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THE INFLUENCE OF EARTHQUAKE SIGNIFICANT DURATION ON LIQUEFACTION POTENTIAL IN AREA PASAR RAYA PADANG

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ABSTRACT: Pasar Raya Padang, located in a seismically active area with a history of liquefaction from the 30 September 2009 earthquake, requires a detailed liquefaction potential analysis. This study aims to determine the influence of earthquake significant duration on ground motions at the site and to address the limitations of the commonly used simplified method. Four synthetic ground motion variations were generated to reflect the site characteristics and used in non-linear numerical analyses to calculate safety factors. The results indicate that both short and long-duration earthquakes, particularly those with late maximum peak ground accelerations, significantly increase the pore water pressure ratio by 20-50%. Short-duration earthquakes with early peak ground accelerations result in higher cyclic stress ratios. Liquefaction potential was identified at depths of 12-20 meters. The study concludes that short-duration earthquakes pose a higher liquefaction risk than long-duration events. The results highlight the critical role of accurately selecting ground motions for risk assessment, which is essential for mitigating liquefaction risk in future construction projects.

Keywords: Liquefaction, Ground Motion, Duration, Peak Ground Acceleration, Earthquake, Synthetic

1. INTRODUCTION

Earthquakes are phenomena that can cause significant damage to infrastructure and buildings, and one of the effects of earthquakes is the occurrence of liquefaction. The analysis methods currently used to assess liquefaction potential generally employ simplified methods, as studied by [1]. According to [2], liquefaction analysis using empirical methods often exceeds predictions due to simplified factors. These simplifications lead to errors in liquefaction potential analysis and mitigation implementation, which can lead to increased construction costs and even casualties.

The factors in empirical calculations that have been simplified method have been extensively studied, including groundwater table (GWT) levels where liquefaction potential exists at depths of 1 to 11.6 m [3], soils with a fines content (FC) greater than the standard 63% that still have the potential to liquefy [4], and the influence of variations in peak ground acceleration (a_{max}) values produced by ground motion [5,6]. To discuss a_{max} in more detail, technological advances in numerical simulation now allow the use of predicted ground motion data [7]. Therefore, according to [8,9], simplifications in numerical methods, mainly due to the influence of ground motion, provide a more accurate analysis compared to empirical methods.

The numerical analysis of liquefaction potential using ground motion data, particularly with respect to earthquake duration factors from ground motion, is currently being extensively researched [10-12]. However, these studies use historical ground motion records that are scaled for adjustment, which can lead to biased results when applied to sites without recording stations [8,10].

This limitation can be overcome by generating synthetic ground motions using the SeismoArtif software. SeismoArtif takes input from three factors that influence the characteristics of ground motions, as formulated by [13] : source, path, and location. These three factors in synthetic ground motions cause the characteristics of the generated motions to closely resemble the natural ground motions occurring at a particular location. As a result, the influence of earthquake duration is more accurately represented for use in certain locations without recording stations. The use of SeismoArtif to generate synthetic ground motions has been widely applied [14,15], and its application to liquefaction analysis in Indonesia has also been carried out [16,17].

Following the Padang earthquake on 30 September 2009, the Ministry of Public Works and Housing initiated the rehabilitation of Pasar Raya Padang. The area around the market has a history of liquefaction [18,19]. In addition, the seismic conditions around the city of Padang have been identified as having high seismic activity, making it vulnerable to liquefaction potential. Therefore, it is necessary to calculate the liquefaction potential at the Pasar Raya Padang site to protect the buildings from liquefaction risks, especially since the market is a community gathering place and a commercial center.

In line with the previous discussion, this study will investigate the influence of earthquake duration on liquefaction potential at the Pasar Raya Padang site. While many studies have investigated the influence of earthquake duration on liquefaction potential, no research has yet applied this to the specific soil characteristics around the city of Padang. In this analysis, four variations of synthetic ground motion will be tested to determine their effect on liquefaction potential at the Pasar Raya Padang site. The results of this study can then be used to analyze the liquefaction potential at sites without recording stations, and the potential results can be used as a reference to determine the type of mitigation [20-22] required at the Pasar Raya Padang site.

