g, only one sample showed liquefaction potential, which was at point 1 in Lolong Belanti Subdistrict, North Padang. Although the sample at point 1 had a higher relative density, its D_{50} value was smaller than the others. This resulted in 50% of the grain size passing through a fine particle size of 0.186 mm, classifying it as fine sand.

Fachriansyah et al. (2025) conducted a geotechnical investigation to predict the liquefaction potential in the Gunung Pangilun area, Padang City. The field investigations carried out included the CPT test (Seed & Idriss method) and sieve analysis test (Tsuchida method). The results of the study indicated that the soil layers in the area have the potential to liquefy at depths greater than 1 meter when analysed using both methods. It shows that the surface of the soil consists of fine sand layer with grains passing sieve no. 200 is 0% and dry soil condition (the groundwater level is at a depth 0f 1.2 m), based on the size distribution graph and D_{50} value, soil samples on the soil surface do not have the liquefaction potential.

Ismaili & Asyifa (2022) analysed the liquefaction potential based on SPT and CPT data in the Yogyakarta International Airport area. The initial step they took was collecting soil data obtained from field tests conducted by PT. Pembangunan Perumahan (Tbk) incollaboration with Yogyakarta International Airport. Then conducted an analysis by determining the Safety Factor (SF) value by comparing the CRRMW value with the CSR value. If SF<1, it can be concluded that the soil layer has the potential to undergo liquefaction with an earthquake magnitude of 7.5 Mw. SF value is an indicator where a study area has liquefaction potential or does not have liquefaction potential. From the two data used, namely SPT and CPT, in general the location or area of the Yogyakarta International Airport has the potential to experience liquefaction. Therefore, appropriate mitigation and handling measures are needed to reduce the risk or impact of liquefaction.

Adji et al. (2021) observed a study on liquefaction disaster mitigation along the railway corridor in Padang City, West Sumatera. This research was carried out by plotting of four liquefaction events and liquefaction potential in Padang City. The results were then combined with the railway corridor in Padang City. There are four segments of the railroad corridor in Padang City, which are in areas with potential for liquefaction, namely in Air Tawar water areas (Basko Mall), Alai area, Simpang Haru and Sungai Air, Kota Tua.

Rahayu et al. (2021) investigated the potential for liquefaction using CPT (Cone Penetration Test) and grain size distribution analysis, with a case study in Lolu Village, Jono Oge Subdistrict, Palu City. In evaluating liquefaction potential, the CPT data is processed with the Idriss-Boulanger method, referring to the value of soil safety factors based on the ratio between ground resistance to liquefaction (CRR) and earthquake (CSR). Whereas grain size distribution tests are carried out based on ASTM, referring to soil type composition's influence on the level of liquefaction potential. The results from eight CPT in Lolu village shows that liquefaction potential occurs at a depth of 5 to 10 m with varying end resistance and friction ratio values of the soil. Likewise, grain size distribution tests indicate that soil types are dominated by sandy soils vulnerable to liquefaction.

Yuliet et al. (2019) evaluated the Nurul Haq shelter building constructed on liquefaction prone area in Padang City, Indonesia. The evaluated of liquefaction potential using the Seed & Idriss method. From the result of the soil evaluation, it was found that the soil in the shelter location has high liquefaction potential. Therefore, the shelter structure is analysed using specific response spectrum of the earthquake loads. Considering soil liquefaction, which is 1.5 higher than those on the non-soil liquefaction. The tsunami loads were calculated used based on FEMA P-646. The analysis result shows that the shelter building is not capable of resisting the working loading, in which the elements of the beams and foundations do not have enough capacity to resist the working loads, especially earthquake and tsunami loads. Furthermore, the shelter building should be retrofitted before being used as a vertical evacuation building.

Mase (2017) observing the study of liquefaction time stages due to a short duration shaking. The main point that can be concluded in his study are as follows : the maximum excess pore water pressure is the main factor in studying liquefaction. In this study, the maximum excess pore water pressure ratio resulted on each test is larger than one, which means all dynamic loads applied trigger the soil liquefaction showing that the considered PGAs of 0.3g, 0.35g, and 0.4g, potentially triggered soil liquefaction in Southern Opak riverbank. Then soil condition, soil type, and the dynamic loads may influence the liquefaction potential during a short shaking duration. The applied dynamic loads can influence the initial time of liquefaction, the initial time of pore water pressure dissipation, and the liquefaction duration.

