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LIQUEFACTION RESISTANCE ANALYSIS USING STANDARD PENETRATION TEST (SPT) AND SEED & IDRISS SIMPLIFIED METHOD: A CASE STUDY OF THE KARANGGINAS II PEDESTRIAN UNDERPASS PROJECT, SEMARANG

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Abstract

A phenomenon known as liquefaction occurs when soil loses strength and turns to mud due to earthquake shaking, which can cause damage to infrastructure such as underpass boxes. Based on data from the National Center for Earthquake Studies, Semarang City has a history of earthquakes dating back to 1856 with varying degrees of infrastructure damage. Currently, the phenomenon poses a threat to the people of Semarang City caused by an active fault that runs along the north coast of Central Java. So, this research aims to analyze the soil resistance to liquefaction in the Preliminary Project of Capacity Improvement of Pedestrian Box Underpass Karangingas II Semarang using the Standard Penetration Test (SPT). The data obtained were analyzed using the simplified method proposed by Seed & Idriss (1971). The results show that the soil resistance to liquefaction at a depth of 0 - 4 meters at point BH-02 is quite high, with a safety factor (SF) value greater than 1, so no liquefaction occurs. However, at a depth of 4 - 8 meters, the SF value is less than 1, indicating the liquefaction potential. At points BH-01 and BH-03, the analysis shows the potential for liquefaction at all depths tested. Based on the analysis results, two of the three locations of the box underpass capacity enhancement project have the potential to experience liquefaction, with point two only experiencing liquefaction at a certain depth. Therefore, liquefaction prevention measures are required in these areas.

Keywords: Liquefaction; Earthquake; Cyclic Stress Ratio (CSR); Cyclic Resistance Ratio (CRR); Soil.

Introduction

Indonesia is a country that has a high level of earthquake vulnerability. Earthquakes can trigger various kinds of natural disasters, one of which is liquefaction. Liquefaction occurs when the soil loses its strength and turns into mud due to earthquake shocks (Hardiyatmo 2022). The phenomenon can cause significant damage to buildings and infrastructure. In line with the research of Pratama et al. (2022), it shows that an earthquake with a magnitude of 7.7 (Mw) in Palu City caused hundreds of buildings to collapse and be buried in the ground due to liquefaction. Therefore, the strength and stability of the soil must be considered in construction planning.

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Based on data contained in the National Center for Earthquake Studies (PUPR 2017), the city of Semarang has a history of earthquakes since the 19th century. Initially, it was recorded on January 19, 1856, with the strength of VI-VII *Modified Mecallly Intensity* (MMI) which caused damage to buildings and panic in the surrounding community. The incident became one of the largest in the history of the earthquake in Semarang. Furthermore, data contained in the Meteorology, Climatology, and Geophysics Agency (BMKG) of a large earthquake that occurred on May 27, 2006, with a magnitude of 6.3 in Yogyakarta, the tremors were felt in the city of Semarang with an intensity of III-IV MMI but did not cause significant damage. Then, the latest earthquake phenomenon occurred on June 30, 2023, in Bantul with a magnitude of 6.6 Mw. Semarang City was one of the cities affected by the tremor, but there were no reports of damage. The latest phenomenon occurred in Tuban with a magnitude of 6.5 Mw, with a depth of 12 kilometers in the Java Sea region at a distance of 114 km on March 22, 2024, so that the tremors reached the city of Semarang.

In today's modern era, earthquakes are still a threat to the people of Semarang City. This is caused by the activity of the Kaligarang fault which is an active fault that stretches along the northern coast of Central Java. The existence of the Kaligarang fault is well recorded in quaternary-old rocks consisting of fault mirrors, erosion sturge, drag folds, and many locations of soil movement along Kaligarang. This evidence suggests that the fault is still active and could result in future earthquakes. With a shear speed rate of 0.1 mm/year, this fault stores a magnitude of 6.5 in the future (Hidayat 2013).