The subsequent section of this article is structured as follows. Section 2 discusses the significance of the research and explains its implications. Section 3 examines the study area, covering geological conditions, seismicity, field survey results, and the history of liquefaction disasters at the research site. Section 4 outlines the methodology used to assess the effect of earthquake duration on liquefaction potential at the site, using variations of synthetic ground motions followed by non-linear calculations. Section 5 presents the research results showing the effect of synthetic ground motion variations on the liquefaction potential calculation. Finally, Section 6 summarises the main findings and provides recommendations for the selection of ground motions for liquefaction potential planning.

2. RESEARCH SIGNIFICANCE

This study provides a detailed analytical method for assessing liquefaction potential using synthetic ground motions. This knowledge allows synthetic ground motion data to be generated for sites without recorded ground motion data. It provides an understanding of the type and duration of ground motions that pose the highest liquefaction risk, which can be used in the design planning process. In addition, understanding the influence of earthquake significant duration in liquefaction potential analysis, which previously did not consider this factor, results in more accurate analysis results. This allows for more effective selection of liquefaction mitigation measures and more efficient budget planning.

3. GEOLOGY AND SEISMICITY OF THE STUDY AREA

Padang, located in the West Sumatra province, is the largest city on the west coast of Sumatra Island and is bordered by hilly terrain. Padang is characterized by three main geological formations, as shown in Figure 1 the alluvial formation (Qa) in the central city area, the Pleistocene volcanic rock formation (QTv) in the southeastern hilly area, and the Tertiary volcanic rock [19].

Padang is located near three fault lines: the Sumatra Fault Segment Sumpur, Sianok and Sumani, the Mentawai Fault, and the Sumatra Megathrust. This makes Padang very vulnerable to earthquakes. Based on earthquake history data obtained from the USGS catalog over 100 years, within a radius of 300 km and with a magnitude greater than 5, there have been 420 recorded earthquakes around Padang [23], as shown in Figure 2. The largest recorded earthquakes occurred in 1979, 1943, and 2009, with magnitudes (Mw) of 8.7, 7.73, and 7.6, respectively.

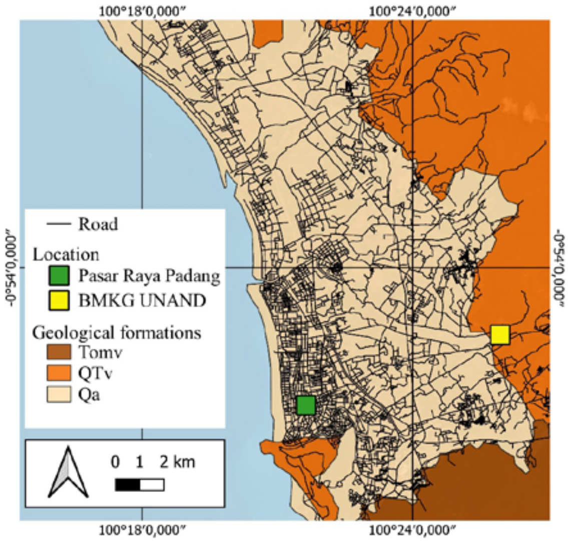

Fig. 1 Geological Map of Padang City region modified [19]

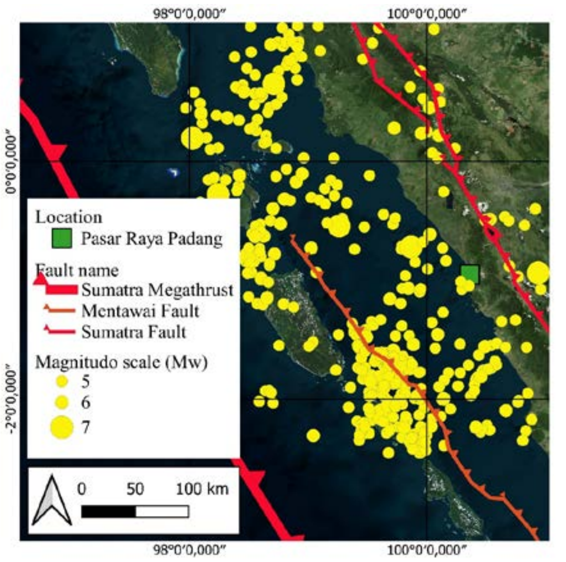

Fig. 2 Earthquake distribution in a 300 km radius around Padang City modified [23,24]

Soil investigation data at Pasar Raya Padang includes four soil borings to a depth of 30 meters accompanied by SPT, three CPT tests, Atterberg limits, sieve analysis, and soil properties. The characteristics of the site are predominantly sandy with some silts, are shown in Table 1. The silt at Pasar Raya Padang falls into the sand-like category under the soil liquefaction susceptibility criteria [25], so the evaluation or analysis was carried out using liquefaction calculations for sandy soils.

