Interdisciplinary Social Studies
P-ISSN: 2808-0467
E-ISSN: 2808-5051

The Effect of Encapsulated Stone Column Geometric Variations on Bearing Capacity and Road Embankment Stability over Soft Soil (Case Study: Aruk – Sp. Take Road Section, West Kalimantan)

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Keywords:

Encapsulated Stone Column;
Soft soil;
Bearing capacity;
Embankment stability;
Area replacement ratio (as).

ABSTRACT

Soft soil with low bearing capacity and high compressibility is the primary cause of damage to road embankments on the Aruk – Sp. Take Road Section, West Kalimantan. This study aims to evaluate the effectiveness of using Encapsulated Stone Columns (ESC) as a ground improvement alternative to increase bearing capacity and embankment stability. The analysis was conducted using secondary soil investigation data (SPT) at the most critical location (BH.04). Column geometry variations were modeled with diameters (D) of 0.7 m, 0.8 m, and 0.9 m, as well as variations in column spacing (s) to obtain the optimal design configuration. Bearing capacity analysis was performed using the Terzaghi method, while embankment stability was analyzed using the Geo5 auxiliary program11. The results indicate that the foundation bearing capacity is a more critical design criterion compared to global slope stability. ESC models with a low area replacement ratio (as < 0.19) were proven capable of maintaining slope stability (SF > 1.5) but failed to support the design embankment load of 3.3 meters height. Increasing the as value by enlarging the diameter or reducing column spacing significantly increases the safety factor. The recommended geometric configuration is a model with as ≥ 0.19, which is proven safe against both bearing capacity failure and embankment sliding.

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INTRODUCTION

Soft soil often presents a major challenge in the execution of construction projects in Indonesia due to its poor mechanical properties, such as low bearing capacity, high compressibility, and large settlement potential. This condition can lead to structural failure if adequate ground improvement efforts are not undertaken. These geotechnical challenges were faced by the National Road Implementation Agency of West Kalimantan (BPJN Kalimantan Barat) in the construction project on the Aruk – Sp. Take Road Section, STA. 99+000 to STA. 99+550. This section is part of the cross-border road between Indonesia and Malaysia, specifically on the Aruk – Siding/Seluas District Boundary Road in Sambas Regency, West Kalimantan Province. Based on field surveys, damage occurred in 2022 along 550 m of the road embankment, which has an average height of 1.512 m. The location

of the road section and documentation of the road embankment condition are shown in Figure 1 and Figure 2.

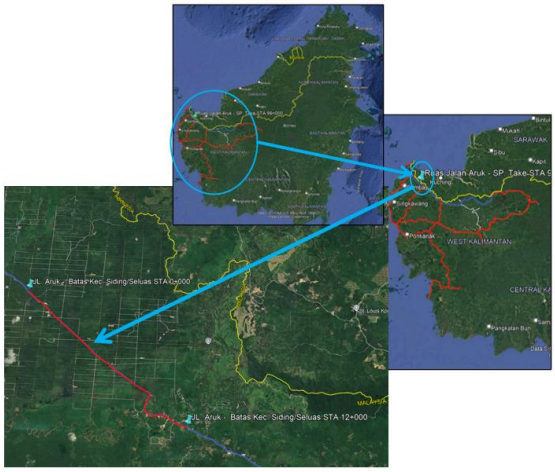


Figure 1. Location of the Aruk – Sp. Take Road Section, STA. 99+000 to STA. 99+550
(source : Google Earth Pro processing , 2025)



Figure 2. Aruk – Sp. Take Road Section Condition
(source : BPJN West Kalimantan, 2022)

One alternative suitable for this condition is a road embankment over soft soil reinforced with Encapsulated Stone Columns (ESC). Stone Columns are a ground improvement method frequently used due to their effectiveness in increasing bearing capacity, reducing soil settlement, accelerating the consolidation process, and lowering the risk of liquefaction (Barksdale and Bachus, 1983; Han, 2014). Conventional Stone Columns (Ordinary Stone Columns/OSC) are suitable for stabilizing soil with Undrained Shear Strength (UCS) values above 15 kPa, with typical depths between 5–10 m and a maximum of up to 30 m25. Conversely, for very soft soil conditions or organic soils with UCS values of 5–15 kPa, Stone Columns equipped with a geosynthetic encasement (Encapsulated Stone Column/ESC) are a more effective choice (Han, 2015). The success of Encapsulated Stone Columns (ESC) relies heavily on the careful design of their geometric parameters. Design aspects such as length, diameter, column spacing, and configuration pattern directly control the interaction mechanism between the column, the soft soil, and the embankment above it. Therefore, this study aims to analyze the influence of the diameter and spacing of Encapsulated Stone Columns (ESC) on the bearing capacity and stability of road embankments over soft soil, with the study location at the Aruk – Sp. Take Road Section STA. 99+000 to STA. 99+550.