Hakam & Ismail (2016) have studied the liquefaction potential based on laboratory tests. Based on that study, the method to assess the liquefaction potential then is proposed. In laboratory tests, the vibration source is given by using the shaking table. During the tests, the acceleration and settlement are recorded. It then concluded that there is a relationship between density and grain size particle associated with liquefaction resistance for certain acceleration of vibration. The cone penetration and relative density relationship has been developed based on experiments in laboratory. Based on the results of those laboratory tests, the liquefaction potential of a certain site then assessed. It is found that the relative density and mean gain size relationship can be used to assess liquefaction potential in sand deposits.

Uyanik (2020) conducted soil liquefaction analysis based on soil and earthquake parameters. This study is based on 315 case history data gathered from 22 earthquake. In addition, these data were examined using another liquefaction analysis method and the results were compared with the proposed method. The proposed method was applied to 315 data collected from liquefied or non-liquefied regions. This method determined the liquefaction potential of 118 data collected from liquefied regions with 100% reliability. Additionally, the method correctly predicted the non-liquefaction conditions of 197 data from non-liquefied regions with 66% reliability. In order to increase the reliability of this method, additional region work for either liquefied or non-liquefied soil types is required, using denser soil (Vs_c > 250 m/s) subject to more powerful ground movement (a_{max} = 0,48g), especially in deeper deposits (z> 15m).

Ntritsos & Cubrinovsk (2020) in their paper mention that they present the key steps of an advanced seismic effective stress analysis procedure, which on one hand can be fully automated and, on the other hand, requires no additional input (at least for preliminary applications) compared to simplified cone penetration test (CPT) based liquefaction procedures. In this way, effective stress analysis can be routinely applied for quick, yet more robust estimations of liquefaction hazards, in a similar fashion to the simplified procedures. Important insights regarding the dynamic interactions in liquefying soils and the actual system response of a deposit can be gained from such analyses, as illustrated with the application to two sites from Cristchurch, New Zealand.

Hossain et al. (2020) studied the assessment of seismic hazard potential for a small town (Moulvibazar) in northeastern Bangladesh. Documenting liquefaction potential indices for different surface geological units using an earthquake of moment magnitude Mw 8 having a peak horizontal ground acceleration (PGA) of 0.36g. Twenty five standard penetration test (SPT) boreholes were completed within the study area to obtain SPT-N values for two surface geological units: (1) Holo-Pleistocene low elevated terrace deposits (Zone 1) and (2) Holocene flood plain deposits (Zone 2). Using the SPT-N values, the LPI values have been calculated for the soil profile of each borehole. The LPI values in the town vary from 0 to 42.33, whereas values from 1.42 to 7.52 are in Zone 1 and values from 0 to 42.34 are in Zone 2. It has been predicted that 42% and 78% areas of Zone 1 and Zone 2, respectively, might exhibit surface manifestation of liquefaction. The results of this study can be used for seismic risk management of Moulvibazar town.

Cappellaro et al. (2021) investigated the liquefaction resistance of sandy soils from Christchurch, New Zealand using direct simple shear tests. The study focuses on the combined effects of soil density and fines content on liquefaction resistance of sandy soils. The results of cyclic direct simple shear tests for soils containing up to 30% fines show reasonably consistent liquefaction resistance relative to estimates from empirical CPT-based liquefaction triggering relationships.

Pratama et al. (2021) analyzed liquefaction potential using the simplified procedure based on the Standard Penetration Test (SPT) and Cone Penetration Test (CPT). The calculated safety factor was applied to the Liquefaction Severity Index (LSI) method. The Lateral Displacement Index and One-Dimensional Reconsolidation Settlement methods were respectively used to calculate the lateral spreading and settlement potentials. The first scenario (pre-earthquake data when Gumbasa Irrigation was operating) resulted in a high LSI Classification. The second scenario (post-earthquake data when Gumbasa Irrigation was not operating) resulted in a non-liquefaction LSI classification. Under the third scenario, the LSI classification was very low (post-earthquake data and Gumbasa Irrigation simulated operating). The results showed that the liquefaction potential of Gumbasa Irrigation Area when either on/ off operating conditions was related to the role of groundwater level.

