Analysis of Soil Improvement using Stone Columns in Reducing Liquefaction Potential (Case study: Runway 3 of Soekarno-Hatta Airport)

Enden Mina [1*], Rama Indera Kusuma[2], Woelandari Fathonah[3], Rona Ulita Tarihoran[4]
[1,2,3,4]Department of Civil Engineering, Sultan Ageng Tirtayasa University, Indonesia

Article Info

Article history:

Received April 3, 2023
Accepted April 22, 2023
Published April 30, 2023

Keywords:

Stone column, liquefaction, SPT, LPI.

ABSTRACT

This research discusses the use of stone columns in increasing the value of the safety factor on soils that have the potential to experience liquefaction. This study aims to determine the safety factor value of sandy soil in the study area and the safety factor value after Stone Column planning. The method used to determine the value of liquefaction potential is the method of Seed et al., based on the interpretation of SPT (Standard Penetration Test) data and using the stone column as a soil improvement method. Based on the study's results, it is known that each point has the potential to experience liquefaction except at points BH 7, BH 8, and BH 9. The LPI value is > 15, so the research area has the potential to experience liquefaction. Before planning, the safety factor value is 0.43-0.87, and after planning the stone column using an equilateral triangle pattern, the safety factor value increases to 1.21-2.3 while using a square pattern of 0.95-1.94.

Available online at http://dx.doi.org/10.36055/fondasi

Corresponding Author:

Enden Mina ,
Department of Civil Engineering,
Sultan Ageng Tirtayasa University,
Jl. Jendral Soedirman Km 3, Banten, 42435, Indonesia.
Email: *enden@untirta.ac.id

1. INTRODUCTION

Soil is made up of particles, each particle related to other particles. Because of the weight of the soil particles, there is an inter-particle force. This force allows each soil particle to remain in its position [1]. Settlement in clay soils generally takes longer because the water seepage capacity is deficient, while in sandy soils, the settlement runs faster [2]. Liquefaction is the loss of soil layer strength due to pore water stress arising from cyclical loads [3]. Liquefaction usually occurs in loose sandy and water-saturated soils [4]. Liquefied soil cannot withstand the weight of anything above it because the soil particles have turned into liquid..

Based on the map of liquefaction vulnerability zones of Banten Province, the research area is included in the moderate liquefaction vulnerability zone, which is a vulnerability zone that can experience liquefaction unevenly, and the soil structure is generally damaged. The type of damage to the soil structure occurs in lateral shifting, subsidence, and minor damage to the soil structure [5]. Based on previous research conducted by Mina et al., 2020 with a case study of the East Cross Taxiway of Soekarno-Hatta Airport, it is known that the area has the potential to experience liquefaction with silty sand soil types [6].

The stone column is practical for increasing bearing capacity and slope stability, reducing total and differential settlement, increasing consolidation settlement time with a drainage system in cohesive soil, and reducing liquefaction potential in non-cohesive soil [7]–[10]. Stone Column installation is done by making a hole in the soil that will be increased bearing capacity. Next, granular material of various sizes will be inserted into the hole made by the Vibro compaction process, which makes the granular material denser. Vibro compaction is one of the techniques in soil improvement using mechanical vibration to strengthen the soil so that it is denser and can carry heavier loads [11].

The stone column has two types of patterns in its implementation: triangular and square. Each pattern has its advantages and disadvantages. The triangular pattern is more effective, stable, and uniform land subsidence than the square pattern, but implementing the square pattern construction is easier to install [12]. Stone Column is one of the frequently used soil improvement methods that serve to eliminate the danger of liquefaction in sandy soil layers during cyclic/dynamic load applications and can increase the bearing capacity of the soil. This is the background of research related to using stone columns to increase the value of the safety factor when liquefaction potential occurs in the research area.