METHOD

The research method used in this journal is an analytical study. The analytical study was conducted on secondary data in the form of Standard Penetration Test (SPT) results and undisturbed soil sample test data at the study location at BH.04. To examine the influence of ESC geometry on bearing capacity and embankment stability, several variations of diameter and column spacing with a triangular configuration were used. The ESC geometry variations are presented in Table 1.

Table 1. ESC Geometry Variations

Model Code	Column Diameter (D)	Column Length (L)	Column Spacing (s)	Triangular Conf. Constant (C)	as
	m	m	m		
ESC.7.A	0.7	8	2	0.907	0.11
ESC.7.B	0.7	8	1.75	0.907	0.15
ESC.7.C	0.7	8	1.5	0.907	0.20
ESC.7.D	0.7	8	1.25	0.907	0.28
ESC.8.A	0.8	8	2	0.907	0.15
ESC.8.B	0.8	8	1.75	0.907	0.19
ESC.8.C	0.8	8	1.5	0.907	0.26
ESC.8.D	0.8	8	1.25	0.907	0.37
ESC.9.A	0.9	8	2	0.907	0.18
ESC.9.B	0.9	8	1.75	0.907	0.24
ESC.9.C	0.9	8	1.5	0.907	0.33
ESC.9.D	0.9	8	1.25	0.907	0.47

Source : data processing

This research is limited to secondary data analysis using Microsoft Excel and the Geo5 software to review embankment stability. The focus is restricted to ESC for road embankment reinforcement on soft soil.

Soil Parameters and ESC Fill Material

SPT testing at BH.04 was conducted to a depth of 20 m. Based on SPT results, the soil consistency is very soft at depths of 0 – 2 m, medium stiff at 2 – 8 m, stiff at 4 – 14 m, and very stiff at 14 – 20 m. The soil parameter and effective stress data are presented in Table 2.

Table 2. Soil Parameters and Effective Stress

No	Description	Color	Depth (m)	Z (m)	NSPT	Consistency	ϕ Soil (°)	cu (kPa)	γsat Soil (kN /m³)	γ' (kN /m³)	σ'0 Soil (kN /m2)
1	Organic Silt	Yellowish Red	0 - 1	0.5	0	Very Soft	1.00	8.29	10.56	0.56	5.28
2	Organic Silt	Yellowish Red	1 - 2	1.5	0	Very Soft	1.00	9.25	10.56	0.56	10.84
3	Sandy Silt	Brown	2 - 3	2.5	4	Medium Stiff	1.00	24.00	18.00	8.00	15.13
4	Silty Clay	Brownish Gray	3 - 4	3.5	4	Medium Stiff	1.00	24.00	18.00	8.00	23.13
5	Silty Clay	Brownish Gray	4 - 5	4.5	7	Medium Stiff	1.00	43.75	18.00	8.00	31.13

6	Silty Clay	Brownish Gray	5	-	6	5.5	6	Medium Stiff	1.00	37.50	18.00	8.00	39.13
7	Silty Clay	Brownish Gray	6	-	7	6.5	7	Medium Stiff	1.00	43.75	18.00	8.00	47.13
8	Silty Clay	Brownish Gray	7	-	8	7.5	6	Medium Stiff	1.00	37.50	18.00	8.00	55.13
9	Silty Clay	Brownish Gray	8	-	9	8.5	9	Stiff	1.00	56.25	19.00	9.00	63.63
10	Sandy Silt	Blackish Gray	9	-	10	9.5	8	Stiff	10.00	50.00	19.00	9.00	72.63
11	Sandy Silt	Grayish Brown	10	-	11	10.5	11	Stiff	10.00	62.50	19.00	9.00	81.63
12	Sandy Silt	Grayish Brown	11	-	12	11.5	11	Stiff	10.00	62.50	19.00	9.00	90.63
13	Fine to Medium Sand	Gray	12	-	13	12.5	11	Stiff	31.31	1.00	19.00	9.00	99.63
14	Fine to Medium Sand	Gray	13	-	14	13.5	10	Stiff	31.17	1.00	19.00	9.00	108.63
15	Fine to Medium Sand	Gray	14	-	15	14.5	31	Very Stiff	39.26	1.00	20.00	10.00	118.13
16	Fine to Medium Sand	Gray	15	-	16	15.5	30	Very Stiff	39.01	1.00	20.00	10.00	128.13
17	Fine to Medium Sand	Gray	16	-	17	16.5	30	Very Stiff	39.09	1.00	20.00	10.00	138.13
18	Fine to Medium Sand	Gray	17	-	18	17.5	30	Very Stiff	38.85	1.00	20.00	10.00	148.13
19	Fine to Medium Sand	Gray	18	-	19	18.5	29	Very Stiff	38.63	1.00	20.00	10.00	158.13
20	Fine to Medium Sand	Gray	19	-	20	19.5	28	Very Stiff	38.40	1.00	20.00	10.00	168.13