Jalil et al. (2020) analyzed the liquefaction potential conducted on 16 boreholes incorporating Standard Penetration Test (SPT) that investigated the soil engineering properties and geological conditions of the study area. The peak ground acceleration (PGA) for each borehole location was obtained from the value determined by the Ministry of Public Works and Public Settlement of Indonesia. The analysis of liquefaction potential in Banda Aceh City adopted the semi-empirical of the Idriss method with an input moment magnitude of 7.8 and 9.2

Mw, respectively. The liquefaction potential was evaluated at 5m, 10m, and 15m depths below the ground surface. The analysis resulted in 4 zones of liquefaction potential levels, i.e., very high, high, low, and very low. High liquefaction potential zones occur in the Sub-districts of Baiturrahman, Kuta Alam, and Syiah Kuala. Meanwhile, low and very low liquefaction potential spread over the northeast, western, and southern parts of Banda Aceh.

Sukkarak et al. (2021) conducted a liquefaction analysis on sandy soils when a strong earthquake struck northern Thailand. This research augmented experimental results with numerical methods to evaluate the liquefaction potential of Mae Lao sand in Chiang Rai province of northern Thailand. Results from numerical simulation of sand liquefaction were used to characterise the stress-strain-pore water pressure response of Mae Lao sand. 1D site response analysis determined seismic response with different geological and groundwater conditions. All put together, the results showed that pore water pressure ratio decreases with increasing sand stiffness, the thickness of a soil layer significantly increase its liquefaction potential, and in-situ conditions and groundwater depths have major influences on the liquefaction potential of sand layers.

3. Results and Discussions

In this study, the CPT testing location was carried out at four points in the area around the railway bridge in Nagari Sintuak, Sintuk Toboh Gadang District, Padang Pariaman Regency. Similar to the CPT test, the boring and SPT tests were also carried out at four points where the test points were approximately 2 meters from the test point. For more details, see Figure 3.

Fig. 8. Research Location at Railway Bridge In Sintuk Toboh Gadang District, Padang Pariaman Regency, West Sumatera.

3.1. Results of Liquefaction Potential Analysis

At point 1, the sounding test data obtained in the field were then analyzed for liquefaction potential using the Shibata & Teparaksa (1988) method. The summary of the liquefaction potential calculation is presented in the table below.

Table 1 - Results of Liquefaction Potential Analysis of Point 1 Shibata & Teparaksa Method (1988)

No	Depth (m)	q_c (Kg/ cm²)	CSR	q_{c1} (Kg/ cm²)	Liquefaction Potential? Yes/No
1	1	9	0.377	19.321	Yes
2	2	15	0.382	29.183	Yes
3	3	21	0.365	36.589	Yes
4	4	47	0.350	73.465	Yes
5	5	7	0.282	8.153	Yes
6	6	78	0.330	101.113	No

No	Depth (m)	q_c (Kg/ cm²)	CSR	q_{c1} (Kg/ cm²)	Liquefaction Potential? Yes/No
7	7	75	0.325	90.214	Yes
8	8	40	0.328	46.095	Yes
9	9	8	0.364	9.769	Yes
10	10	11	0.259	8.427	Yes
11	11	62	0.319	61.605	Yes
12	12	70	0.314	66.008	Yes
13	13	105	0.292	88.161	No
14	14	80	0.302	68.459	Yes
15	15	45	0.296	36.805	Yes
16	16	185	0.276	134.955	No

Next, the sieve analysis test obtained from sampling using boring point 1 was analyzed for liquefaction potential using the Tsuchida method (1970), producing a resume as below.

