Settlement Reduction Analysis on Soft Soil in Demak-Kudus National Highway with Stone Column

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ABSTRAK: Jalan Nasional Pantai Utara Jawa, terutama pada ruas Demak-Kudus didominasi batuan alluvium dimana umum ditemukan tanah lunak. Hal ini diperkuat dari hasil uji SPT dan *boring* yang menunjukkan terdapat deposit tanah lunak pada kedalaman 0-18 m di titik penyelidikan. Keberadaan tanah lunak ini yang menimbulkan terjadinya penurunan sehingga timbul kerusakan pada jalan eksisting. Pada kasus ini tidak dimungkinkan pembongkaran timbunan jalan maka diusulkan menggunakan perbaikan dengan *stone column* dengan tujuan densifikasi dan reduksi penurunan. Berdasarkan hasil analisis, penurunan tanpa perbaikan pada BH-1 dan BH-2 adalah 0,0424 m dan 0,3277 m. Selain itu, hasil analisis reduksi penurunan menggunakan metode Priebe dan *equibrillium* menunjukkan bahwa *stone column* berdiameter 1 m dapat memenuhi persyaratan penurunan < 0,1 m jika memiliki spasi 1,5 m dan 2,5 m dengan pola segitiga. Penurunan setelah perbaikan secara teoritis menurut metode Priebe dan Equibrillium adalah 0,0717 m dan 0,098 m.

Kata Kunci: konsolidasi, *stone column*, tanah lunak

ABSTRACT: The North Coast of Java Highways, especially the Demak-Kudus Section is dominated by alluvium where soft soil is commonly found. This fact is supported by SPT and boring test results that show soft soil deposits exist in 0-18 m depth of testing points. The soft soil existence is causing settlement and resulting in damage to the existing highway. In this case, it is not possible to dismantle the road embankment and then soil improvement using a stone column is proposed to densify and reduce the settlement of the soil. Based on analysis results, settlements without soil improvement in BH-1 and BH-2 are 0.0424 m and 0.3277 m respectively. Furthermore, the reduction of settlements analysis using the Priebe and Equibrillium method shows that a stone column with a 1 m diameter can satisfy requirements of settlement < 0.1 m if the spaces are 1.5 m and 2.5 m respectively for triangle arrangement. Settlement after improvement theoretically according to the Priebe and equibrillium methods are 0.0717 m and 0.098 m respectively.

Keywords: consolidation, stone column, soft soil

1 INTRODUCTION

The national highway of Semarang-Surabaya has strategic value where the high traffic load must be complied with by sufficient capacity and serviceability. This has become a major concern due to soft soil's existence on the north coast of Java which causes maintenance costs to increase as a result of the frequent defect. Additionally, the existing high traffic load makes either longer construction time or total replacement impossible. Thus, a comprehensive and appropriate improvement is needed to the serviceability level to comply with the standard minimum requirement.

2 GEOLOGICAL AND SOIL CONDITION

The analyzed location is in Nasional 1 Road, Karanganyar District, Demak Regency, Central Java, Indonesia. This highway has been damaged due to subgrade settlement as shown in Fig. 1. Furthermore, based on Kudus

Geological Map, Karanganyar District is dominated by an alluvium layer (Q_a) and this is shown in Fig. 2.

Fig. 1. Existing Pavement in Analyzed Location, Google Street View (2022).

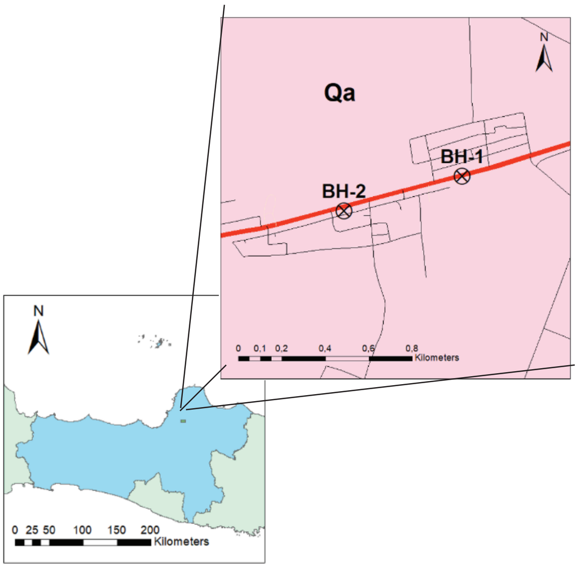

Fig. 2. Geological Condition Karanganyar District, Modified from Suwarti and Wikarno (1992).