Source : data processing

The ESC installation is designed to a depth of 10 meters, where the ESC tip rests on a soil layer with stiff consistency. The ESC fill material is designed as granular material with an internal friction angle ϕ column = 35 ° and unit weight γsat = 20,5 kN/m3. Based on the ESC fill material parameters, the effective vertical stress of the ESC at a depth of 10 m is $\sigma'0$ column = 100,5 kN/m2 and the coefficient K_0 column = 0,43.

Geotextile Requirement Analysis

The geotextile requirement analysis was performed by calculating the maximum lateral stress ($\Delta\sigma h0$ max). This was followed by calculating the required tensile strength of the geotextile, as well as calculating the required number of geotextile layers by comparing T required with T allowable of the geotextile material used. The geotextile requirement analysis is presented in Table 3.

Table 3. Geotextile Requirement Analysis

Model Code	ΔP/Ac (kN /m2)	K0	σh 0 max (kN /m2)	T required (kN /m)	T ult. Geotex (kN /m)	T Allow (kN / m)	Number of Geotextile Sheets
ESC.7.A	624,69	0.43	309,24	108,23	200.00	66.67	2.00
ESC.7.B	455,50	0.43	237,09	82,98	200.00	66.67	2.00
ESC.7.C	334,65	0.43	185,56	64,95	200.00	66.67	1.00
ESC.7.D	244,02	0.43	146,91	51,42	200.00	66.67	1.00
ESC.8.A	478,28	0.43	246,80	98,72	200.00	66.67	2.00
ESC.8.B	348,74	0.43	191,57	76,63	200.00	66.67	2.00
ESC.8.C	256,22	0.43	152,11	60,85	200.00	66.67	1.00
ESC.8.D	186,83	0.43	122,52	49,01	200.00	66.67	1.00
ESC.9.A	377,90	0.43	204,00	91,80	200.00	66.67	2.00
ESC.9.B	275,55	0.43	160,36	72,16	200.00	66.67	2.00
ESC.9.C	202,45	0.43	129,18	58,13	200.00	66.67	1.00
ESC.9.D	147,62	0.43	105,80	47,61	200.00	66.67	1.00

source : data processing

Bearing Capacity Analysis

The bearing capacity of the ESC column is calculated using Terzaghi bearing capacity teory. The q ult net value is greatly influenced by the Terzaghi bearing capacity factors: Nc, Nq, and Nγ. These factors are obtained from the internal friction angle of the soil at a depth of 10 meters (ϕ = 10°). The effective vertical stress of the soil at a depth of 10 m is q = 67,13 kN/m2. The safe bearing capacity (q safe) of each model variation is compared with the stress received by the column due to the embankment load above it and the effective vertical stress of the ESC column itself, where q load = ΔP/Ac + γ'column. The bearing capacity analysis for each model variation can be seen in Table 4.

Table 4. Bearing Capacity Analysis

Model Code	ϕSoil (°)	cu (kN /m^2)	Nc	Nq	Nγ	q (kN /m ^{2})	q Load (kN /m ^{2})	q ult net (kN /m ^{2})	q *safe* (kN /m^2)	Check
ESC.7.A	10.00	50.00	9.61	2.69	0.56	67.13	725,19	597.67	465.57	Not Oke
ESC.7.B	10.00	50.00	9.61	2.69	0.56	67.13	556,00	597.67	465.57	Not Oke
ESC.7.C	10.00	50.00	9.61	2.69	0.56	67.13	435,15	597.67	465.57	Oke
ESC.7.D	10.00	50.00	9.61	2.69	0.56	67.13	344,52	597.67	465.57	Oke
ESC.8.A	10.00	50.00	9.61	2.69	0.56	67.13	578,78	598.20	465.92	Not Oke
ESC.8.B	10.00	50.00	9.61	2.69	0.56	67.13	449,24	598.20	465.92	Oke
ESC.8.C	10.00	50.00	9.61	2.69	0.56	67.13	356,72	598.20	465.92	Oke
ESC.8.D	10.00	50.00	9.61	2.69	0.56	67.13	287,33	598.20	465.92	Oke
ESC.9.A	10.00	50.00	9.61	2.69	0.56	67.13	478,40	598.73	466.28	Not Oke
ESC.9.B	10.00	50.00	9.61	2.69	0.56	67.13	376,05	598.73	466.28	Oke
ESC.9.C	10.00	50.00	9.61	2.69	0.56	67.13	302,95	598.73	466.28	Oke
ESC.9.D	10.00	50.00	9.61	2.69	0.56	67.13	248,12	598.73	466.28	Oke