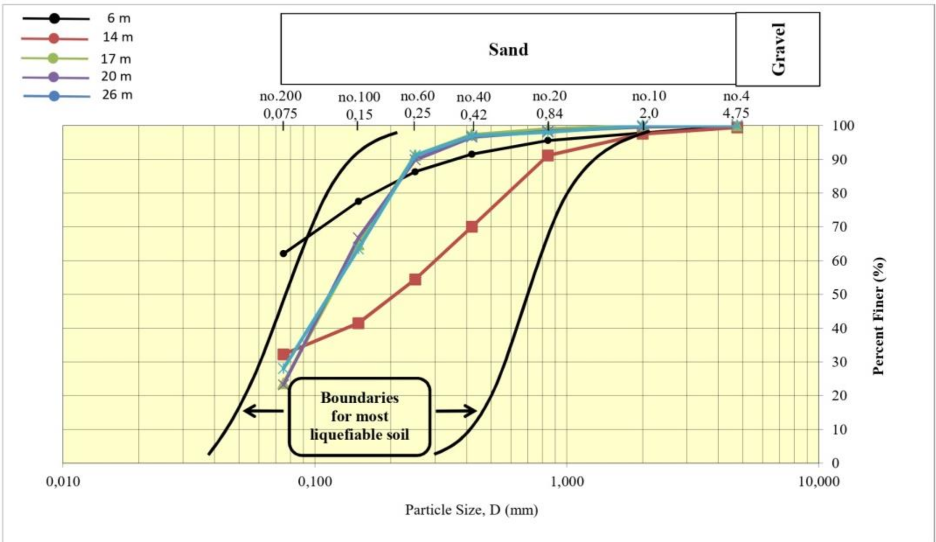

Fig. 9. Results of Liquefaction Potential Analysis of Point 1 Tsuchida Method (1970).

From the graph above, it can be seen that the soil deposit has a high potential for liquefaction because the grain gradation curve is within the liquefaction potential boundary line. A summary of the liquefaction potential of point 1 of the Tsuchida (1970) method can be seen in the table below.

Table 2 - Results of Liquefaction Potential Analysis of Point 1 Tsuchida Method (1970)

No	Depth (m)	Liquefaction Potential? Yes/No
1	6	No
2	14	Yes
3	17	Yes
4	20	Yes
5	26	Yes

Table 2 shows that the liquefaction potential is only based on grain gradation and does not consider seismic parameters such as earthquake intensity, ground acceleration, or vibration duration, which are essential factors in triggering liquefaction. This method does not consider local variations such as soil structure, pore water pressure, or soil stratification effects that can affect liquefaction potential. So, the Tsuchida method is used as an initial screening to detect liquefaction potential based on soil grain gradation to obtain accurate results; further analysis needs to be carried out by taking into account seismic factors, groundwater conditions, and others. Figure 9 shows that soil with uniform gradation and poor gradation has the potential to experience liquefaction. This is similar to the results of the study by Zakirah & Wulandari (2020), which stated that the curve produced in the D_{60} and D_{10} ranges, which are concave and poorly graded, will have liquefaction potential.

3.2. Summary of Liquefaction Potential Analysis Results

The following table presents a summary of the liquefaction potential for the 4 (four) test points. Based on Table 3, it can be seen that by using the Tsuchida method, it shows that at point 1, the liquefaction potential occurs at a depth of 6 - 26 m. This is in contrast to the Seed & Idriss, Shibata & Teparaksa, and Hakam methods. This also occurs at points 2, 3 and 4. The difference in results obtained is due to the Tsuchida method analyzing the liquefaction potential based on the physical properties of the soil alone, namely grain gradation without considering other parameters such as seismic factors, water saturation levels, groundwater levels, geological conditions and others. The Tsuchida method has the advantages of being practical, fast and easy to understand, to obtain more accurate results, provide direct recommendations for mitigation actions based on the results of the analysis and other tests need to be carried out.

Table 3 - Summary of liquefaction potential at Point 1

No	Depth (m)	Liquefaction Potential? Yes/No			
		Tsuchida Method (1970)	Seed & Idriss Method (1971)	Shibata & Teparaksa Method (1988)	Hakam Method (2020)
1	6	No	No	No	No
2	14	Yes	No	Yes	No
3	17	Yes	No	-	No
4	20	Yes	No	-	No
5	26	Yes	No	-	No

In Tables 3, 4, 5 and 6, it can be seen that using the Shibata & Terapaksa method (1988) is not effective for depths of more than 20 m due to the limitations of CPT which only tests soil to depths of less than 20 m, and it is necessary to correlate CPT data with soil types. The advantage of the method compared to the Tsuchida method is that it can determine more details of liquefaction potential by considering local conditions.