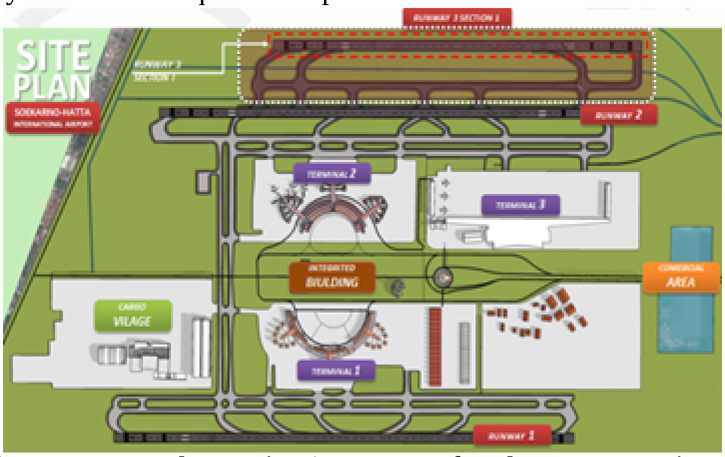


Figure 1. Research Location (Runway 3 of Soekarno-Hatta Airport)

2. METHODS

In general, the conditions for liquefaction in an area are: The soil layer is sand or silt, the soil layer is loose (not dense), the earthquake velocity is more than 0.1 g, and the magnitude is above 5.0 [13]. Liquefaction potential can occur if there are influencing factors such as relative density, soil consolidation rate ratio, initial soil stress, length of vibration time, soil grain size, initial pore pressure, and maximum stress level [14]. Determine the liquefaction potential and the right stone column design requires stages such as the flow chart below:

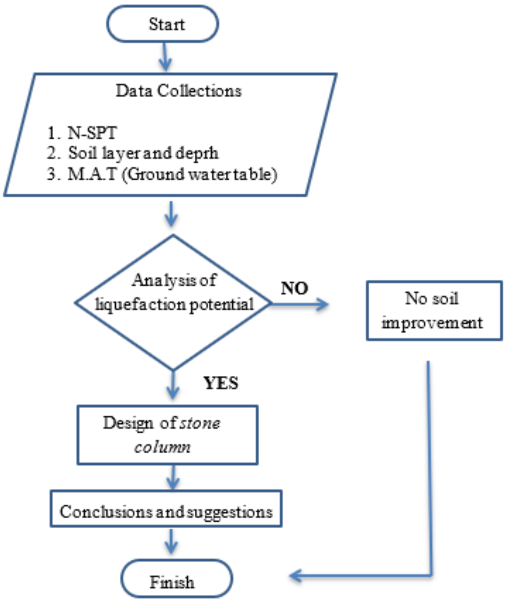


Figure 2. Flow Chart of Research

This research was conducted in several stages, starting with finding data such as N-SPT data, and the depth of the soil layer up to 20 meters with MAT (Groundwater Level) from 0.4 meters - 2.85 meters obtained from SPT results. To find out the maximum acceleration value in bedrock, the author uses the 2017 Indonesian earthquake map with a return period of 1000 years is 0.35g with Mw = 7.5. If there is an earthquake with Mw < 7.5, the effect caused is smaller than the earthquake with Mw > 7.5, assuming the soil has better resistance [15]. The research area has 10 test points, are BH 1, BH 2, BH 3, BH 4, BH 5, BH 6, BH 7, BH 8, BH 9, BH 10.

Analysis of Liquefaction Potential

The next step is to analyze the liquefaction potential. The method used in determining liquefaction potential uses the method of Seed et al. This method requires the CSR (cyclic stress ratio) value, which is the stress value caused by earthquakes. The formula for determining the CSR value is:

$$CSR = 0.65 \text{ x } \frac{amax}{g} \text{ x } \frac{\sigma vo}{\sigma' vo} \text{ x rd} \quad (1)$$

Determining the safety factor value also requires the CRR (Cyclic Resistance Ratio) value, which is the ability of the soil to resist liquefaction. The formula for determining the CRR value is :

$$CRR_{7,5} = \frac{1}{34-(N1)60} + \frac{(N1)60}{135} + \frac{50}{(10\,((N1)60)+45)^2} - \frac{1}{200} \quad (2)$$

$$CRR = CRR_{7.5} \text{ x MSF} \quad (3)$$

After the CSR and CRR values are found, the safety factor can be determined. The formula for determining the factor of safety is :

$$SF = \frac{CRR}{CSR} \quad (4)$$

If SF < 1, liquefaction; if SF > 1, no liquefaction; if FS = 1, critical condition.