Table 1. Soil properties at the Pasar Raya Padang

Depth	Borehole - 02	
(*m*)	SPT	Soil Type
2	60	SP-SM
4	47	SP
6	49	SP
8	49	SP
10	38	SP-SM
12	35	SM
14	8	MH
16	4	ML
18	6	ML
20	6	ML

The Padang earthquake, which occurred on 30 September 2009, indicated the occurrence of liquefaction as evidenced by the effects of sand boils, settlement, and lateral spreading [18,19], as shown in Figure 3. Ground motions were recorded at the BMKG UNAND station located 42.48 km from the epicenter [17], which is further away from the study area and in a hilly area with different geological units.

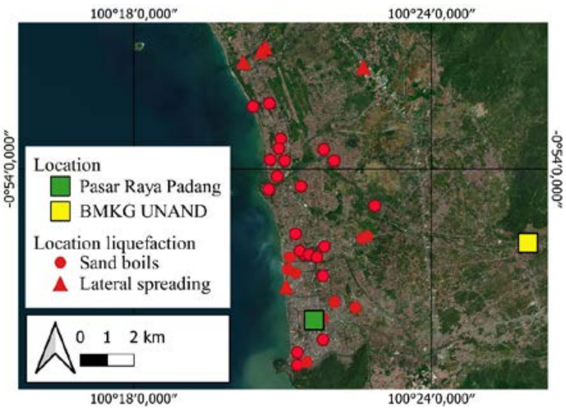

Fig. 3 Liquefaction history distribution from the 30/09/2009 earthquake modified [18,19]

4. METHOD

This study will quantitatively investigate the influence of earthquake significant duration with variation of maximum peak ground acceleration (a_{max}) position at the Pasar Raya Padang generated by synthetic ground motion, on the liquefaction potential. The research methodology is based on an integrated numerical analysis approach consisting of three main stages: validation of the ground motion model, generation of different synthetic ground motion scenarios, numerical analysis to observe the soil response, and calculation of the safety factor number to determine the liquefaction potential of the site.

The synthetic ground motions are generated using the SeismoArtif application, which can generate earthquake accelerograms based on target response spectra using different calculation methods and assumptions. SeismoArtif has been used in several previous studies [14,15]. SeismoArtif uses the method developed by Gasparini and Vanmarcke [26], which is based on the concept that any periodic function can be expressed as a series of sinusoidal waves. To replicate the transient effects of an earthquake, steady-state motions are modified by applying a deterministic envelope function, I(t).

Peak ground acceleration (a) values are obtained from the Indonesian design spectra (https://rsa.ciptakarya.pu.go.id/2021) by entering the coordinates of the Pasar Raya Padang site. These values are then used to generate synthetic ground motions using SeismoArtif. The software processes earthquake parameters like the seismic mechanism, magnitude, and distance to the rupture. Fault parameters recommended by PuSGeN are used [24]. Peak ground acceleration can also be obtained from the design spectrum derived using probabilistic and deterministic approaches, with the results then fed into the EZFRISK program to generate the design spectra [27].

The peak ground acceleration (a) used is the peak ground acceleration with a probability exceeding 2% in 50 years, as recommended by SNI-03-1726-2019 [28]. The choice of return period is influential because a longer return period will reduce the value of the safety factor and cause more potential for liquefaction [5].

The validation of the synthetic ground motion is performed by comparing natural ground motion data with the synthetic ground motion generated by SeismoArtif. Natural ground motion data can be obtained from the nearest BMKG recording station or from databases available on various websites that provide recorded data for the site being analyzed. Once the data are obtained, compare them to see if the results are almost identical, the parameters used are appropriate, and the synthetic ground motion can be used.