In addition, Semarang is in the "Moderate" liquefaction vulnerability zone as can be seen from figure 1 (Buana et al. 2019). Although it is not too dangerous compared to the southern coast of Central Java, it must be noted that Semarang used to be a shallow sea or strait, a part of the ancient Java sea that was then buried by young alluvial deposits (Purwanto 2005).

Figure 1. Liquefaction Susceptibility Zones

Based on the findings of the study, soil resistance analysis can be traced to susceptibility to liquefaction. Research on soil resistance to liquefaction in Semarang City is still very minimal to be done. Therefore, in an effort to prevent liquefaction, it is necessary to have a soil resistance analysis in Semarang City. However, this study only focuses on the area of the Preliminary Project for Capacity Building of the Karangingas II *Pedestrian Underpass Box*, Semarang. Thus, this study aims to determine the soil resistance to liquefaction phenomena that occur in the area.

Liquefaction-induced damage during earthquakes remains a critical concern in geotechnical engineering, particularly in seismically active regions like Indonesia. Previous studies have extensively evaluated liquefaction potential using the Standard Penetration Test (SPT) and the Seed & Idriss (1971) simplified procedure. For instance, Rahman et al., (2020) applied this method to assess liquefaction risk at Yogyakarta International Airport, finding that sandy layers at shallow depths (1–6 m) were non-liquefiable due to high soil density. Similarly, Mina et al., (2020) identified liquefaction susceptibility in Tangerang's Soekarno-Hatta Airport at depths of 6–8 m under peak ground acceleration (PGA) of 0.35 g. However, these studies predominantly focused on coastal or alluvial soils, leaving gaps in understanding liquefaction behavior in urban infrastructure projects, such as underpasses, where soil stratification and groundwater conditions differ significantly.

The novelty of this research lies in its focused application of the Seed & Idriss method to evaluate liquefaction resistance for the Karangginas II Pedestrian Underpass in Semarang—a densely populated city with moderate liquefaction susceptibility (Buana et al., 2019). While prior work by Pratama et al., (2022) highlighted liquefaction risks in Palu's loose sandy soils during the 2018 earthquake, few studies have integrated SPT data with site-specific seismic parameters (e.g., Kaligarang Fault activity) for urban transportation infrastructure. This study addresses this gap by analyzing three borehole locations (BH-01 to BH-03) to delineate depth-dependent liquefaction potential and correlate it with local geological conditions, including high-plasticity clay layers and variable groundwater levels.

The purpose of this study is to provide actionable insights for mitigating liquefaction risks in Semarang's underpass projects. By quantifying safety factors (SF) across depths (0–8 m) and earthquake magnitudes (Mw 6–7.5), the research offers two key benefits: (1) practical guidelines for engineers to prioritize ground improvement techniques (e.g., compaction, stone columns) in liquefaction-prone zones, and (2) academic contributions to refine liquefaction assessment methods for mixed soil types in urban settings. The findings aim to enhance the resilience of critical infrastructure in Central Java, where active faults and rapid urbanization converge.

Method

In this study, quantitative data in the form of numbers can be processed and analyzed using *a simplified method* (Bolton Seed and Idriss, 1971). In the data collection process, the data collected focused on soil testing data tested using standard penetration tests in the Preliminary Project for Capacity Building of the Karangingas II Pedestrian Underpass Box, Semarang which was previously available. The location of the research can be seen in Figure 2.

Figure 2. Research Location

In the data analysis process, the data is translated first using rough data processing before being loaded into the application, while the translated penetration test data includes *soil Properties Index*, soil grain analysis, and soil *log bore* data to then be processed using *Microsoft Excel* with a simple method. The steps of data analysis can be seen in Figure 3.