Soil investigation was conducted with the standard penetration test (SPT) in two borehole locations (BH-1 and BH-2). Soft clay was found up to 20 m depths with N values between 0 and 4. This layer is followed by a firm and stiff clay layer below it.

Table 1. Soil Parameter BH-1 and BH-2.

BH-1					
Depth (m)	0-18	18-30	30-42	42-66	66-70
Soil Type	Soft	Firm	Stiff	Very Stiff	Hard
N-SPT	2.67	8	13.83	29.5	41.5
e_o	1.2052	1.2052	-	-	-
γ_{sat}	16	18	18	18	20
C_u	13.33	40	69.17	147.5	207.5
C_C	0.3408	0.3408	-	-	-
Cs	0.05112	0.05112	-	-	-
k	$4.5.10^{-5}$	$3.9.10^{-4}$	$3.9.10^{-4}$	$2.2.10^{-2}$	$4.3.10^{-2}$
OCR	2.44	2.44	-	-	-

BH-2					
Depth (m)	0-18	18-28	28-44	44-64	64-70
Soil Type	Soft	Firm	Stiff	Very Stiff	Stiff
N-SPT	3.22	6.8	13	27.6	16
e_o	1.976	1.976	-	-	-
γ_{sat}	16	18	18	18	18
C_u	16.11	34	65	138	80
C_C	0.5645	0.5645	-	-	-
Cs	0.08467	0.08467	-	-	-
k	$4.5.10^{-5}$	$4.5.10^{-5}$	$3.9.10^{-4}$	$2.2.10^{-2}$	$2.2.10^{-2}$
OCR	0.914	0.914	-	-	-

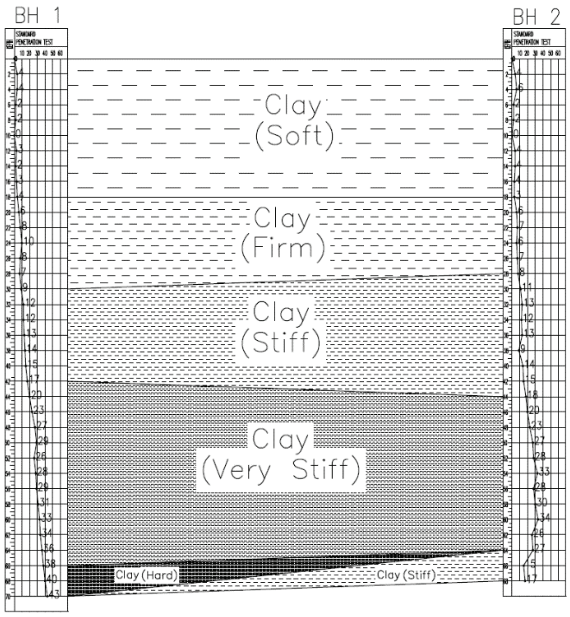

Fig. 3. Soil Stratigraphy in BH-1 and BH-2.