Design the stone column,

Design the stone column, can be strengthened by finding the LPI value. The formula for finding the LPI value :

$$LPI = \int_{0\,m}^{20\,m} F.w\,(z)\,dz \quad (5)$$

$$W(z)=10-0.5z \quad (6)$$

Notes:

LPI = Liquefaction Potential Index value

F = Potential liquefaction event, determined by the equation:

F = (1-SF)
for SF<1, and F=0 for SF>1
w(z) = Depth weighting factor
z = Depth under review (max. 20m)
LPI =0, Very low potential liquefaction
0<LPI<5, Low potential liquefaction
5<LPI<15, High potential liquefaction
LPI>15, Very high liquefaction potential

Liquefaction potential Index (LPI) is a method developed by Iwasaki (1984) to determine the boundaries of liquefaction potential by using the value of the factor of safety and a function of soil depth (w(z)). The resulting liquefaction potential boundaries include high liquefaction potential, very high liquefaction potential, and low liquefaction potential. The equation proposed by (Iwasaki et al., 1984) to determine the Liquefaction Potential Index (LPI) value is as follows [16]:

If liquefaction potential occurs and the LPI value is high, a stone column must be designed to keep the building safe. Stone columns have 2 patterns: triangular and square patterns. these two patterns have differences in finding the equivalent diameter (Dc) formula

Dc = 1.05 x s (triangular pattern) (7)

Dc = 1.13 x s (square pattern) (8)

Note:
s = the distance between stone columns

The ability of this stone column material has a reduction effect on the basic improvement factor (n0), and produces a reduction value (n1) with the formula:

$$n_1 = 1 + \frac{Ac}{A}\left[\frac{5-\frac{Ac}{A}}{4\,\text{Kac}\,(1-\frac{Ac}{A})} - 1\right] \quad (9)$$

The safety factor of liquefied soil before and after using stone columns will be different. If using a stone column, the bearing capacity of the soil will increase and can reduce settlement on sandy soil. Safety factor formula after using stone column

$$FS' = \frac{\text{CRR x n1}}{\text{CSR}} \quad (10)$$

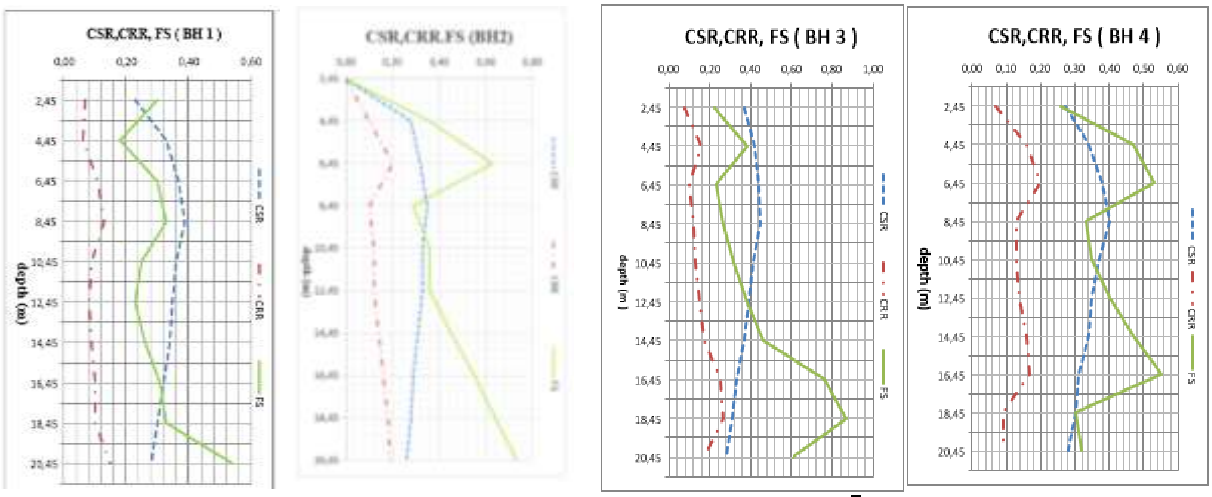
3. RESULTS AND DISCUSSION

Based on known SPT data, points at BH 7, BH 8, and BH 9 only have cohesive soil types. For cohesive soil in the event of an earthquake, the characteristics between particles will bind each other so that they do not have the potential to experience liquefaction. Based on the results of the analysis that has been carried out, the FS value of the test points can be seen in Table 1 and the graphs in Figure 3 until Figure 5.