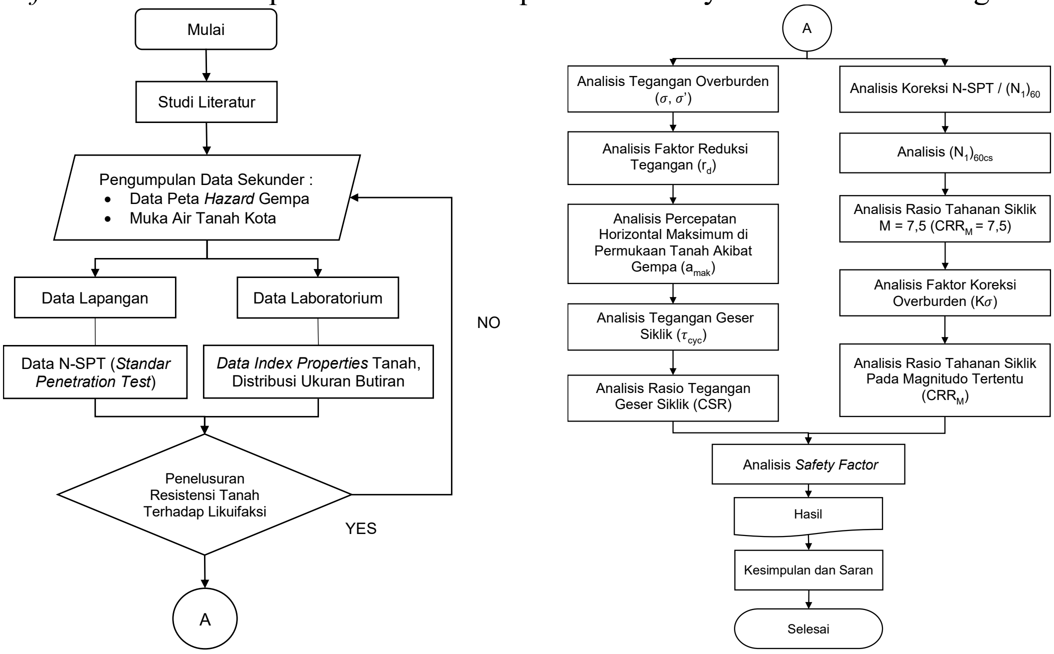

Figure 3. Flowchart

A simple method analysis was carried out to estimate the values *of Cyclic Stress Ratio* (CSR) and *Cyclic Resistance Ratio* (CRR). Then, compare these values to find *the Safety Factor* (SF), which can be reviewed. If the results of the comparison of CSR and CRR are more than one, the soil has liquefaction resistance. Meanwhile, if the yield is less than one, the soil layer has the potential for liquefaction (Hardiyatmo 2022). The steps to analyze soil resistance to liquefaction are described as follows:

1. *Cyclic Stress Ratio* (CSR)

In determining the amount of CSR value, several things need to be considered, including the acceleration of the peak of the horizontal earthquake at the ground level (amax), the amount of gravitational force, reduction factors, *and overburden* pressure. The variables are outlined in the equation (Bolton Seed and Idriss 1971):

$$CSR = \frac{\tau av}{\sigma' vo} = 0,65 \times (\frac{amax}{g}) \times (\frac{\sigma vo}{\sigma' vo}) \times r_d$$

With:

$a$max = Maximum earthquake acceleration
g = Gravitational force
σvo = Total voltage
σ′vo = Effective voltage

The value of rd (reduction stress coefficient) is determined through an equation proposed by Liao, S. S., & Whitman, (1986):

$r_d = 1 - 0{,}00765z$ untuk $z \leq 9{,}15$ m
$r_d = 1{,}174 - 0{,}0267z$ untuk $9{,}15 \text{ m} < z \leq 23$ m

Where z is a representation of the depth being reviewed.

2. *Cyclic Resistance Ratio* (CRR)

The amount of CRR value is obtained through the calculation of test data in the field. CRR states that soil resistance to liquefaction whose value depends on the density or relative density of the soil. Soil density can be determined through *Standard Penetration Test* (SPT) testing. In this study, the analysis was carried out using SPT test data (Seed et al. 1986). The steps to analyze the amount of CRR value with the SPT test are as follows:

a) Determine the corrected value of $(N1)_{60}$ by taking into account the influence of the test procedure, *overburden* pressure, borehole diameter, and drill rod length, which is expressed in the equation (Youd et al. 2002):

$$(N1)60 = N_m C_N C_E C_B C_R C_S$$

Nm is the value of the tax return test results, and others are correction factors. This study uses the correction factor proposed by Seed (2001) which refers to ASTM D1586. The following is a table of correction factors used in this study:

