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Influence of anchor spacing on MSE wall stability

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Abstract

This study investigates the impact of anchor spacing on the stability of Mechanically Stabilized Earth (MSE) walls using a novel configuration of crossbar necklaces and starter ails. The aim is to determine the optimal spacing for anchors to enhance stability while adhering to the SNI 8460-2017 geotechnical standards. The methodology integrates field tensile testing, laboratory experiments, and numerical modeling via PLAXIS 3D software to validate findings. The findings reveal that anchors with ctc spacings of 30 cm and 50 cm meet the design criteria, achieving deformation values of 44.71 mm and 20.10 mm, respectively, below the maximum permissible 70 mm. Additionally, safety factors for these spacings exceed the required threshold of 1.5. Conversely, anchors with a ctc spacing of 70 cm, while demonstrating acceptable deformation (20.22 mm), fail to meet safety requirements due to a factor of 1.481. Field tests corroborated the numerical results, showing tensile capacities of 86.9 kN and 35.2 kN for anchors with ctc spacings of 30 cm and 50 cm, respectively. The results emphasize the significance of optimal anchor spacing in maintaining MSE wall stability, particularly under challenging conditions like high rainfall and limited right-of-way.

Keywords: Anchor, Crossbar necklace, Fish fins, MSE Wall.

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1. Introduction

A retaining wall is a structure designed to withstand lateral and vertical pressure, as well as global forces, particularly in limited right-of-way conditions [1]. Precast *retaining walls* currently come in two types: those using geotextiles and those using plates. Both types of construction have experienced numerous failures, such as landslides. In response to this, a qualified construction method was developed, incorporating anchors, cross necklaces, and fish fins to effectively counter rolling moments, shear moments, and soil bearing capacity [2]. The construction of retaining walls must be capable of withstanding forces such as overturning moments, self-weight forces, active and passive soil/water lateral forces, sliding forces, and *uplift* forces. Therefore, the design of a wall must account for the aforementioned forces [3].

Retaining walls should be designed to prevent a building from collapsing on its natural slope, where the stability of the building is affected by changes in the shape, slope, and form or construction of the slope, as well as by natural or artificial relief or characteristics of the subsoil itself [4]. If earthworks, such as excavation, are carried out, especially if the road is built adjacent to a river or lake, a retaining structure is created to maintain the slope of the land and create a stable foundation on the slope. In addition, the pressure generated by earth mounds and other loads, including uniform load, line load, water pressure, and seismic load, must also be taken into account by the strength of the retaining wall itself [5].

Development in Indonesia is currently being actively carried out, especially in the field of infrastructure, particularly toll roads and bridges for the oprit. Due to development with limited Right Of Way (ROW) land, the oprit road body is not constructed with a certain slope. Therefore, a construction method is needed that does not require much land on the left and right of the road [6].

For this reason, precast soil retaining walls are needed. Generally, precast soil retaining walls, such as Mechanically Stabilized Earth (MSE) Walls, use geosynthetics that are not heat resistant and strip plates. With strip plates, the interlocking between soils is less strong. In connection with this, MSE Wall failures often occur, many of which are caused by these two factors and are influenced by hydrostatic water pressure and soil layers that are less suitable for such construction [3]. While the failure of Mechanically Stabilized Earth Walls is greatly influenced by saturated soil layers that have been saturated with water for a long period of time, considering that the dissipation of water is not channeled, causing active pressure to be greater than passive pressure [7].

To anticipate these failures, new technological innovations are needed to adopt heat resistance, strong soil interlocking, and resistance and strength to the intensity and duration of long rains [8]. The failure of the retaining system is prone to occur due to the intensity of rainfall and the duration of rain that occurs for a long time. Infiltration of rainwater into the soil causes the water level behind the wall to rise, resulting in greater lateral forces on the wall. However, if the wall has good drainage, the water behind the wall can flow immediately. In connection with the above, it is necessary to have novel Mechanically Stabilized Earth Walls with anchor strength, where along the anchor there is a cross necklace and at the end there is a fish fin startail whose function is to resist shear and provide stronger soil interlocking.

The previous research has been conducted by Koerner and Koerner [9], “The Importance of Drainage Control for Geosynthetic Reinforced Mechanically Stabilized Earth Walls.” This study highlights the importance of drainage control in geosynthetically reinforced soil retaining walls, which is one of the main factors causing MSE wall construction failures. This study supports the finding that saturated soil conditions and hydrostatic water pressure affect structural stability, in line with the context of this research.