source : data processing

Analysis of Equivalent Parameters and Road Embankment Stability

The road embankment stability analysis was conducted using the Geo5 software. The analysis in the Geo5 program begins by calculating the stress concentration ratio (n = σ ESC column/ σsoil), and continues with calculating the equivalent parameters of the soil stabilized with Encapsulated Stone Columns (ESC). Calculation of equivalent parameter value for Model ESC.7.A is presented in Table 5. The same analysis done for all model.

Table 5. Equivalent Parameters of Model ESC.7.A

Depth (m)			Soil			Column			ESC.7.A			
			ϕ Soil (°)	cu (kPa)	γsat Soil (kN /m³)	ϕ Column (°)	γsat Column (kN /m³)	as	γ, eq (kN /m³)	cu, eq (kN /m2)	[tanϕ] eq	ϕ eq (°)
0	-	1	1.00	8.29	10.56	35	20,05	0,11	11,62	7,36	0,41	22,28
1	-	2	1.00	9.25	10.56	35	20,05	0,11	11,62	8,22	0,41	22,28
2	-	3	1.00	24.00	18.00	35	20,05	0,11	18,23	21,33	0,41	22,28
3	-	4	1.00	24.00	18.00	35	20,05	0,11	18,23	21,33	0,41	22,28
4	-	5	1.00	43.75	18.00	35	20,05	0,11	18,23	38,89	0,41	22,28
5	-	6	1.00	37.50	18.00	35	20,05	0,11	18,23	33,33	0,41	22,28
6	-	7	1.00	43.75	18.00	35	20,05	0,11	18,23	38,89	0,41	22,28
7	-	8	1.00	37.50	18.00	35	20,05	0,11	18,23	33,33	0,41	22,28
8	-	9	1.00	56.25	19.00	35	20,05	0,11	19,12	50,00	0,41	22,28
9	-	10	10.00	50.00	19.00	35	20,05	0,11	19,12	44,44	0,48	25,52
10	-	11	10.00	62.50	19.00							
11	-	12	10.00	62.50	19.00							
12	-	13	31.31	1.00	19.00							
13	-	14	31.17	1.00	19.00							
14	-	15	39.26	1.00	20.00							
15	-	16	39.01	1.00	20.00							
16	-	17	39.09	1.00	20.00							
17	-	18	38.85	1.00	20.00							
18	-	19	38.63	1.00	20.00							
19	-	20	38.40	1.00	20.00							

source: data processing

After obtaining the equivalent parameter values for all model variations, the ESC embankment and reinforcement modeling was performed in the Geo5 program. The modeling began with a staged embankment stability analysis, followed by an analysis of the influence of ESC geometric variations on embankment stability.

RESULTS AND DISCUSSION

Based on the analysis above, the recapitulation of the bearing capacity and road embankment stability analysis results is presented in Table 6.