Table 1. N-SPT Correction Factors

Factor	Tool Variations	Correction Value
Overburden Correction (CN)	-	$(Pa/\sigma_{v'})^{0.5} \leq 1{,}7$
Energy Ratio (CE)	Safety *hammer*	0,75
Borehole diameter (CB)	65-115 mm	1,00
Sampler tube (CS)	Standard *sampler* tubes	1,00
Drill rod length (CR)	<3 m	0,75

b) Determine the fine grain content (FC) and then calculate the sand containing fine grains (N1)60cs using the value of (N1)60, using the equation (Youd et al. 2002):

$$(N_1)_{60cs} = \alpha + \beta(N_1)_{60}$$

With:
$\alpha = 5, \geq$ for $FC \geq 35\%$
$\beta = 1.2 \geq$ for $FC \geq 35\%$

c) Determining the CRR value at the magnitude of the M = 7.5 earthquake and the adjustment of N for the equivalent clean sand, using the equation (I. M. Idriss 2008):

$$CRR_{M=7,5} = exp\ (\frac{(N1)60cs}{14,1} + (\frac{(N1)60cs}{126})^2 - (\frac{(N1)60cs}{23,6})^3 + (\frac{(N1)60cs}{25,4})^4 - 2,8)$$

d) Determining the overburden *pressure correction factor* (K) The σoverburden *pressure correction* is calculated based on the equation (Idriss and Boulanger 2004):

$$K\sigma = 1 - C\sigma \times In(\frac{\sigma v\prime}{Pa}) \leq 1,1$$

With:

$$C\sigma = \frac{1}{18,9 - 2,55\sqrt{(N1)60cs}}$$

e) Determine the corrected CRR value at the magnitude of the M = 6 earthquake using the equation (Seed 1983):

$$CRR_M = CRR_{7,5} \times MSF \times K\sigma$$

f) The last stage is to determine the Safety *Factor* (SF) value using the cyclic shear resistance method, with the equation (Seed, Arango, and Chan 1975):

$$SF_M = \frac{CRR\ M \times \sigma v'}{\tau cyc}$$

You can also use other methods:

$$Safety\ Factor = \frac{CRR}{CSR}$$

With:

τ_{cyc} = Cyclic shear voltage

$\sigma v'$ = Effective overburden pressure

Results and Discussion

Based on the purpose of this study, is to determine the soil resistance to liquefaction in the area of the Karangingas II *Pedestrian Box Underpass* Capacity Building Preliminary Project, Semarang. Research data was obtained from the results of field tests and laboratory tests. The results of the data are processed and displayed in the form of tables and graphs. The following shows a data analysis table along with graphs:

1. *Bore Hall* – 01

Table 2. Recapitulation of BH-01 Points

Titik Bor	Layer	Depth	N-SPT	CSR	CRR 6	CRR 7,5	SF 6	Information	SF 7,5	Information
BH-01	1	-1,45	7	0,752	0,295	0,203	0,392	Likuifaksi	0,270	Likuifaksi
	2	-4	9	0,709	0,251	0,173	0,354	Likuifaksi	0,244	Likuifaksi
	3	-6	14	0,683	0,293	0,200	0,428	Likuifaksi	0,292	Likuifaksi
	4	-8	15	0,661	0,259	0,184	0,391	Likuifaksi	0,279	Likuifaksi

