Journal of Civil Engineering and Vocational Education
EISSN: 2622-6774
Vol 10 No.3 September 2023
http://cived.ppj.unp.ac.id/index.php/CIVED

Modification Effect of Stone Column Dimensions and Configuration on Bearing Capacity Efficiency and Settlement in Soft Soils

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Received 29th July 2023; Revision 25th July 2023; Accepted 29th August 2023

ABSTRACT

In airport construction, one crucial aspect to consider is the condition of the underlying soil on the runway. Following soil investigations at X project, it was determined that the soil condition is primarily characterized by soft soil layers, with Standard Penetration Test (SPT) values ranging from 4 to 10. In response to this condition, soil reinforcement was carried out using the stone column method. The objective of this study was to compare the bearing capacity and settlement of stone columns under various dimensional variations (spacing of 1.5 m, 2.0 m, 2.2 m; diameters of 0.4 m, 0.5 m, 0.6 m) and configuration patterns (square and triangular). Bearing capacity calculations were done manually, and settlement calculations were performed both manually and with the assistance program. The results were presented in tables and graphs. Using the FHWA method for bearing capacity calculations, it was found that bearing capacity increases as the diameter is increased and the spacing is reduced. Conversely, bearing capacity decreases as the diameter is reduced and the spacing is increased. The ultimate bearing capacity value for the triangular pattern installation exceeded that of the square pattern. Regarding settlement calculations after manual stone column installation, it was observed that settlement decreases as the diameter increases and the spacing between columns decreases. Settlement increases under opposite conditions. Settlement calculations using the Plaxis program focused on diameter and spacing between stone columns. During the service life, the highest settlement occurred with the triangular pattern, while the square pattern exhibited the lowest settlement.

Keywords: *Bearing Capacity; Settlement; Dimensions; Configuration Pattern; Stone Column.*

INTRODUCTION

In airport construction, one crucial aspect to consider is the condition of the underlying soil on the runway. Following soil investigations at X project, it was determined that the soil condition is primarily characterized by soft soil layers, with Standard Penetration Test (SPT) values ranging from 4 to 10. A soil condition is considered as soft soil if it has an N-SPT value of less than 15[1]. The values for bearing capacity, permeability, and frictional resistance for soft layers are low, while their compaction ability is high[2]. In connection with this condition, it is necessary to perform soil reinforcement as appropriate, and this is achieved through a soil reinforcement method known as stone columns.

The stone column method can reduce the potential for lateral spreading and liquefaction, improve slope stability, enhance bearing capacity (240 - 480 kPa or 5 - 10 ksf), reduce seismic settlement, and decrease foundation settlement [3]. Furthermore, stone columns have the capability to mitigating the potential risk of liquefaction and reducing consolidation time [4].

CIVED Journal of Civil Engineering and Vocational Education

EISSN: 2622-6774
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In a journal titled "Parametric Study of the Influence of Stone Columns on Soft Soil Bearing Capacity" [2], it is revealed that the bearing capacity increases with larger column diameter and shear angle, decreases with greater spacing between stone columns, and when compared to a square pattern, a triangular pattern results in higher bearing capacity.

Based on the conditions at the airport and the results of previous studies, the author is interested in carrying out calculations to determine the effectiveness of stone columns when modifications are made to their dimensions and configuration patterns. In conducting these calculations, several supporting data are used, such as Standard Penetration Test (SPT) and Plate Load Test (PLT) data. Through this data, information about the soil's depth, soil characteristics, thickness, and soil layer types are determined. Furthermore, soil bearing capacity can be assessed through PLT testing. The calculations will be performed manually and with the assistance program. The calculation data will be presented in the form of tables and graphs.

MATERIALS AND METHODS

This research is being carried out following the steps shown in the flowchart, which you can see in Figure 1.