Table 1. Recapitulation of Safety Factor values

Point	h (m)	FS	Potential
BH 1	20,45	0,54	L
BH 2	6,45	0,63	L
BH 3	14,45	0,46	L
BH 3	18,45	0,87	L
BH 3	20,45	0,61	L
BH 4	6,45	0,53	L
BH 5	4,45	0,57	L
BH 6	4,45	0,48	L
BH 6	6,45	0,64	L
BH 6	8,45	0,43	L

BH 10	16,45	0,87	L



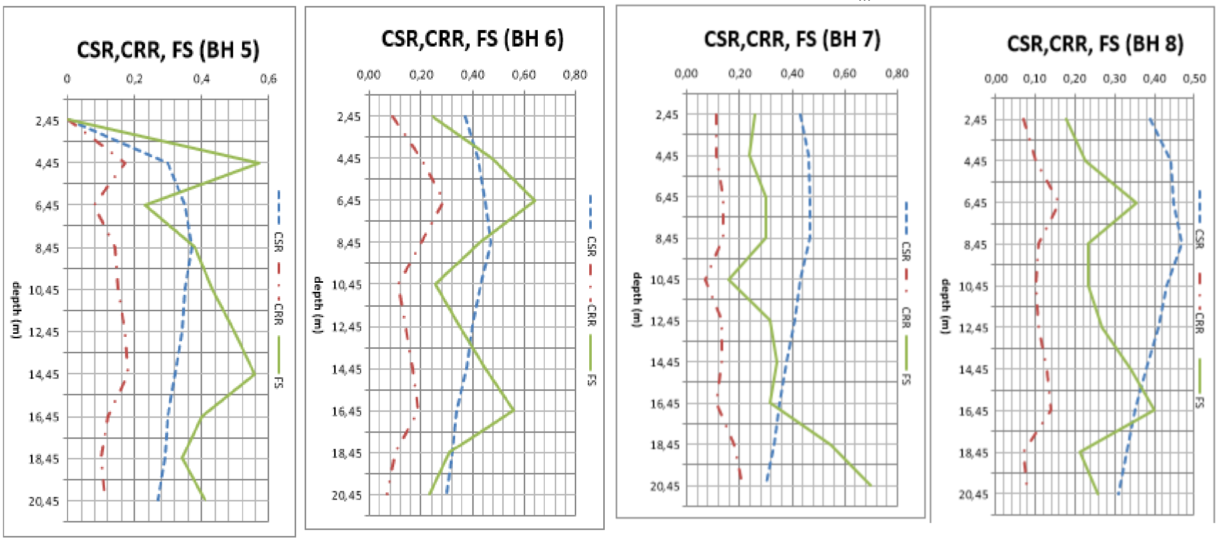


Figure 4. Calculation Chart of Liquefaction Potential in BH 5, BH 6, BH 7, and BH 8

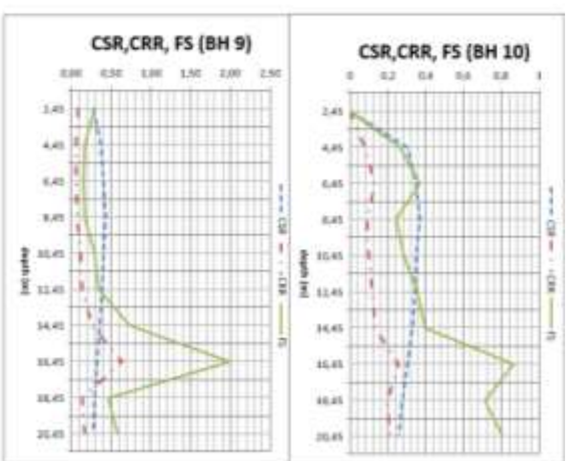


Figure 5. Calculation Chart of Liquefaction Potential in BH 9 and BH 10

Design of Stone Column

To determine the correct pattern to use in planning, it is necessary to first calculate the planning of stone columns by comparing equilateral triangle patterns and square patterns. The calculations are shown in Figure 6.