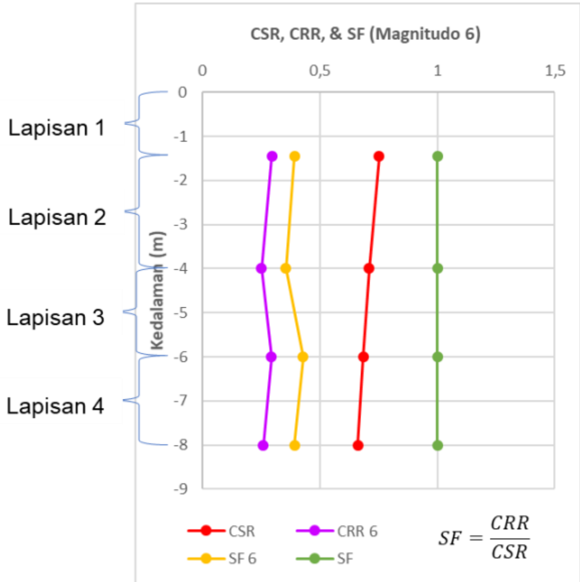

Figure 4. Chart of CSR, CRR, & SF BH-01 (Magnitude 6)

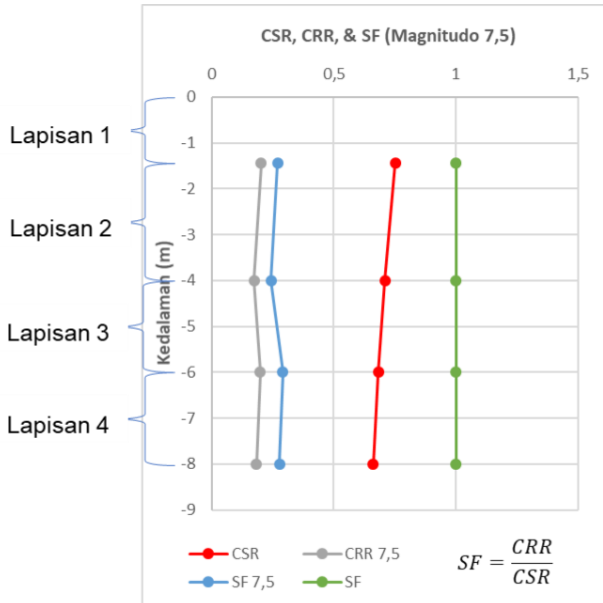

Figure 5. Chart of CSR, CRR, & SF BH-01 (Magnitude 7.5)

Based on Figure 4 and Figure 5, it shows that the results of data analysis at point BH-01, the soil has the potential for liquefaction, because the SF value is < 1. The results of the SF value search with a magnitude of 6 in layer 1 are 0.392, in layer 2 is 0.354, in layer 3 is 0.428 and in layer 4 is 0.391. Then at magnitude 7.5 it shows the SF result in layer 1 of 0.270, in layer 2 of 0.244, in layer 3 of 0.292 and in layer 4 of 0.279.

2. *Bore Hall* – 02

Table 3. Recapitulation of BH-02 Points

Titik Bor	Layer	Depth	N-SPT	CSR	CRR 6	CRR 7,5	SF 6	Information	SF 7,5	Information
BH-02	1	-2,8	39	0,311	18,346	12,635	58,983	No Liquefaction	40,622	No Liquefaction
	2	-4	27	0,373	0,651	0,444	1,749	No Liquefaction	1,191	No Liquefaction
	3	-6	24	0,435	0,373	0,269	0,858	Likuifaksi	0,618	Likuifaksi
	4	-8	7	0,471	0,153	0,114	0,324	Likuifaksi	0,243	Likuifaksi

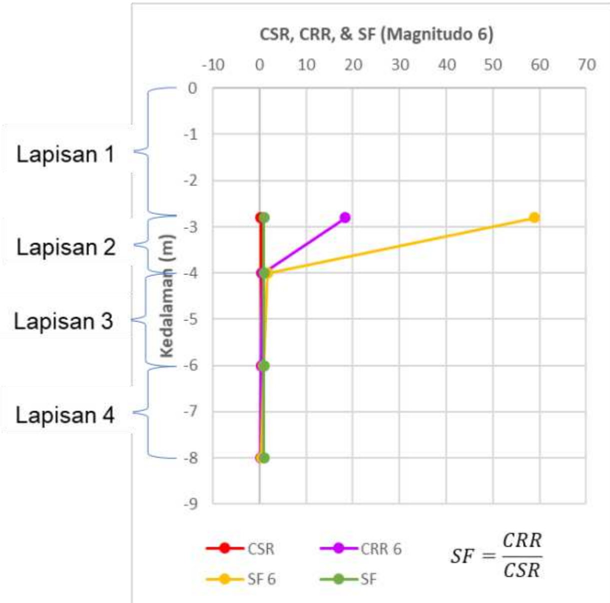

Figure 6. Chart of CSR, CRR, & SF BH-02 (Magnitude 6)