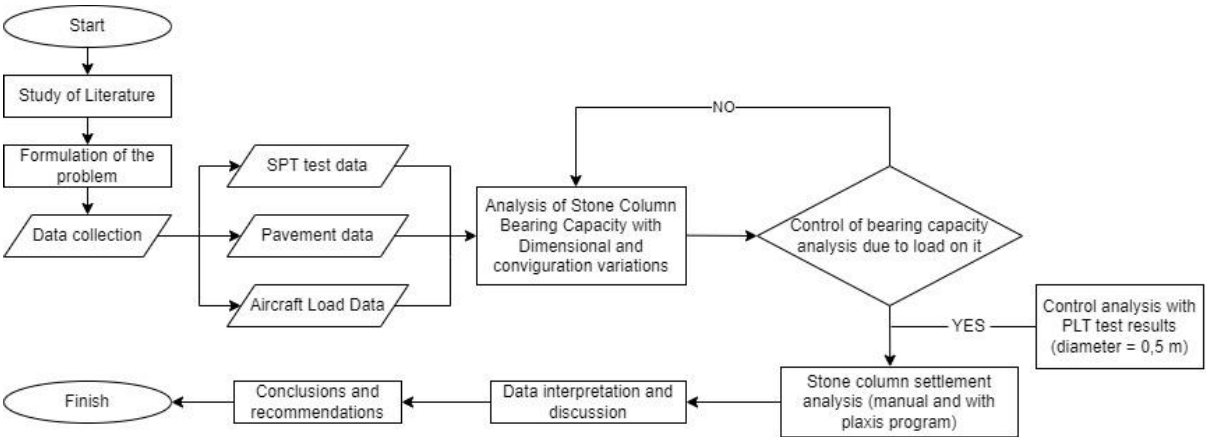

Figure 1. Flowchart of Research Process

Before discussing further about the methods and data that will be used, here is a brief explanation of soil condition and stone columns. The soil conditions in each region exhibit varying fundamental properties or characteristics. These soil conditions give rise to different geotechnical issues. For instance, in Southeast Asia, common geotechnical challenges include construction on soils with organic content, peat, and soft soils [5]. In Indonesia, one of the geotechnical issues that can be encountered is soft soil. The distribution of soft soil is estimated to cover approximately 20 million hectares, which is about 10 percent of Indonesia's total land area[6]. In soft soil, subsidence problems are often encountered, requiring specific treatment. Soil subsidence occurs when the soil undergoes significant loads and experiences a decrease in bearing capacity[7].

One of the soil improvement methods for soft soil is through the use of stone columns. The stone column method is a type of soil improvement technique in which the process of filling the stone column material is done using a vibrating pipe equipped with a vibrator at the top. At the bottom of the pipe, there is a cover that can open automatically when the pipe is raised and close when the pipe enters the ground [8]. After the stone columns have been applied to the soil, they require testing. This testing can be conducted using Plate Load Tests (PLT). PLT involves applying a static load to a plate placed on top of the columns[9].

Returning to the employed methodologies and collected data. Below are some data that will be used in calculations, such as NSPT data and the required load data (embankment, pavement, and aircraft). This data can be seen in Table 1 and Figure 2.

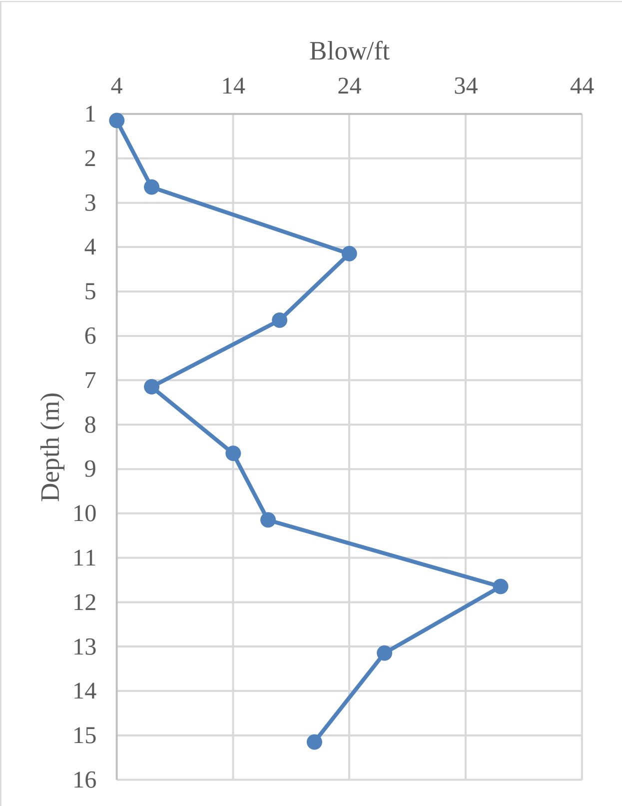

Figure 2. Field NSPT testing data

Table 1. Load Data

Type	q (kN/m2)
Embankment	88,25
Asphalt	4,74
Plane (B777-300ER)	386,02
Total	479,01