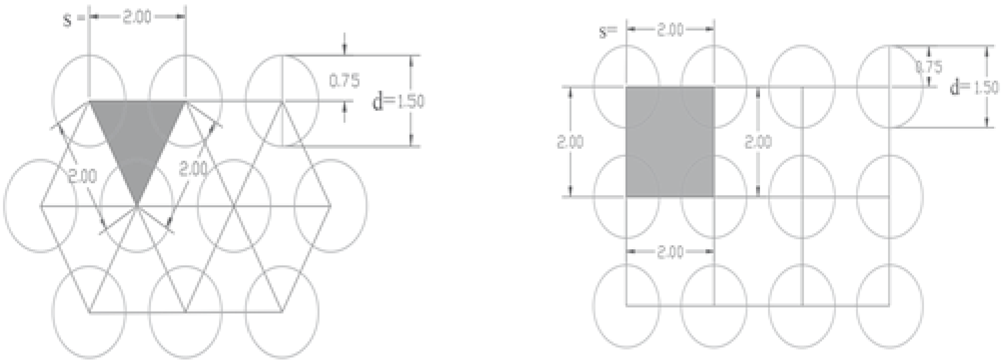


Figure 6. Triangle and Square Patterns on Stone Columns

When loading occurs, the total settlement in the stone column or the surrounding soil is the same. The stress concentrated more on the stone column will reduce the total overburden stress and also, on the other hand, increase the soil resistance (cyclic resistance ratio) as the effect of soil densification [17]. Where FS' is the safety factor after stone column planning.

$$FS' = (CRR \times n_1)/CSR \quad (11)$$

The following results of comparing stone column planning using a triangular pattern and a square pattern can be seen in Table 2 and Figures 7 to Figure 10.

Table 2. Comparison of Safety Factor Values After Using Stone Column

Point	FS	FS' Triangular Pattern	FS' Square Pattern
BH 1	0.54	1.43	1.19
BH 2	0.63	1.66	1.39
BH 3	0.46	1.22	1.02
BH 3	0.87	2.32	1.94
BH 3	0.61	1.62	1.35
BH 4	0.53	1.40	1.17
BH 5	0.57	1.51	1.26
BH 6	0.48	1.27	1.06
BH 6	0.64	2.28	1.44
BH 6	0.43	1.21	0.95
BH 10	0.87	2.31	1.93
BH 10	0.71	1.90	1.59

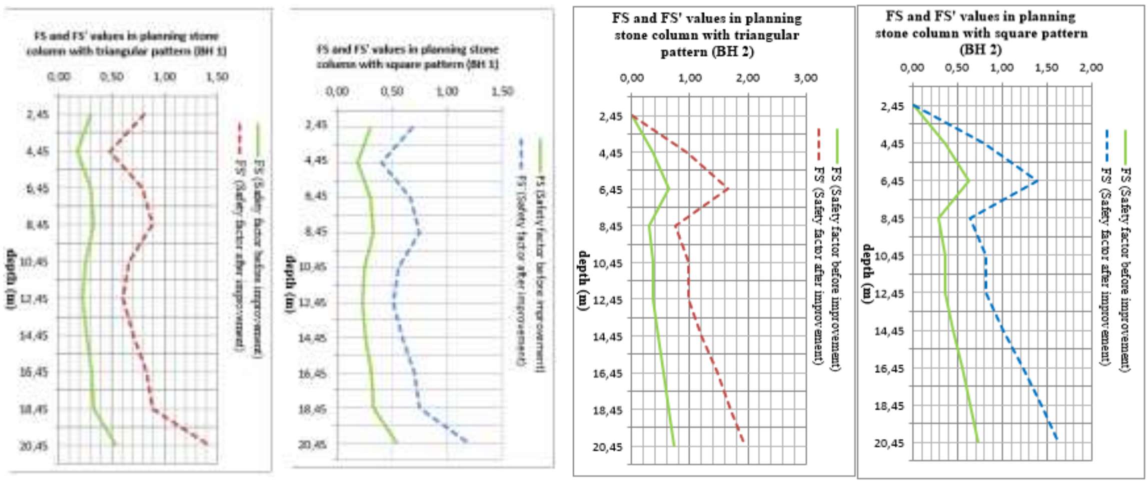


Figure 7. Comparison of FS' Values in Triangular Pattern and Square Pattern at BH 1 and BH2