3 STRESS ANALYSIS

According to Balaam and Booker (1981), stone column tributary diameter based on grid formation can be calculated using Eqn. (1) and (2).

a. Rectangle Grid

$$d_e = 1.13\ s \quad (1)$$

b. Triangle Grid

$$d_e = 1.05\ s \quad (2)$$

In establishing column and soil stress ratio, the stress concentration factor (SCF) is needed based on Barksdale (1981), for stone column without geotextile, the ratio is approximately 3-6. Further analysis uses assumption that SCF =

3 and column diameter = 1 m. The area of the stone column (A_c) is 0.785 m^2. Stress on column and soil is calculated with Eqn. (3) and (4)

Aboshi et al. (1979) proposed unit cell stress that is analyzed using Eqn. (5).

$$\sigma_c = \frac{1}{1+(SCF-1)\times\alpha_c} \times \sigma \quad (3)$$

$$\sigma_s = \frac{1}{1+(SCF-1)\times(1-\alpha_c)} \times \sigma \quad (4)$$

$$\sigma_{unit\ cell} = \sigma_s\,\alpha_c + \sigma_c\,(1-\alpha_c) \quad (5)$$

The installation of stone column-induced stress is analyzed in Table 2.

Table 2. Installation of Stone Column Induced Stress.

Space (m)	d_e (m)	α_c	σ_c (kPa)	σ_s (kPa)	$\bar{\sigma}_{unit\ cell}$ (kPa)
Triangle					
1.5	1.575	0.403	12.302	10.129	11.332
2.0	2.100	0.227	15.287	8.726	13.240
2.5	2.625	0.145	17.221	8.200	15.192
3.0	3.150	0.101	18.493	7.940	16.722
3.5	3.675	0.074	19.354	7.791	17.863
4.0	4.200	0.057	19.957	7.698	18.709
Rectangle					
1.5	1.695	0.348	13.100	9.645	11.682
2.0	2.260	0.196	15.968	8.519	13.871
2.5	2.825	0.125	17.767	8.082	15.826
3.0	3.390	0.087	18.926	7.863	17.286
3.5	3.955	0.064	19.701	7.736	18.345
4.0	4.520	0.049	20.239	7.657	19.117

The bearing capacity of a stone column can be calculated by using Eqn. (6) and (7).

a. FHWA Method, Barksdale and Bachus (1983)

$$q_{ult} = c \times Nc \quad (6)$$

b. Hughes et al. (1975) Method

$$q_{ult} = \tan^2\left(45+\frac{\theta}{2}\right)(4\,C_u + \sigma_r) \quad (7)$$

$$\sigma_r = 1 - 2\,Cu \quad (8)$$

Bearing capacity analysis using both methods is shown in Table 3 (the stone column is assumed that have N_c = 20 dan φ = 42.5°).

Table 3. Bearing Capacity of Stone Column.

Bore Hole	C_u	σ_r (kPa)	Q_{ult} FHWA (kPa)	Q_{ult} Hughes (kPa)
BH-1	13.30	19.950	266.0	377.823
BH-2	16.11	24.165	322.2	457.649

4 SETTLEMENT ANALYSIS

Consolidation settlement is assumed that only be caused by traffic load (q_L) and pavement (q_p) above the embankment. The applied load is calculated as follows:

$\Delta\sigma = q_p + q_L$
$= (t_{pavement} \times \gamma_{pavement}) + q_L$
$= (0.3\ m \times 24\ kN/m^3) + 15\ kPa$
$= 22.2\ kPa$

This is impossible to conduct a full replacement of the existing road.

Calculation of consolidation settlement uses Eqn. (9) and (10) as follow:

a. If $P'_o + 2\Delta P > P'_c$

$$S_C = \frac{C_S H}{1+e_o}\log\frac{\sigma'_c}{\sigma'_o} + \frac{C_c H}{1+e_o}\log\left(\frac{\sigma'_o+\Delta\sigma'}{\sigma'_c}\right) \quad (9)$$

b. If $P'_o + 2\Delta P < P'_c$

$$S_C = \frac{C_S H}{1+e_o}\log\left(\frac{\sigma'_o+\Delta\sigma'}{\sigma'_c}\right) \quad (10)$$

The compressible layer in BH-1 is located between 0-30 m depths and in BH-2 between 0-28 m. The settlement that is calculated using Eqn. (9) and (10) showed in Table 4.

Table 4. Consolidation Settlement in BH-1 and BH-2.