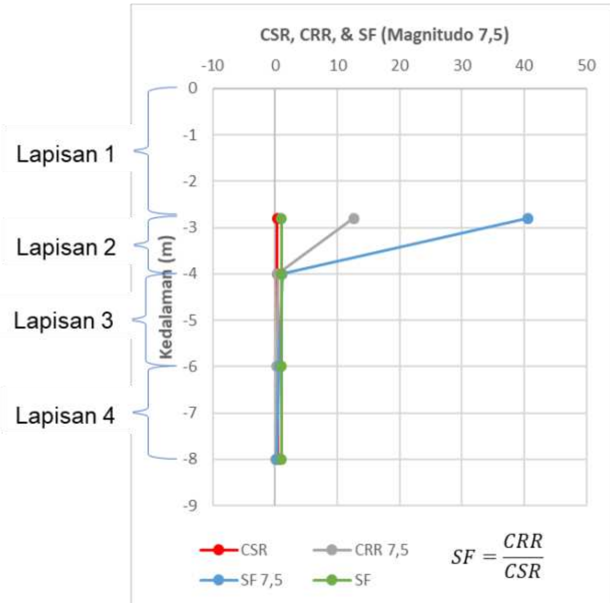

Figure 7. Chart of CSR, CRR, & SF BH-02 (Magnitude 7.5)

Based on Figure 6 and Figure 7, the results of data analysis at point BH-02, layer 1, and layer 2 on the soil are resistant to liquefaction, with a magnitude of 6 and magnitude 7.5 because of the SF value of > 1. Meanwhile, layers 3 and 4 have the potential to experience liquefaction because of the SF value of < 1. The results of the SF value tracing with a magnitude of 6 in layer 1 are 58.983, in layer 2 is 1.749, in layer 3 is 0.858, and in layer 4 is 0.324. Then at magnitude 7.5 it shows the SF results in layer 1 of 40.622, in layer 2 of 1.191, in layer 3 of 0.618 and in layer 4 of 0.243.

3. Bor Hall – 03

Table 4. Point BH-03 Recapitulation

Titik Bor	Layer	Depth	N-SPT	CSR	CRR 6	CRR 7,5	SF 6	Information	SF 7,5	Information
BH-03	1	-1,5	5	0,682	0,221	0,152	0,324	Likuifaksi	0,223	Likuifaksi
	2	-4	12	0,688	0,305	0,210	0,444	Likuifaksi	0,305	Likuifaksi
	3	-6	11	0,657	0,236	0,164	0,359	Likuifaksi	0,250	Likuifaksi
	4	-8	14	0,635	0,234	0,169	0,368	Likuifaksi	0,266	Likuifaksi

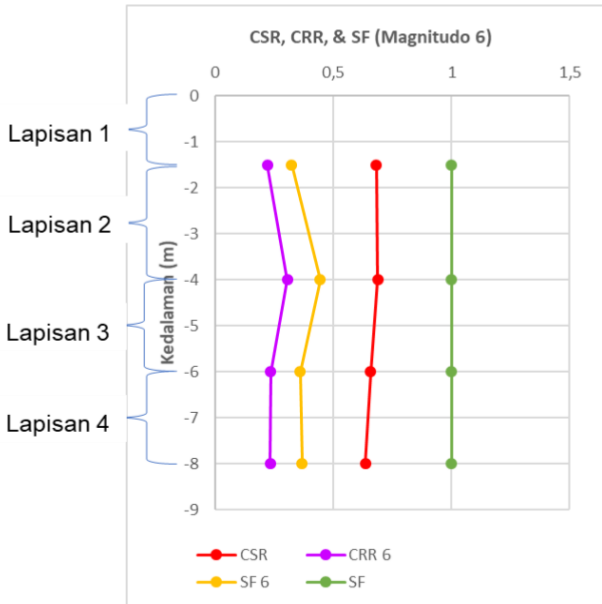

Figure 8. Chart of CSR, CRR, & SF BH-03 (Magnitude 6)