Furthermore, Hidayat [10] "Analysis of Retaining Wall Stability." This study discusses the analysis of the stability of soil retaining walls against forces such as active and passive soil pressure, as well as groundwater pressure due to rain. The results emphasize the need for drainage systems and adequate structural strength to deal with extreme conditions, which is relevant to the approach of using struts and crossbars in this research.

This study aims to analyze the effect of the distance between anchors (center to center) on the stability of the Mechanically Stabilized Earth (MSE Wall) by applying an innovative model in the form of a crossbar necklace and fish fin startail, as well as testing its effectiveness through field tensile tests and numerical simulations using PLAXIS 3D software in accordance with the SNI 8460-2017 standard. The results of this study are expected to contribute to the development of soil-retaining structure technology that is more efficient and resistant to extreme conditions, especially in red soils and areas with limited land. In addition, this research is also useful as a practical reference for geotechnical construction planners and implementers in determining the optimal configuration and distance between anchors to increase safety factors and minimize horizontal deformation.

2. Research Methods

The research flow chart of the development of the crossbar necklace and fin startail models in the MSE MSE Wall in red soil layers. Starting with data collection, both laboratory data verified technically and numerically with the finite element program were checked for validity with field tests, as well as checking shear stability, overturning stability, and soil bearing capacity stability. In this research, the research location was chosen, namely the Jababeka IX Industrial Estate Bridge Construction located in the Jatireja area, East Cikarang, West Java, where due to the limited *Right of Way*, it is necessary to use Mechanically Stabilized Earth Walls with a cross necklace system and where the ends are fish fin startails.

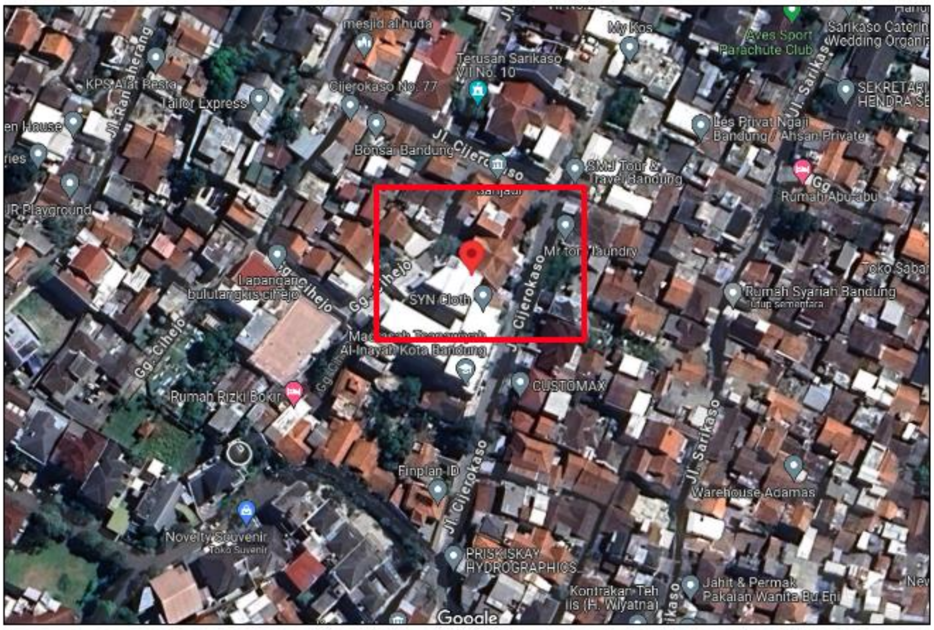

Figure 1.
Research Location.

The soil description at the Jababeka IX location is silt loam, brown, with a consistency ranging from soft to very stiff, with hard soil layers reaching a depth of 18 m (Nspt 60). An 80 cm silent pile foundation is used for both abutments, and the allowable bearing capacity per point for an 80 cm silent pile is 170 tons, with the following soil consistency:

The data used in this research are correlation data from various references. This correlation data collection is done through existing literature, including previous studies that are relevant and closely related to the research topic. Furthermore, the correlation data that have been collected will be processed and analyzed using PLAXIS software. PLAXIS was chosen as the analysis tool due to its ability to perform accurate and reliable geotechnical simulations. The process of inputting data into PLAXIS involves a verification and validation stage to ensure that the data entered matches the field conditions as well as the predefined parameters. This includes parameters such as soil cohesion, deep shear angle, and modulus of elasticity, all of which are obtained from correlation data. The data processing also involves model calibration to ensure that the simulation results obtained are close to the real conditions in the field.