Next, synthetic ground motions with two different durations were generated based on the data from the Pasar Raya Padang site. The durations were divided into two categories from previous research [29] : short-duration with significant duration (D_{s5-75}) below 25 seconds and long-duration with significant duration (D_{s5-75}) above 25 seconds. The influence of the a_{max} position was also considered by splitting the a_{max} into two positions, early and late. This condition makes four variations: short early, short late, long early, and long late.

A one-dimensional site response analysis was conducted using the Deepsoil application [30], involving three key steps: choosing constitutive models and hysteresis rules, creating a one-dimensional soil column model, and inputting seismic motion. The soil column model for this analysis was developed using soil investigation data from BH-02 at the Pasar Raya Padang site. The results of the calculations produced Cyclic Stress Ratio (CSR) values for each combination, and the numerical analysis results were interpreted to determine the influence of earthquake significant duration on liquefaction potential.

The highest CSR value is used as a reference to calculate the Safety Factor (FS) determined using Eq. 3 combined with empirical calculations using the Cyclic Resistance Ratio (CRR) from [1] with the following Eq. 1 - 7 :

$$CRR_{M=7.5,\, \sigma_v'=1\ atm} = exp\left(\frac{(N_1)_{60cs}}{14.1} + \left(\frac{(N_1)_{60cs}}{126}\right)^2 - \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.8\right) \quad (1)$$

$$CRR_{M,\, \sigma_v'} = CRR_{M=7.5,\, \sigma_v'=1\ atm} \cdot MSF \cdot K_\sigma \quad (2)$$

$$MSF_{max} = 1.09 + \left(\frac{(N_1)_{60cs}}{31.5}\right)^2 \leq 2.2 \quad (3)$$

$$MSF = 1 + (MSF_{max} - 1)(8.64\ exp\left(\frac{-M}{4}\right) - 1.325) \quad (4)$$

$$C_\sigma = \frac{1}{18.9 - 2.55\sqrt{(N_1)_{60cs}}} \leq 0.3 \quad (5)$$

$$K_\sigma = 1 - C_\sigma \ \ln\left(\frac{\sigma_v'}{P_a}\right) \leq 1.1 \quad (6)$$

$$FS = \frac{CRR_{M,\, \sigma_v'}}{CSR} \quad (7)$$

Where $(N_1)_{60cs}$ is the adjusted N-SPT value based on fines content corrections, MSF is the magnitude scaling factor, (C_σ) is the stress correction factor, and (K_σ) represents the effective overburden stress. Liquefaction is likely if the safety factor (FS) is less than 1; otherwise, liquefaction is unlikely. The FS results can be used as a reference for engineers to determine potential liquefaction analysis before construction.

5. RESULT AND DISCUSSION

The ground motion recorded at the BMKG UNAND site is used for validation because it is closest to the Pasar Raya Padang site. However, these data will give different values from those at Pasar Raya Padang due to the influence of geological factors, distance, depth, and type of bedrock. Previous studies support this [31,32] that have carried out micro zonation mapping using microtremors, at the BMKG site, the shear wave velocity (V_s) ranges from 400 to 600 m/s with a seismic intensity (I_{JMA}) of 4+, while the Pasar Raya Padang site has a V_s value of less than 200 m/s and an I_{JMA} of 5+. These values indicate that the ground motion at the Pasar Raya Padang site will be greater than that at the BMKG UNAND site.

Before synthesizing the ground motions, it is first necessary to identify the potential duration types that may occur at the Pasar Raya Padang site. This identification is done using the earthquake ground motion duration prediction method [33], as described in Eq. 8:

$$log\ (D_{S5\text{-}75}) = (-0.473 + 0.31 \cdot log\,R)^{0.2} + 0.089 \cdot M^{1,2} + (-0.068 \cdot S) \quad (8)$$

Where R is the closest site source distance, M is moment magnitude, and S is site condition or soil type. The results of the prediction calculations for the site are shown in Table 2, based on three criteria. The earthquake recorded by BMKG UNAND has a larger R-value, and the site is classified as category 2 (350 < V_s < 750). Meanwhile, for potential earthquakes that could occur, based on the Indonesia Earthquake Source and Hazard Map 2017 [24], the Mentawai fault could generate a magnitude of up to 8.2 M_w. Based on this potential, the Padang area may experience two types of earthquake durations: short-duration and long-duration, depending on the conditions of the three parameters R, M, and S at the site.