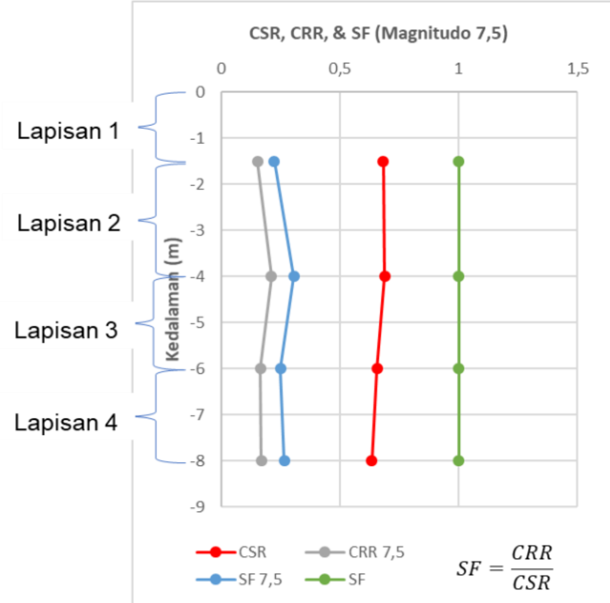

Figure 9. Chart of CSR, CRR, & SF BH-03 (Magnitude 7.5)

Based on figures 8 and 9, show that the results of data analysis at point BH-03, the soil at that point has the potential to undergo liquefaction, because of the value of SF < 1. The results of the SF value tracing with a magnitude of 6 in layer 1 are 0.324, in layer 2 is 0.444, in layer 3 is 0.359 and in layer 4 is 0.368. Then at magnitude 7.5 it showed the SF result in layer 1 of 0.223, in layer 2 of 0.305, in layer 3 of 0.250 and in layer 4 of 0.266.

Conclusion

From the results of the analysis of soil resistance to liquefaction in the case study of the preliminary project *of the Karangingas II pedestrian underpass box*, Semarang, it can be concluded that at that location the data obtained based on soil classification is in the form of clay soil with low plasticity to high plasticity. Based on the results of the analysis of soil resistance to liquefaction, it can be concluded that the relationship between magnitude variation and *safety factor* is very influential. Because, the greater the magnitude, the more influential it is also resistant to liquefaction.

It is known that from the results of data analysis at point BH-01, liquefaction occurred at earthquake magnitudes 6 and 7.5 at a depth of 0 – 8 meters. With the amount of *safety factor* at each depth less than the safe threshold limit or SF < 1 and the results obtained from magnitude 6 ranged from 0.354 - 0.428 and at magnitude 7.5 ranged from 0.244 - 0.292. From the results of data analysis at point BH-02, at the magnitude of the earthquake 6 to 7.5 at a depth of 0 - 4 meters, it is resistant to liquefaction, because it has an SF value of > 1 with the results obtained at magnitude 6 ranging from 1,749 to 58,983 and at magnitude 7.5 ranging from 1,191 to 40,622. This happens because the groundwater level is found at a depth of 2.8 meters and at a depth of 4 meters has a high level of soil density. However, at a depth of 4 – 8 meters, it experiences liquefaction. From magnitude 6 it ranges from 0.324 - 0.858 and at magnitude 7.5 it ranges from 0.243

- 0.618. And based on the results of data analysis at point BH-03, at magnitude 6 to 7.5 at a depth of 0 – 8 meters experienced liquefaction, because it had an SF value > of 1 with results obtained at magnitude 6 ranging from 0.324 – 0.444 and at magnitude 7.5 ranging from 0.223 – 0.305. This happens because the groundwater level is 0.5 meters deep.

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