3. Results and Discussion

3.1. Tensile Testing of Crossbar Necklace Anchor

Testing was conducted in 2 stages, namely:

1) Stage 1 Testing.
2) Phase 1 Testing.

Stage 1 Testing:

Phase 1 testing was carried out by placing a 50 x 50 cm finned Cross Necklace Angkur at the bottom, and a 30 x 30 c to c Cross Necklace at the top.

Stage 2 Testing:

Phase 1 testing was conducted by placing the Cross Necklace Angkur with 50 x 50 cm fins at the top, and the Cross Necklace with center to center 30 x 30 cm at the bottom.

On July 6, 2024, a tensile test was conducted on an anchor with a cross necklace and a D19 startail that had been buried in soil and compacted. The following shows the plan of the Pull-Out Test point, where the test was performed on 2 points of Angkor that had been buried by soil.

On July 15, a tensile test was carried out on an anchor with a cross necklace and a D19 start tail that had been buried in soil and compacted. The following shows the plan of the *Pull-Out Test* point, where the test was carried out on 2 points of the Angkur that had been buried by the soil.

Table 1.
Tensile Test Results of the Anchor Crossbar Necklace Stage 1.

Load Test Summary							
Project Name	Anchor With Crossbar Necklace And Startail						
Testing Equipment	Enerpac Rch 302 (Cylinder Effective Area 46.6 Cm²)						
Base Material				Type Of Fastening System		Rebar D 19	
Compressive Strength				Note			
Test Result							
No	**Anchor Details**	**Date Of Test**	**Design Resistance [Kn]**	**Ultimate Resistance [Kn]**	**Recorded Test Load [Kn]**	**Remarks**	**Map Distance**
1.	Point No. 1 (1,200 Psi)	6-07-2024			38.4 Kn	Bottom Anchor	C To C 50cm
2.	Point No. 2 (1,000 Psi)	6-07-2024			32.1 Kn	Top Anchor	C To C 30cm

Table 2.
Tensile Test Results of Stage 2 Crossbar Anchors.

Load Test Summary							
Project Name	**Anchor With Crossbar Necklace and Startail**						
Testing Equipment	Enerpac Rch 302 (Cylinder Effective Area 46.6 Cm²)						
Base Material				Type Of Fastening System		Rebar D 19	
Compressive Strength				Note			
Test Result							
No	Anchor Details	Date Of Test	Design Resistance [Kn]	Ultimate Resistance [Kn]	Recorded Test Load [Kn]	Remarks	Mast Distance
1.	Point No. 1 (2,800 Psi)	15-07-2024			89.6 Kn	Bottom Anchor	C To C 30 Cm
2.	Point No. 2 (1,100 Psi)	15-07-2024			35.2 Kn	Top Anchor	C To C 50 Cm

From the results of the tensile strength test of the Cross Necklace Angkur that has been carried out, it is found that the value of the tensile strength of the Angkur has a tensile strength of 38.4 KN for the Cross Necklace c to c 50 cm (in the lower anchor section) and for the cross necklace c to c 30 cm (in the Upper Anchor Section) of 32.1 KN in the Phase 1 Testing scheme, and on the Crossbar Necklace c to c of 50 cm (in the upper anchor section) of 35.2 KN on the Crossbar Necklace c t o c 30 cm (in the lower anchor section) cm of 89.6 KN in the Phase 2 Testing Scheme.

3.2. Pull Out Analysis Using Plaxis 3D Software

The modeling performed with PLAXIS 3D in this study has been geometrically adjusted to the conditions tested in the field. These geometric adjustments included the dimensions and configuration of the red soil and the position and orientation of the anchor. Every geometric detail was carefully considered so that the modeling could represent the real conditions at the research site. This process ensured that the simulation provided accurate results that were relevant to the field conditions.

The pull-out test stages have also been adapted to the procedures carried out in the field. The test began by pulling out the first anchor in the lower position with a center-to-center (ctc) distance of 30 cm. At this stage, tensile force was applied gradually until the anchor reached its maximum capacity. The data obtained from this test were used to validate the model and ensure that the soil response to the tensile force was as expected.