Table 2. Criteria for determination of significant duration

	R (km)	M	S	$D_{S5\text{-}75}$	Duration Prediction
Earthquake 30/09/2009 at BMKG UNAND **[17]**	42.48	7.6	2	24.06	Short Duration
Earthquake 30/09/2009 at Pasar Raya Padang	37.58	7.6	1	30.85	Long Duration
Prediction of Potential Earthquake at Pasar Raya Padang **[24]**	37.58	8.2	1	38.56	Long Duration

The validation of the synthetic ground motions is performed by comparing the natural accelerogram data recorded by BMKG UNAND with the synthetic ground motion results from SeismoArtif. The synthetic ground motion results yield seven alternative ground motions with varying mean errors compared to the target spectra, with the smallest error being 7.91% is therefore used. As shown in Figure 4, the synthetic ground motion results closely match the natural ground motion, proving that the synthetic ground motion is fit for use in this study.

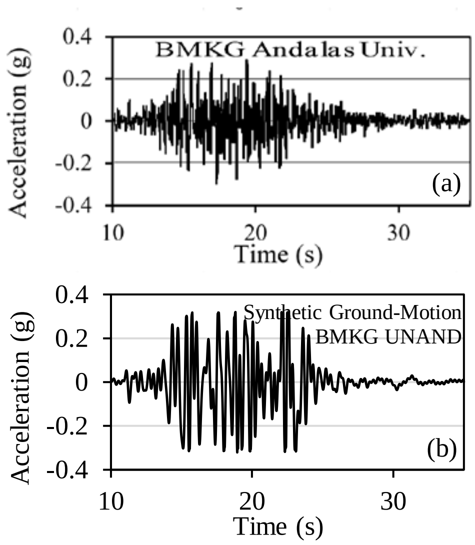

Fig. 4 (a) Natural ground motion recorded BMKG UNAND modified [17], (b) synthetic ground motion generated SeismoArtif

The results of the synthetic ground motion generated are shown in Figure 5 and Figure 6. The synthetic ground motion uses the same design spectra, resulting in similar a_{max}, frequency, and amplitude values for each duration variation. Similar values provide more comprehensive comparison results compared to historical data, which have differences in frequency and amplitude due to different source, path, and location influences. The minimum duration used for short duration conditions also incorporates the previous theory of [8] that the minimum duration to trigger liquefaction is 13.6 s.

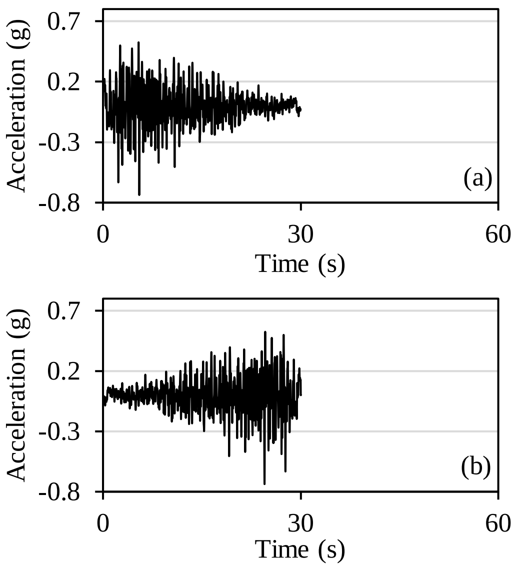

Fig. 5 Result of synthetic ground motion at Pasar Raya Padang (a) short-duration with early a_{max} and (b) short-duration with late a_{max}