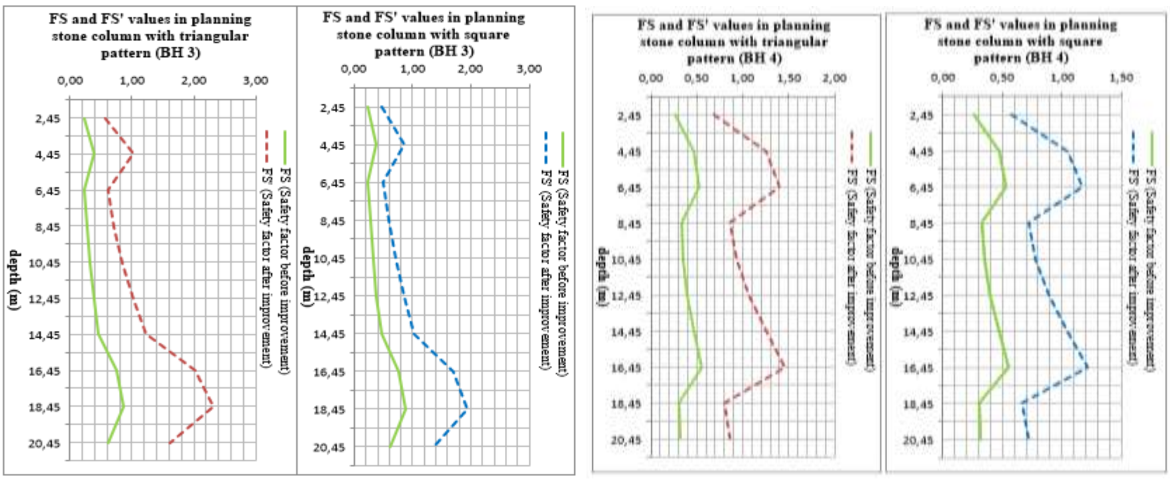


Figure 8 . Comparison of FS' Values in Triangular Pattern and Square Pattern at BH 3 and BH 4

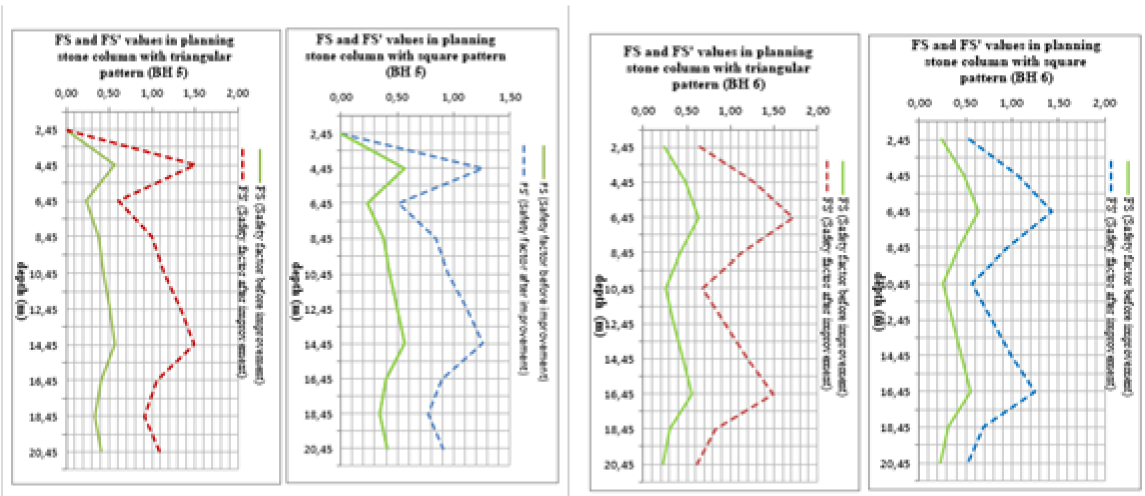


Figure 9 . Comparison of FS' Values in Triangular Pattern and Square Pattern at BH 5 and BH 6

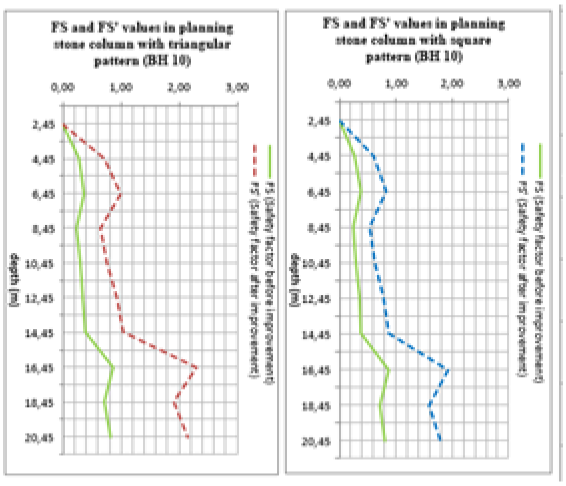


Figure 10. Comparison of FS' Values in Triangular Pattern and Square Pattern at BH 10

After knowing the value of comparing the two patterns, it is known that the most considerable corrected improvement factor value uses an equilateral triangle pattern. So the pattern used in the implementation uses a triangular pattern. The graph of Ishihara (1985) can be used to determine the depth of the stone column. The Ishihara (1985) graph depends on the thickness of the layer. H1 is soil with no liquefaction potential, and H2 is soil with liquefaction potential.