The type of aircraft used is the B777-300ER aircraft. Some of the characteristics of this aircraft include the following: one landing gear of the B777-300ER is in the form of Triple Dual Tandem (TDT)[10]. The tire pressure is 220 Psi[11]. The footprint shape of the aircraft wheel contact area is modeled as elliptical/oval/semi-circular[12].

Table 2. Variation of Diameter and Spacing center to center of stone column

S	D
m	**m**
1,5	0,4

EISSN: 2622-6774
Vol 10 No.3 September 2023
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1,5	0,5
1,5	0,6
2,0	0,4
2,0	0,5
2,0	0,6
2,2	0,4
2,2	0,5
2,2	0,6

In table 2 there are variation of stone column dimension, configuration pattern which is used in this research is rectangle and triangle pattern.

Bearing Capacity Analysis

The shear angle within the material and the soil strength in its vicinity determine the bearing capacity of the stone column. This is because, without any supporting material, the stone column would collapse. Therefore, the stone column acts as support for the surrounding soil and provides passive resistance from the material. The calculation of the bearing capacity for a single stone column employs the Brauns method (1978). Brauns simplified the method for calculating the ultimate bearing capacity of rock columns in fully saturated soft soil conditions under undrained conditions based on an axi-symmetric model[13]. The collapse model is depicted in Figure 3. Equation used in the calculation of ultimate bearing capacity for a single stone column is as follows.

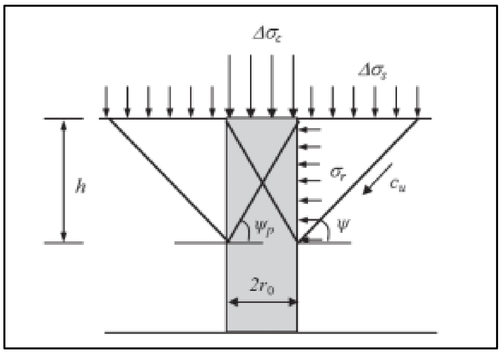

Figure 3. Modelling of a single stone column collapse

$$q_{ult} = q_{ult,c}\ as + q_{ult,s}\ (1 - as)$$
$$= K' \frac{1+\sin(\phi_s)}{1-\sin(\phi_s)} c_u\ C1 \times \left(\frac{D}{s}\right)^2 + 5\ c_u \left(1 - C1 \times \left(\frac{D}{s}\right)^2\right)$$

where $q_{ult,c}$ = ultimate bearing capacity of stone column (granular column)
$q_{ult,s}$ = bearing capacity of the surrounding soil
as = area replacement ratio
K' = constant
ϕ_s = shear angle of stone column
C1 = constant
D = diameter of stone column
s = spacing of stone column center to center

The constant value, C1, depends on the pattern of the stone column used. If the pattern used is

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EISSN: 2622-6774
Vol 10 No.3 September 2023
http://cived.ppj.unp.ac.id/index.php/CIVED

a square pattern, then the value of C1 is 0.785. If the pattern of the stone column used is a triangular pattern, then the value of C1 is 0.907[14]. And the value of K' is based on Table 3.