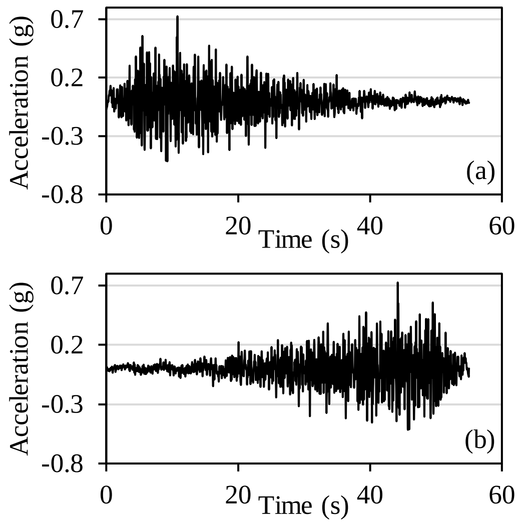

Fig. 6 Result of synthetic ground motion at Pasar Raya Padang (a) long-duration with early a_{max} and (b) long-duration with late a_{max}

The input ground motion results in non-linear analysis Deepsoil shows the influence of the position of the a_{max} on the increase in the pore water pressure ratio (R_u). Figure 7 shows that placing amax at the late position, whether for short or long durations, results in a greater increase in R_u compared to placing a_{max} at the early position. This is because the causes the water to be pressurized and begin to release energy before it finally receives the a_{max}, resulting in a greater pore water pressure (u).

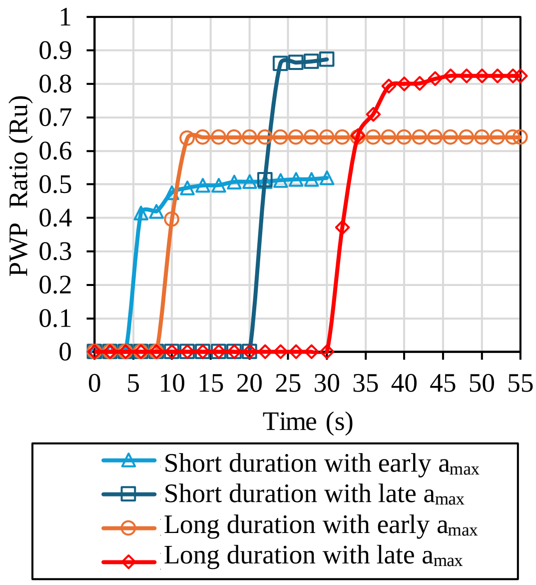

Fig. 7 Relationship between R_u values and time in the soil at 16 m depth with four variation ground motion synthetics.

The value of a_{max} strongly influences the increase in Ru. The influence of duration and frequency of earthquakes do not have a significant influence on the increase in R_u because the behavior of the pore water pressure does not show a significant change before and after reaching the a_{max}. The results of the influence of earthquake duration on u are in agreement with previous research [11], but the case is different for displacement, which shows an increase with longer earthquake duration.

However, the results for CSR shown in Figure 8, show a contrast to the increase in R_u. For CSR, placing a_{max} in the early position results in a higher CSR than if a_{max} is in the late position. This is because soils receiving more initial a are more compacted than soils receiving late a_{max}. In addition, the analysis shows that longer durations do not result in higher cyclic shear stress than shorter durations.

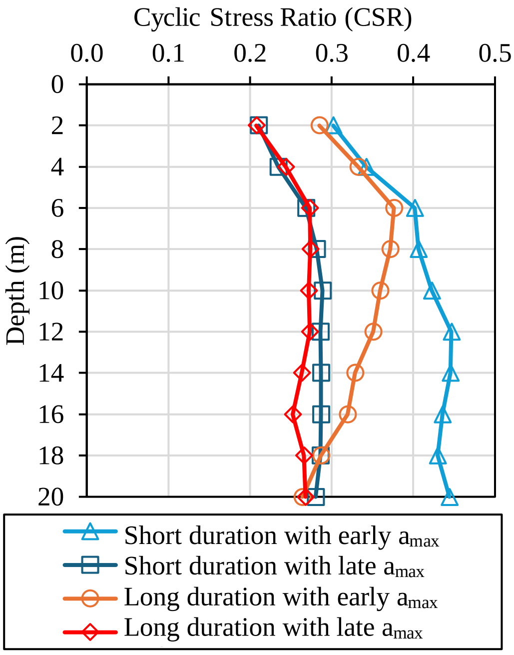

Fig. 8 CSR for each depth using varying synthetic ground motion

This difference makes sense when it is combined with the theory of the shear strength of the soil, as shown in the following Eq. 9, 10, and 11:

$$\tau = c + (\sigma - u)\, tg\, \varphi \tag{9}$$

$$R_u = \frac{\Delta u}{\sigma} \tag{10}$$

$$CSR = \frac{\tau_{cyc}}{\sigma'_v} \tag{11}$$

Where τ is the shear strength of the soil (kPa), c is the cohesion of the soil (kPa), u is the pore water pressure (kPa), σ is the normal stress applied to the soil (kPa), and ϕ is the angle of internal friction (degrees).