Table 4 - Summary of liquefaction potential at Point 2.

No	Depth (m)	Liquefaction Potential? Yes/No			
		Tsuchida Method (1970)	Seed & Idriss Method (1971)	Shibata & Teparaksa Method (1988)	Hakam Method (2020)
1	9	No	No	No	No
2	11	Yes	No	No	No
3	23	Yes	No	-	No
4	26	Yes	No	-	No

Table 5 - Summary of liquefaction potential at Point 3.

No	Depth (m)	Liquefaction Potential? Yes/No			
		Tsuchida Method (1970)	Seed & Idriss Method (1971)	Shibata & Teparaksa Method (1988)	Hakam Method (2020)
1	5	No	No	Yes	-
2	8	Yes	Yes	Yes	Yes
3	14	Yes	Yes	No	Yes
4	17	Yes	No	No	No
5	23	Yes	No	-	No
6	26	Yes	No	-	No

The Seed & Idriss method (1971) provides fairly accurate analysis results based on empirical data from various well-documented liquefaction events, can be used in various geotechnical conditions and soil types, is relatively easy to apply and requires parameters that are generally available from standard soil tests, such as SPT (Standard Penetration Test). The disadvantages of this method are that data analysis is complicated and uses many correction factors, does not always take into account specific local conditions, such as micro geological variations, the quality of predictions is highly dependent on the accuracy and consistency of SPT data, which can vary.

Table 6 - Summary of liquefaction potential at Point 4.

No	Depth (m)	Liquefaction Potential? Yes/No			
		Tsuchida Method (1970)	Seed & Idriss Method (1971)	Shibata & Teparaksa Method (1988)	Hakam Method (2020)
1	8	Yes	Yes	Yes	Yes
2	17	Yes	No	Yes	No
3	23	Yes	No	-	No
4	29	Yes	No	--	No

The Hakam Method (2020) shows similarities to the results of the Seed & Idriss (1971) method. The advantage of the Hakam (2020) method is that it is a simple analysis method (Dr - D_{50}), and the results are quite convincing and do not require complicated correction factors. However, the disadvantage of this method is that it does not consider the influence of groundwater levels. Hakam's method (2020) analyzes liquefaction potential more easily and practically based on testing the physical properties of the soil, namely grain gradation, so that the D_{50} value is obtained and then the relative density value of the soil (Dr) is tested. Vibration tests are carried out on soil samples with maximum ground acceleration (a_{max}) = 0.3g and 0.6g. By using the relationship graph between relative density (Dr) - D_{50} value and maximum ground acceleration (a_{max}), the liquefaction potential can be determined. Hakam's method is a useful and practical tool for predicting liquefaction potential, especially when geotechnical data such as SPT or CPT are available. However, like all prediction methods, the results must be used in conjunction with local knowledge and additional analysis to ensure the reliability and accuracy of the predictions in the specific context of the location being studied. Based on the results of the analysis above, the Seed & Idris method (1971) and Hakam Method (2020) gave the same results, both of these methods have not only predicted liquefaction based on grain gradation but have also taken into account seismic factors.

4. Conclusion

The most effective method to analyze liquefaction potential is the Hakam method (2020). This method, which is a simple analysis method, provides convincing liquefaction potential analysis data that is close to the results of the Seed & Idriss (1971) method and the liquefaction vulnerability zone maps. Based on these two methods, it can be concluded that the location of the Sintuk Toboh Gadang railway, Padang Pariaman, at points 1 and 2, does not have the liquefaction potential. In contrast, at point 3, the liquefaction potential is at a depth of 8 m - 14 m, and at point 4, the liquefaction potential is at a depth of 8 m. To prevent the impact of liquefaction at this location, a foundation design is needed that penetrates the liquefaction zone so that it remains stable and no damage occurs to the railway construction.

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