Table 3. The Ultimate Bearing Capacity of a Single Stone Column

c_u (kPa)	Soil Type	K'	K' K_p	Reference
19,4	Clay	4,0	25,2	Hughes dan Withers (1974)
19,0	Clay	3,0	15,8 – 18,8	Mokashi dkk. (1976)
-	Clay	6,4	20,8	Brauns (1978)
20,0	Clay	5,0	20,0	Mori (1979)
-	Clay	5,0	25,0	Broms (1979)
15,0 – 40,0	Clay	-	14,0 – 24,0	Han (1992)
-	Clay	-	12,2 – 15,2	Guo dan Qian (1990)

The bearing capacity of stone columns in a group is calculated using the FHWA method (1983). The bearing capacity is considered for a group or row assumed to support or withstand the rigid concrete foundation located at the surface of the clay soil. Below is the equation used in the calculation of the bearing capacity of the stone column.

$$q_{ult} = \sigma_3 \tan^2 \beta + 2\, c_{avg} \tan \beta$$

where σ_3 = average lateral confining pressure
β = inclination of the failure surface
c_{avg} = composite cohesion on the shear surface beneath the foundation

Settlement Analysis

The settlement of the subsoil before soil improvement with stone columns is calculated using the following formula[15].

$$St = \frac{Cc}{1 + e_o} H \log \frac{\sigma_o' + \Delta\sigma_c}{\sigma_o'}$$

where St = primary consolidation settlement occurring over a distance H of stone column treated ground
C_c = compression index from one-dimensional consolidation test
e_0 = initial void ratio
H = vertical height of stone column treated ground over which settlements are being calculated
σ_o' = average initial effective stress in the clay layer
$\Delta\sigma_c$ = change in stress in the clay layer due to the externally applied loading

In the settlement of the soil due to the presence of stone columns, the change in stress within the clay is multiplied by the factor of stress concentration of the rock column. This stress concentration factor is calculated using the equation below.

$$\sigma_c = \frac{n}{1 + (n-1)as} . \sigma$$

where n = stress concentration factor
as = area replacement ratio
σ = average externally applied stress

RESULTS AND DISCUSSION

After performing bearing capacity calculations of single and group of stone column based on the obtained data, the results are as seen in the Table 4, Table 5, and Figure 4.

Tabel 4. Bearing Capacity of Single Stone Column (Rectangle)

S	D	as	qultc	qults	qult
m	m		kN/m²	kN/m²	kN/m²
1,5	0,4	0,06	4169,68	708,33	901,55
1,5	0,5	0,09	4169,68	708,33	1010,24
1,5	0,6	0,13	4169,68	708,33	1143,08
2,0	0,4	0,03	4169,68	708,33	817,02
2,0	0,5	0,05	4169,68	708,33	878,16
2,0	0,6	0,07	4169,68	708,33	952,88
2,2	0,4	0,03	4169,68	708,33	798,16
2,2	0,5	0,04	4169,68	708,33	848,68
2,2	0,6	0,06	4169,68	708,33	910,44

Table 5. Bearing Capacity of Single Stone Column (Triangle)

S	D	as	qultc	qults	qult
m	m		kN/m²	kN/m²	kN/m²
1,5	0,4	0,06	4169,68	708,33	931,58
1,5	0,5	0,10	4169,68	708,33	1057,16
1,5	0,6	0,15	4169,68	708,33	1210,64
2,0	0,4	0,04	4169,68	708,33	833,91
2,0	0,5	0,06	4169,68	708,33	904,55
2,0	0,6	0,08	4169,68	708,33	990,88
2,2	0,4	0,03	4169,68	708,33	812,12
2,2	0,5	0,05	4169,68	708,33	870,49
2,2	0,6	0,07	4169,68	708,33	941,85

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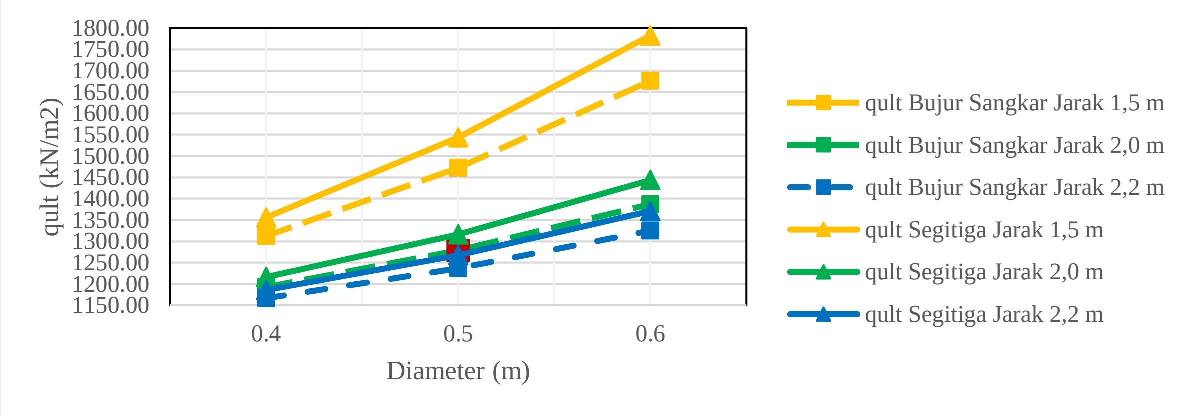