From Eq. 9, 10, and 11, a lower R_u value results in a higher CSR because the ratio of σ is greater than the change in u, resulting in a higher soil shear strength. However, this is only true if R_u has not reached one (1) or if the resulting CSR does not exceed the CRR.

A short earthquake duration with an a_{max} in the early position is more suitable for analyzing the liquefaction potential at the Pasar Raya Padang site because it produces a higher CSR and a higher risk of liquefaction potential. The CSR value is then divided by the CRR value obtained using the simplified method [1]. The selection of CSR values has already taken the influence of u values. This is because the simplified method does not take the influence of u in their calculations, which can increase the liquefaction potential by 40%-70% due to the influence of u [34].

The resulting FS is shown in Figure 9 it is shown that at depths of 12 to 20 meters, the Pasar Raya Padang site has liquefaction potential because the SF is less than 1. These results indicate that the Pasar Raya Padang site has liquefaction potential, which requires mitigation efforts to minimize the impact of liquefaction at the site.

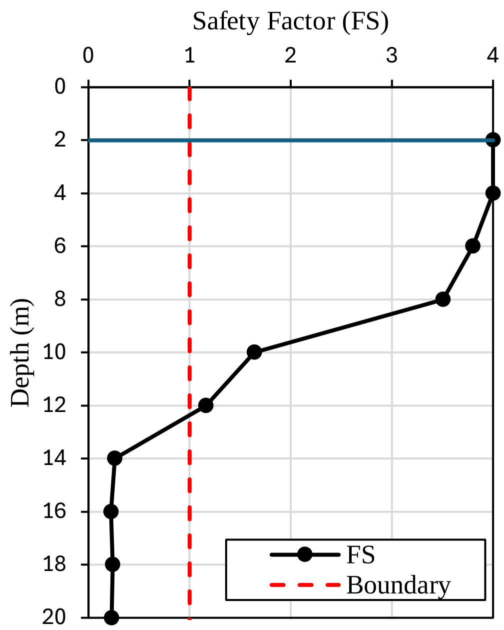

Fig. 9 Safety factor for each depth at Pasar Raya Padang

6. LIMITATION

The study has several limitations. First, the data on soil characteristics is specific to the city of Padang, particularly the Pasar Raya Padang development area, so its applicability to soils with different characteristics may be different. Second, the lack of experimental modeling limits the validation of the numerical model. Third, return period probabilities only use 2% for 50 years for building structures, so it is necessary to model using other return periods for different types of buildings as they will give different a_{max} values.

7. CONCLUSION

The influence of earthquake significant duration on the liquefaction potential analysis mainly affects the CSR and displacement values. Meanwhile, the values of R_u are significantly influenced by the position and a_{max} value of the soil. Four variations of synthetic ground motions generated using SeismoArtif were applied to numerical nonlinear analysis calculations using Deepsoil to analyze the behavior and influence of earthquake significant duration on liquefaction potential in Pasar Raya Padang.

The results show that the R_u value is 20-50% higher when the a_{max} position is in a late position for both short and long durations. However, for the CSR values, a short duration with an initial position results in higher CSR values due to the lower R_u value, which in turn results in higher CSR values. These CSR values are then used in the liquefaction potential analysis calculations, resulting in FS < 1 at depths of 12 to 20 meters, indicating that the Pasar Raya Padang site is susceptible to liquefaction.

This research will be highly beneficial in selecting ground motion to be used at sites where liquefaction potential analysis is to be carried out, ensuring that the results can mitigate the highest liquefaction risk at the site. A structural foundation investigation is required to determine if reinforcement is required to mitigate the liquefaction hazard at the Pasar Raya Padang project.

8. ACKNOWLEDGMENTS

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