After the pull-out test on the first anchor was completed, the next step was to continue the test on the second anchor with a distance between the anchors (center to center) of 50 cm. This procedure was repeated using the same method, ensuring that the tensile force was applied consistently and the results obtained could be compared with those of the first anchor. Each stage of the test was designed to provide a clear picture of how the red soil reacted to the tensile force applied to the anchor.

Results from pull-out simulations using PLAXIS 3D were analyzed to understand the behavior of the soil and the anchor in more depth. Stress and strain distribution around the anchor, soil deformation, and interaction between the anchor and red soil were thoroughly evaluated. The data from these simulations provided important insights into the load transfer mechanism and failure potential of the anchor system in red soil. This analysis helps in identifying key factors affecting the performance of the anchor and provides a basis for recommendations for improved design and construction methods. The parameters used for the embankment soil in this PLAXIS 3D modeling are red soil.

Table 3.
Red Soil Parameters of Hardening Soil Model Pull Out Testing.

Parameter	Symbol	Unit	Value
Material type	-	-	Undrained A
Unsaturated Weight	Greased	kN/m³	17.03
Saturated content weight	Iwasat	kN/m³	17.46
Horizontal directional permeability coefficient	kx	m/day	2.59E-05
Vertical directional permeability coefficient	ky	m/day	2.59E-05
Fish Ratio	v		0.2
Effective cohesion	c	kN/m²	18.5
Effective deep shear angle	or	°	29.4
Angle of dilation	Ïˆ	°	0
Strong shear reduction factor interface	Rinter	-	0,7
Modulus of stiffness of the shear at a stress of 100 kPa	E50ref	kN/m²	59040.0
Modulus of tangent stiffness for oedometer conditions at reference stress	Eoed_ref	kN/m²	47970.0
Young's modulus for unloading and reloading at the reference constraint pressure	Eur_ref	kN/m²	177100.0

By adjusting the geometry and test stages to follow field conditions, modeling using PLAXIS 3D offers a comprehensive and realistic approach in analyzing the performance of anchors in red soil. The results of this analysis not only enhance theoretical understanding but also provide practical guidance that can be applied in geotechnical projects involving the use of anchorage in similar soil conditions. *In* addition to field *pull-out* tests, *pull-out* tests were also conducted using Plaxis 3D software.

3.3. Design Criteria

Based on SNI 8460-2017 on Geotechnical Design Requirements, the maximum value of horizontal movement during construction for MSE Wall is about H/250 for rigid reinforcement and H/75 for flexible reinforcement. The slope due to the difference in horizontal movement from the bottom to the top of the wall is estimated to be < 4 mm/m wall height. The post-construction horizontal movement will be very small.

Based on its type, the reinforcement used in this case study is flexible reinforcement, so the criterion used is H/75, where H is the height of the MSE wall. In this case study, the H value of 5.25 m is calculated from the existing soil, so the permissible design criteria are 0.07 m or 70 mm.

In addition to reviewing the magnitude of the horizontal deformation criteria, the MSE Wall also refers to the global *Safety Factor* criteria based on SNI 8460-2017 regarding the minimum safety factor for four potential external failures as in the Table 4.

Table 4.
Summary of minimum safety factors for four potential external failures.

No.	External Failure Potential	Minimum Factor of Safety (FK)	Other requirements	Corrective Steps if FK is not Met
1	Lateral shear at base	1.5	-	Extend L
2	Eccentricity of the resultant forces (rolling moment)	2 (bolster)	$e \leq L/6$	Extend L
3	Carrying capacity	2.5	-	Improve soil Foundation or deepen D_m
4	Global stability	1.3	-	Extend L or improve the foundation soil
Description				
L is the length of the reinforcement				
e is the eccentricity of the resultant forces				

3.4. Modeling Results

In this study, three modeling variations have been conducted using PLAXIS 3D to understand the effect of *center-to-center* (ctc) spacing on the tensile capacity of anchors in red soil. The variations analyzed include 30 cm ctc, 50 cm ctc, and 70 cm ctc. Each of these variations provides important insights into how the spacing affects the distribution of stresses, strains, and the maximum tensile capacity achievable by the anchor in red soil.

Table 5.
Recapitulation of Modeling Results.