Figure 4. Bearing Capacity of group stone column

Table 6. Factor of Safety Calculation

S	D	FS	FS
m	m	Rectangle	Triangle
1,5	0,4	2,76	2,85
1,5	0,5	3,10	3,25
1,5	0,6	3,53	3,75
2,0	0,4	2,51	2,56
2,0	0,5	2,69	2,77
2,0	0,6	2,92	3,04
2,2	0,4	2,45	2,49
2,2	0,5	2,60	2,67
2,2	0,6	2,79	2,88

The data points marked in red represent the bearing capacity under the same diameter, spacing, and pattern configuration as observed in the field. In Table 7 and table 8 are displays the results of calculations for settlement before and after the installation of stone columns.

Table 7. Settlement before the installation of stone column

Depth	e_o	Cc	σ_o'	Sc
m				m
1	0,55	0,08	8,74	0,095
2	0,53	0,08	26,33	0,065
3	0,59	0,10	43,73	0,065
4	0,42	0,05	61,68	0,030
5	0,50	0,07	73,87	0,039
6	0,59	0,10	86,69	0,049
7	0,74	0,14	97,11	0,063
8	0,59	0,10	106,68	0,044
9	0,51	0,07	117,49	0,033
10	0,78	0,15	127,82	0,058
11	0,35	0,02	138,04	0,012
Total				0,553

Table 8. Settlement after the installation of stone column

S	D	Settlement (St)	
		Rectangle pattern	Triangle Pattern
m	m	m	m
1,5	0,4	0,533	0,535
	0,5	0,522	0,526
	0,6	0,510	0,515
2,0	0,4	0,541	0,543
	0,5	0,535	0,537
	0,6	0,528	0,531
2,2	0,4	0,543	0,545
	0,5	0,538	0,540
	0,6	0,532	0,534

Table 9. Calculation of Settlement with Plaxis

D	S	Settlement
m	m	cm
0,4	1,5	7,475
	2	7,755
	2,2	7,798
0,5	1,5	6,875
	2	7,51
	2,2	7,234
0,6	1,5	6,802
	2	7,118
	2,2	6,998

Based on the calculations above about bearing capacity, it can be concluded that ultimate bearing capacity is directly proportional to the diameter of the stone column. This means that the value of ultimate bearing capacity will increase as the diameter of the stone column is increased, and it will decrease as the diameter of the stone column is reduced. Additionally, what can be inferred from these calculations is that ultimate bearing capacity is inversely proportional to the spacing between the stone columns. Inversely proportional means that the value of ultimate bearing capacity will increase as the spacing between stone columns is reduced, and it will decrease as the spacing between stone columns is increased. In these calculations, it is evident that the ultimate bearing capacity value for the triangular pattern installation is greater than the ultimate bearing capacity value for the square pattern installation. In selecting variations of stone column dimensions and configuration patterns that are most effective, the criterion is to consider their Factor of Safety (FS) values. The closer the FS value is to 2.5, the more efficient it is considered. Based on the settlement calculations, it is known that the magnitude of settlement will decrease as the diameter increases and the spacing between columns decreases. Settlement will increase as the diameter decreases and the spacing between columns increases.

CONCLUSION

Diameter, spacing, and pattern configuration have an impact on the bearing capacity and settlement magnitude of the stone column. Based on the FS calculations (considering the load acting on them), the stone column with a diameter of 0.4 meters and spacing of 2 meters, and a square pattern configuration is considered to be the most effective variation in terms of dimensions and configuration.

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