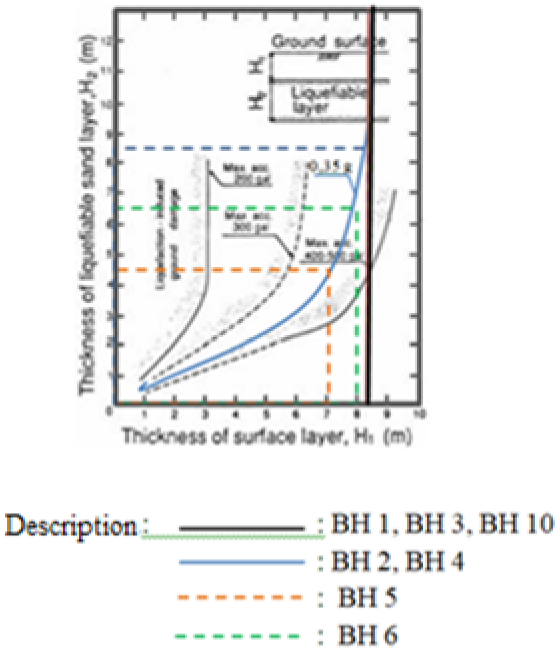


Figure 11. Ishihara (1985) Liquefaction Potential Criteria Chart

The evaluation method by Ishihara (1985) uses the ratio of the thickness of the surface soil that is not potentially subject to liquefaction to the thickness of the soil beneath the soil layer that is subject to liquefaction. For each different peak ground acceleration, the curve used will be different [18].

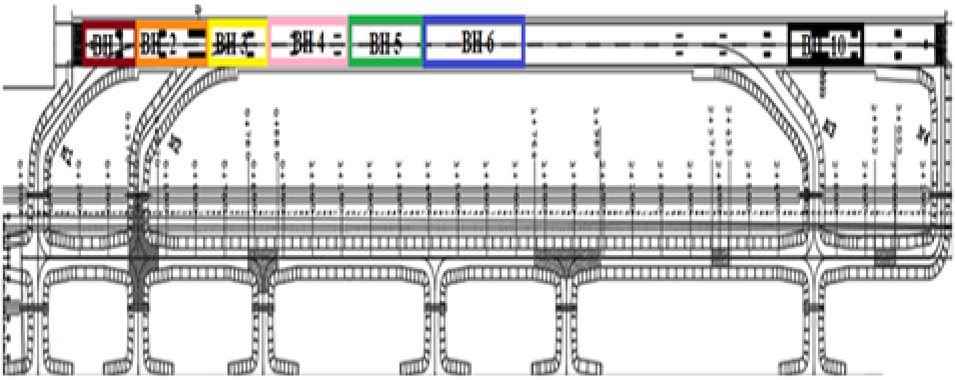


Figure 12. Location of stone column installation

Based on previous calculations, the pattern to be used in the installation of the Stone Column is an equilateral triangle pattern with a diameter of 1.5 m, and the spacing between columns is 2 m. Based on the Ishihara chart, the planning depth of Stone Column at BH 5 is 7 m, and BH 1, BH 3, BH 6, and BH10 is 8.5 m, while BH 2 and BH 4 are at a depth of 8 m.

4. CONCLUSION

From the data and the results of the calculation analysis that has been carried out, the conclusions are obtained:

1. Based on NSPT data, it is known that there are several layers of sandy soil in the research area except at points BH 7, BH 8, and BH 9. The factor of safety (SF) at points that have a layer of water-saturated sand ranges from 0.43-0.87 (FS <1), which has the potential to experience liquefaction.
2. It is based on the calculation of Stone Column planning using an equilateral triangle and square pattern with a diameter of 1.5 m and a distance of 2.0 m between columns. Planning with an equilateral triangle pattern can increase the value of the safety factor more significantly than using a square pattern. The value of the safety factor after planning with an equilateral triangle pattern is 1.21-2.3, while with a square pattern of 0.95-1.94.

REFERENCES

[1] I. Rifa, "Analisis Potensi Likuifaksi dari Data CPT dan SPT dengan Studi Kasus PLTU Ende Nusa Tenggara," Universitas Indonesia, 2011.

[2] B. M. Das, *Mekanika Tanah II (Prinsip-prinsip Rekayasa Geoteknis), Jilid 1 dan 2*. Jakarta: Erlangga, 1994.