Bore hole	Depth (m)	σ_o (kPa)	$\sigma_o + \Delta\sigma$ (kPa)	S_c (m)
BH-1	0-18	132.0	154.2	0.0282
	18-30	178.2	200.4	0.0142
				0.0424
BH-2	0-18	138.0	160.2	0.2212
	18-28	161.3	183.5	0.1062
				0.3274

The requirement for the maximum settlement on a highway based on Pavement Design Manual 2017 is 10 cm. Based on Table 4, BH-2's settlement without soil improvement is 0.3274 m and soil improvement is needed to reduce settlement. This improvement can prevent damage to the pavement due to settlement and make the pavement comply with the standard. The settlement reduction factor is analyzed with Priebe and equibrillium method as follows:

a. Priebe Method (1995)

$$\beta = \frac{s}{s_i} = 1 + \frac{A_c}{A}\left(\frac{0{,}5+f(\mu_s,\alpha_c)}{K_c\, x\, f(\mu_s,\alpha_c)} - 1\right) \quad (11)$$

$$f(\mu_s, \alpha_c) = \frac{1-\mu_s{}^2}{1-\mu_s-2\mu_s{}^2}\, x\, \frac{(1-2\mu_s).(1-\alpha_c)}{(1-2\mu_s+\alpha_c)} \quad (12)$$

$$K_c = \tan^2(45° - \varphi_c/2) \quad (13)$$

b. Equibrilium Method, Aboshi et al. (1979)

$$\beta = 1 + \frac{SCF-1}{A/A_c} \quad (14)$$

Used space is considered based on required reduction and in this case, the used space must make the settlement become less than 10 cm. The BH-2 required reduction factor is calculated as follows:

St < 0.1 m
Sc/β < 0.1 m
β $> 0.3274/0.1$
β > 3.274

Settlement after soil improvement is analyzed by calculating the reduction factor as shown in Table 5 and 6.

Table 5. Settlement Reduction Factor After Improvement with Priebe Method.

Space (m)	α_c	α_s	$f(\mu_s, \alpha_s)$	β
Triangle Grid				
1.5	0.403	0.597	0.551	4.565
2.0	0.227	0.773	0.954	2.558
2.5	0.145	0.855	1.248	1.904
3.0	0.101	0.899	1.458	1.598
3.5	0.074	0.926	1.609	1.427
4.0	0.057	0.943	1.719	1.321
Rectangle Grid				
1.5	0.348	0.652	0.653	3.824
2.0	0.196	0.804	1.054	2.295
2.5	0.125	0.875	1.336	1.763
3.0	0.087	0.913	1.533	1.508
3.5	0.064	0.936	1.671	1.365
4.0	0.049	0.951	1.771	1.275

Table 6. Settlement Reduction Factor After Improvement with Equibrillium Method.

Space (m)	$A_{rectangle}$ (m^2)	$B_{rectangle}$	$A_{triangle}$ (m^2)	$B_{triangle}$
1.5	2.256	4.067	1.948	4.350
2.0	4.011	3.486	3.464	3.586
2.5	6.268	3.286	5.412	3.339
3.0	9.026	3.190	7.793	3.224
3.5	12.285	3.136	10.607	3.159
4.0	16.046	3.102	13.854	3.120

Based on Table 5 and 6, the settlement reduction can satisfy the requirement if the used space is 1,5 m with either rectangle or triangle grid for the Priebe method. Otherwise, if the analysis uses the Equibrillium method, the improvement can meet the requirement by installing stone column with either a rectangle or triangle grid (with space ≤ 2.5 m). Settlement after improvement calculation is shown as follow:

Scenario 1 – Priebe Method
s = 1.5 m with triangle grid
β = 4.565
St = 0.3274/4.565 = 0.0717 m

Scenario 2 – Equibrillium Method
s = 2.5 m with triangle grid
β = 3.339
St = 0.3274/3.339 = 0.098 m

5 INFLUENCE OF STONE COLUMN LENGTH ON SETTLEMENT REDUCTION

To obtain the maximum settlement, further analysis is conducted by using finite element software. The model can be seen in Fig. 4.