Table 6. Recapitulation of Analysis Results

Model Code	D	s	as	T Ult. Geotextile (kN /m2)	Number of Geotextile Sheets	Bearing Capacity Analysis (kN /m2)			Embankment Stability Analysis		
	m	m				Load	Resistance	Satus	SF Plan	SF	Status
Timb . 1.4 m									1.5	2,14	Oke
Timb . 2.4 m									1.5	1,31	Not Oke
Timb . 3.3 m									1.5	1,03	Not Oke
Timb . 3.3 m + qLL									1.5	0,93	Not Oke
ESC.7.A	0.7	2	0.11	200.00	2.00	725,19	465.57	Not Oke	1.5	1,56	Oke
ESC.7.B	0.7	1.75	0.15	200.00	2.00	556,00	465.57	Not Oke	1.5	1,58	Oke
ESC.7.C	0.7	1.5	0.20	200.00	1.00	435,15	465.57	Oke	1.5	1,59	Oke
ESC.7.D	0.7	1.25	0.28	200.00	1.00	344,52	465.57	Oke	1.5	1,6	Oke
ESC.8.A	0.8	2	0.15	200.00	2.00	578,78	465.92	Not Oke	1.5	1,58	Oke
ESC.8.B	0.8	1.75	0.19	200.00	2.00	449,24	465.92	Oke	1.5	1,6	Oke
ESC.8.C	0.8	1.5	0.26	200.00	1.00	356,72	465.92	Oke	1.5	1,61	Oke
ESC.8.D	0.8	1.25	0.37	200.00	1.00	287,33	465.92	Oke	1.5	1,65	Oke
ESC.9.A	0.9	2	0.18	200.00	2.00	478,40	466.28	Not Oke	1.5	1,59	Oke
ESC.9.B	0.9	1.75	0.24	200.00	2.00	376,05	466.28	Oke	1.5	1,61	Oke
ESC.9.C	0.9	1.5	0.33	200.00	1.00	302,95	466.28	Oke	1.5	1,65	Oke
ESC.9.D	0.9	1.25	0.47	200.00	1.00	248,12	466.28	Oke	1.5	1,67	Oke

source : data processing

The analysis of the influence of Encapsulated Stone Column (ESC) geometric variations on geotextile reinforcement requirements shows an inverse relationship between the Area Replacement Ratio (as) and the required geotextile tensile strength. Based on the calculation results, models with a low as ratio, such as ESC.7.A (as = 0.11) and ESC.8.A (as = 0.15), produce a very high maximum lateral stress (Δσh0 max), reaching 309.24 kN/m² and 237.09 kN/m², respectively. The magnitude of this high lateral stress is caused by the large concentration of vertical stress on a relatively small column cross-sectional area, thus requiring double-layer geotextile reinforcement to fulfill the safety criteria (Tallow > Trequired). Conversely, in models with larger geometry, such as ESC.9.D (as = 0.47), the lateral stress decreases significantly to 105.80 kN/m², so using a single layer of geotextile is sufficient. This indicates that enlarging the diameter or decreasing the spacing between columns can reduce the lateral loads that must be withstood by the geotextile encasement.

From the bearing capacity aspect, geometric variation plays a crucial role in determining the success of the composite foundation design. The analysis results show that not all geometric configurations are capable of withstanding the design embankment load of 3.3 meters. Models with an area replacement ratio below 0.19 (as < 0.19), such as ESC.7.A, ESC.7.B, and ESC.8.A, experience bearing capacity failure ("Not OK"), where the working load (q load) exceeds the allowable bearing capacity (q safe). For example, the ESC.7.A model receives a load of 725.19 kN/m², which is far above the allowable capacity of 465.57 kN/m². Bearing capacity safety is only achieved in models with as ≥ 0.19, where the increased effective column cross-sectional area reduces the vertical stress acting on the column, making the design safe.

Meanwhile, the influence of geometry on the global stability of the embankment shows a positive trend across all model variations. Based on the Geo5 analysis, the embankment without reinforcement experiences failure with a safety factor (SF) of 1.03, which is below the minimum requirement of 1.5. The implementation of ESC has proven to significantly increase stability; even in the smallest geometry configuration (ESC.7.A), the SF value increases to 1.56. Increasing the as value through column diameter enlargement is directly proportional to the increase in the safety factor, where the largest model (ESC.9.D) produces the highest SF of 1.67. However, it is necessary to note that although all models meet the slope stability requirements, bearing capacity becomes the more critical design criterion, as some models that are safe in terms of global stability still experience foundation bearing capacity failure.

CONCLUSION

Based on the results of the analysis and discussion, several conclusions can be drawn: The use of Encapsulated Stone Columns (ESC) has proven effective in increasing the stability of the road embankment on soft soil at the Aruk – Sp. Take section, increasing the Safety Factor (SF) from 1.03 (without reinforcement) to a minimum of 1.56 across all model variations. Column geometry significantly influences geotextile requirements; as the Area Replacement Ratio (as) decreases, the lateral stress increases, requiring geotextiles with higher tensile strength or additional layers. Foundation bearing capacity is a more critical design criterion compared to global stability. Models with as < 0.19 were proven to fail in withstanding the design load, even though they were safe against global slope failure. The recommended design configuration is a model with as ≥ 0.19, which meets the safety requirements for both bearing capacity and embankment stability.

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