No.	Construction Stages	CTC 30 - Ux (mm)	CTC 30 - SF	CTC 50 - Ux (mm)	CTC 50 - SF	CTC 70 - Ux (mm)	CTC 70 - SF
1	Put on MSE, Stack, Put Anchor 1	7.203	5.4	7.625	6.559	7.612	6.62
2	Put on MSE, Piled Up, Put Anchor 2	9.06	4.42	12.16	3.843	12.13	3.82
3	Put on MSE, Stack, Put Anchor 3	9.745	3.03	14.43	2.514	13.31	2.53
4	Put on MSE, Stack, Put Anchor 4	14.76	2.48	15.03	2.098	14.17	2.09
5	Put on MSE, Stack, Put Anchor 5	23.42	2.15	12.32	1.911	11.49	1.84
6	Put on MSE, Piled Up, Put Anchor 6	30.02	1.96	11.31	1.54	9.92	1.56
7	Put on MSE, Pilpil, Put Anchor 7	37.6	1.73	10.59	1.566	15.61	1.54
8	Final Construction	44.71	1.6	10.2	1.524	20.22	1.48
9	1 year operational	15.04	1.58	10.37	1.563	18.61	1.44
10	10 years operational	15.05	1.67	10.4	1.568	18.81	1.44

When referring to SNI 8460-2017 regarding horizontal deformation clearance requirements, it is said to be safe if the value of Horizontal Deformation (Ux) during final construction is < 70 mm and the SF value is > 1.5. Based on Table 5, it can be concluded that CTC 30 and CTC 50 meet the requirements of the design criteria listed in SNI 8460-2017 where the value of Horizontal Deformation (Ux) during final construction for CTC 30 is 44.71 mm and for CTC 50 is 20.10 mm. Likewise, the *safety factor* values for CTC 30 and CTC 50 have met the requirements because > 1.5. As for CTC 70, when looking at the horizontal deformation value, it meets the design criteria of 20.22 mm at the time of final construction, which means < 70 mm. However, when looking at the SF value, CTC 70 is not qualified because SF<1.5.

4. Conclusions

Research on the development of a crossbar strength model with anchor and stirrups on Mechanically Stabilized Earth Wall (MSE Wall) produced various data related to safety factors. The results show that the safety factors of overturning stability of 8.62, sliding stability of 3.56, bearing capacity of 12.92, and anchorage of 6.141, all of which are greater than the minimum limit of 2.5, are considered safe. In addition, the backfill media using red soil layers achieved a fairly high density, with a California Bearing Ratio (CBR) value of 9.5%, exceeding the SNI Geotechnical 8460 2017 standard which requires a minimum value of 6.5%.

In the pull-out test of the Ø19 iron crossbar anchor, the results from Stage 1 showed that the lower anchor with a center-to-center (c to c) distance of 50 x 50 cm produced a pulling force of 38.4 KN, while the upper part with a c to c of 30 x 30 cm produced 32.1 KN. In Stage 2, the bottom anchor with c to c 30 x 30 cm produced 86.9 KN, and the top with c to c 50 x 50 cm produced 35.2 KN. Based on SNI 8460 of 2017, the allowable deformation for the 5.25 m high MSE wall is a maximum of 70 mm, and the results of Plaxis 3D calculations with ctc anchor bars of 30 and 50 cm show that the deformation is still within safe limits.

The study also revealed that the tensile strength of the bottom anchor is greater due to the larger soil mass and soil depth in the bottom area, represented by the gamma value (ϒ). The effective anchor, crossbar necklace, and startail lengths are 0.5-0.7 of the MSE wall height (H), with the anchor length needing to pass through the active zone (0.3 H) and have an inclination angle of $45° + \phi/2$.

A comparison of the results between the three test methods—Oversen and Stroman, Plaxis 3D, and the actual field test on Jl Geger Kalong Hilir Bandung—showed that the crossbar necklace with a ctc of 30 cm gave consistent results of 86.18 KN (Oversen and Stroman method), 87.9 KN (Plaxis 3D), and 86.9 KN (field test). As for the 50 cm ctc, the results were 40.23 KN (Oversen and Stroman methods), 45.2 KN (Plaxis 3D), and 35.2 KN (field test).

Crossbar necklaces with ctc 30 and 50 cm meet the design criteria in SNI 8460-2017, with final construction horizontal deformation (Ux) of 44.71 mm for ctc 30 cm and 20.10 mm for ctc 50 cm, both of which are below the maximum deformation limit of 70 mm. The factor of safety for both also meets the requirement of more than 1.5. However, for the crossbar necklace with a ctc of 70 cm, although its horizontal deformation value of 20.22 mm met the design criteria, the factor of safety (SF) of 1.481 did not meet the requirements as it was less than 1.5.

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