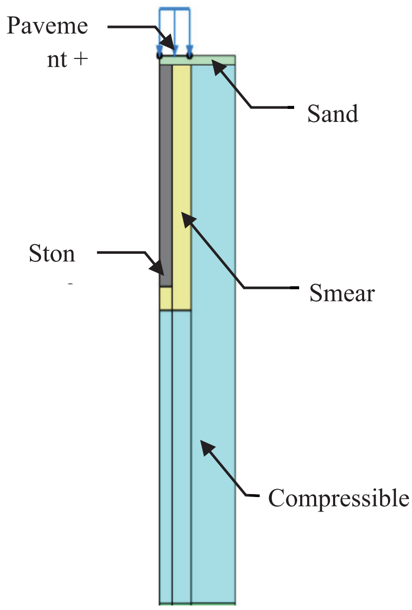

Fig. 4. Stone Column Model on Finite Element Software.

In analysis, the used parameter and analysis result is shown in Table 7 and Fig. 5. respectively.

Table 7. Stone Column Parameter on BH-2 Model.

Material	Stone Column	Smear Zone	Sand Blanket	Clay 0-18 m	Clay 18-28 m
Material Model	Mohr-Coulumb	*Soft Soil*	Mohr-Coulumb	*Soft Soil*	*Soft Soil*
E	$4.5.10^4$	-	2.10^4	-	-
ν	0.2	-	0,3	-	-
γ_{sat}	21	16	17	16	16
C_u	5	16.11	5	16.1	34
φ	42.5	1	39.5	1	1
k	7.128	$1.5.10^{-5}$	-	$4.5.10^{-5}$	$4.5.10^{-5}$
C_s	-	0.08468	-	0.08468	0.08468
C_c	-	0.5645	-	0.5645	0.5645
e_o	-	1.976	-	1.976	1.976

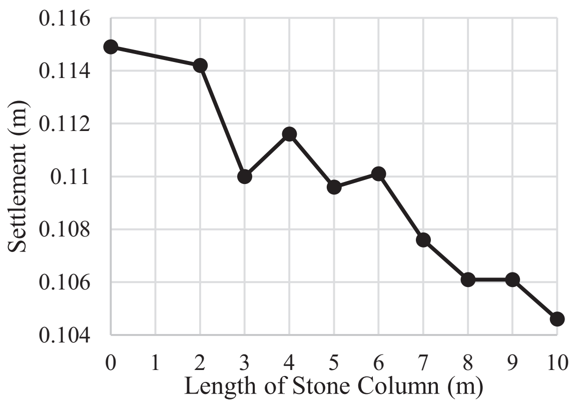

Fig. 5. Consolidation Settlement with Certain Stone Column Depth.

Settlement numerical analysis does not show the significant influence of length on settlement reduction. The settlement is only reduced slightly by the length of the stone column.

6. CONCLUSION

Based on the result of the analysis, consolidation settlement without improvement will be 0.0424 m in BH-1 dan 0.3277 m in BH-2. According to the standard requirement which is required the settlement must be less than 0,1 m, and the settlement of BH-2 is higher therefore soil improvement is needed.

Two methods, Priebe and Equibrillium methods, are used in reduction analysis with stone column. The result of analysis with the Priebe method has a more conservative result rather than Equibrilium one. Using the Priebe method, to comply with the standard (the settlement must be less than or equal to 0.1 m), if the stone column has a 1 m diameter, the space must be less than 1.5 m with a triangle grid. On the other hand, equibrilium method suggests that if the stone column diameter is 1 m, the space must be not more than 2.5 m with a triangle grid.

Stone column analysis with finite element software to investigate settlement in a singular column. The graph illustrates the settlement reduced as the column length extended. However, the result implies that the longer stone column does not mean less settlement. Furthermore, until the 10 m length of the column, the settlement in finite element analysis is not less than 0.1 m as the numerical analysis suggest. Consequently, further analysis is needed to obtain the optimum length and spacing for the stone column.

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