[3] M. HUTAGALUNG and S. D. TARIGAN, "Analisis Potensi Likuifaksi Akibat Gempa (Studi Kasus : Reklamasi Pelabuhan Kontainer Belawan Fase-2)," *J. Rekayasa Konstr. Mek. Sipil*, vol. 2, no. 1, pp. 15–34, 2019, doi: 10.54367/jrkms.v2i1.433.

[4] S. Barhi, "Studi Perencanaan Perbaikan Tanah dengan Stone Column pada Stock Pile Batu Bara Rencana PLTU Sorong (4x7 MW)," Universitas Brawijaya, 2017.

[5] "ESDM,Atlas Zona Kerentanan Likuefaksi Indonesia, https://www.esdm.go.id/assets/media/content/content-atlas-zona-likuefaksi-indonesia.pdf, 2019." .

[6] E. Mina, R. I. Kusuma, and K. A. Muzaky, "Analisis potensi likuifaksi berdasarkan data penyelidikan tanah standard penetration test (SPT) (studi Kasus cross taxiway timur Bandara Soekarno Hatta Tangerang)," *Tek. J. Sains dan Teknol.*, vol. 16, no. 1, p. 128, 2020, doi: 10.36055/tjst.v16i1.8261.

[7] R.D.Barksdale and R.C.Bachus, *Design and Construction of Stone Columns Volume I,*

Publication No.FHWA-RD-83-026. 1983.

[8] A. G. D. Abdelrazek and S. A. Y. Akl, "Estimating Liquefaction Resistance Improvement Due To Stone Columns From Quality Control Tests," *Int. J. GEOMATE*, vol. 21, no. 86, pp. 147–158, 2021, doi: 10.21660/2021.86.j2304.

[9] Y. Zhou, Z. Sun, J. Chen, Y. Chen, and R. Chen, "Shear wave velocity-based evaluation and design of stone column improved ground for liquefaction mitigation," *Earthq. Eng. Eng. Vib.*, vol. 16, no. 2, pp. 247–261, 2017, doi: 10.1007/s11803-017-0380-2.

[10] L. Tang, X. Zhang, and X. Ling, "Numerical simulation of centrifuge experiments on liquefaction mitigation of silty soils using stone columns," *KSCE J. Civ. Eng.*, vol. 20, no. 2, pp. 631–638, 2016, doi: 10.1007/s12205-015-0363-7.

[11] A. Ramadhan, "Analisis Penggunaan Stone Column pada Daerah Berpotensi Likuifaksi (Studi Kasus Proyek Airstrip Tanjung Ulie, Halmahera, Maluku Utara)," Institut Teknologi Bandung, 2011.

[12] Y. Fajarwati and R. I. Kusuma, "Analisis Potensi Likuefaksi dan Perbaikan Tanah dengan Stone Column: Studi Kasus pada Coal Shelter PLTU Lontar, Banten," *INERSIA lNformasi dan Ekspose Has. Ris. Tek. SIpil dan Arsit.*, vol. 17, no. 1, pp. 27–35, 2021, doi: 10.21831/inersia.v17i1.40570.

[13] E. Mina, R. I. Kusuma, and S. Sudirman, "Analisa Potensi Likuifaksi Berdasarkan Data Spt (Studi Kasusproyek Pembangunan Gedung Baru Untirta Sindang Sari)," *J. Fondasi*, vol. 7, no. 1, pp. 11–21, 2018, doi: 10.36055/jft.v7i1.3298.

[14] B. M. Das, *Fundamental of Soil Dynamics*. New York: Elsevier Pub, 1983.

[15] W. B. and I.M.Idriss, *Soil Liquefaction During Earthquakes*. Earthquake Engineering Research Institute, 2008.

[16] K. I. Iwasaki, T., Arakawa, T., & Tokida, "Simplified procedures for assessing soil liquefaction during earthquakes," *Int. J. Soil Dyn. Earthq. Eng.*, 1984.

[17] W. Fathonah, E. Mina, R. Indera Kusuma, and R. Hutami, "Analisis Potensi Likuifaksi Dan Alternatif Perbaikannya Dengan Metode Stone Coloumn," *Pros. Semin. Nas. Apl. Sains Teknol.*, p. 2021, 2021.

[18] H. W.Tehputra, "Analisis Likuifaksi di Paisubololi, Sulawesi Tengah," Institut Teknologi Bandung, 2013.