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Study on Pull-Up Behavior of Double Fold Anchor with Field Full Scale Test

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Abstract

Several studies have been conducted on the use of anchors, including numerical analysis, experimental testing, and field-scale testing. These studies have provided insights into anchor behavior in terms of pull-up capacity and soil failure models under tensile loading. Specifically, for the use of anchors in cohesive or soft soils, it is possible to innovate by using anchor elements with various dimensional or surface area changes. This research aims to design anchors for cohesive soils that can be easily applied in the field and have high tensile capacity, determine the pull-up capacity of double-fold type ground anchors, and analyze the effect of the depth of double-fold anchors. The results of pullout and tensile capacity testing on double-fold anchors showed significant variations at each test location. At the first location, Sungai Kariango, high tensile capacity occurred at relatively shallow embedment depths, influenced by the type and bearing capacity of the soil at the test site. At the second location, although the soil was relatively soft, the tensile capacity was similar to the first location but with deeper embedment depths. At the third location, the consistency of soil type and soil strength at the two test points resulted in similar tensile capacities. This indicates that the type and strength, or bearing capacity, of the soil at the test site, as depicted by cone resistance parameters (qc), significantly affect the tensile capacity of the anchor. The better the soil strength and bearing capacity at the test site, the greater the tensile capacity of the anchor that can be achieved. A deep understanding of soil characteristics through CPT is essential in determining the design and embedment depth of anchors to achieve optimal tensile capacity. Through this research, it is expected to obtain optimal tensile capacity results for anchors and develop a double-fold type ground anchor model that is easy to install in the field, suitable for various structures with high tensile loads, and susceptible to uplift in soft soil layers.

Keywords: Pull-Up Capacity; Gound Anchor; Double Fold Anchor Type; Soft Soil.

1. Introduction

Indonesia is known as a maritime nation due to its numerous islands and coastlines stretching for thousands of kilometers. These geographical characteristics offer significant potential for harnessing marine resources and developing efficient inter-island connectivity. To realize this potential, the development of infrastructure along coastlines and between islands is crucial. This includes constructing modern ports, improving maritime and air transportation networks, and strengthening maritime security systems. Additionally, the development of tourism and other economic sectors reliant on coastal and inter-island connectivity is also a priority.

One of the main challenges in infrastructure development in Indonesia is the presence of soft soil in several coastal areas. This type of soil tends to have low shear strength and can pose stability issues for buildings or structures erected on it. Soft soil is typically characterized by low shear strength, high compressibility, and low permeability [1]. To anticipate the hazards of soft soil, various ground improvement methods and retaining structures are used, one of which

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is known as a ground anchor. Ground anchors, commonly referred to as "tiebacks" or "tiedowns," have been widely used to support deep excavations, stabilize slopes and landslides, retain soil/rock masses, and prevent the uplift of submerged structures [2-4]. The pull-out capacity of anchors is crucial in designing and constructing stable structures on soft soil with high tensile loads.

Research on anchor behavior can be approached through three main methods: experimental, numerical, and analytical. Many researchers have conducted laboratory modeling and field testing to understand failure mechanisms [5], studied the effects of embedment depth, examined the influence of anchor size and shape, and evaluated the impact of soil shear angles. The complex nature of anchor behavior embedded in soil has led to conflicting theories in the literature. Accurately modeling anchor behavior is a challenging problem (Das 1990). Research on various types of anchors has shown that anchors are developed for different purposes, depending on the size and type of load, the structural type, and local soil conditions. Studies on circular, square, and strip-shaped anchor plates using the lower bound method aim to develop anchor elements that are easy to install and provide adequate bearing capacity [6]. Anchor plates offer sufficient safety against axial compression, uplift forces, and/or lateral loads [7, 8]. In addition, research has also been conducted on star-shaped anchor elements embedded in cohesive soil through laboratory experiments, providing a variety of anchor design options for soil anchoring [9]. Other research, such as the behavior of anchor plates in various types of soil, includes a parametric study on the effect of ground anchors on excavation stability in soft soils, which have a high level of soil instability [10]. They explored the characteristics of embedded anchor plates and developed analytical results to measure the maximum uplift capacity of circular anchor plates in cohesive soils [11]. They found that the maximum uplift capacity depends on the relative strength of the cohesive soil layers, both saturated and unsaturated, and the anchor embedment depth ratio.

The ground anchor systems commonly used today consist of ordinary steel tendons and cement grout. Grouted anchors are crucial for stabilizing structures and slopes [12]. Some research has been developed to understand the tensile capacity of these types of ground anchors by developing nondestructive evaluation methods using elastomagnetic sensors to effectively detect damage in embedded tendons [13]. However, these anchors have two main drawbacks: a difficult installation process that requires pre-drilling, poor material performance, and high installation costs. These systems are typically designed with deeper embedment lengths to compensate for poor material performance [14]. Worse, conventional steel tendons and cement grout face critical issues of poor durability and are vulnerable to corrosion attacks from aggressive environments, especially in mountainous or water-rich areas [15]. For ground anchors intended for offshore infrastructure, as water depth increases, the installation of anchors becomes increasingly complex, time-consuming, and expensive. This complexity arises from the need for longer and deeper boreholes, which require specialized drilling equipment and techniques to maintain accuracy and stability.

One of the ground anchor systems used for offshore structures is the Drag Embedment Anchor (DEA). DEA is an attractive option for mooring in deep water due to its relatively low installation cost and high holding capacity, even in soft clay soils. In recent years, there has been significant progress in utilizing new technologies and/or materials to enhance the durability of ground anchors [16, 17]. However, there have been limited changes in anchor design [18]. Current design methods determine the ultimate bond stress between the rock/soil and the anchor to estimate the ultimate load capacity. The folded-type soil anchor model consisting of four leaves is a recent innovation developed in current research. The pullout capacity model of this folded-type anchor will be tested in cohesive soil, particularly soft soil, to determine the maximum achievable tensile force [19]. This testing is crucial because cohesive soils have different mechanical properties compared to other soil types such as sand or gravel, being softer and more plastic. Laboratory and field tests will apply gradual tensile forces to anchors embedded in cohesive soil to measure their pullout capacity and ensure that the design can withstand the required tensile forces without failure.

This research introduces an innovation through the use of a double-fold anchor consisting of two layers of leaves, a design that has not been extensively explored in the existing literature. This anchor is specifically designed to address load-bearing capacity challenges in clayey soils, which often cause stabilization issues in infrastructure construction such as retaining walls or building foundations. By employing the double-fold design, this research aims to enhance the efficiency and effectiveness of anchor use in soft and unstable soil conditions, which are often difficult to manage with traditional anchor methods. This innovation is expected to provide a better and more cost-effective solution to stability problems at construction sites with cohesive or unstable soils.

The experimental approach in this study involves comprehensive testing to understand the behavior of the double-fold anchor under various soil conditions. The tests will include analyses of the anchor's pullout and uplift capacities at different embedment depths and soil variations, offering deep insights into how the anchor performs in practice. The findings from this research are anticipated to introduce more advanced and reliable anchor technologies for future construction projects. By gaining a thorough understanding of the anchor's response to mechanical loads and soil characteristics through detailed testing, the study aims to improve the sustainability and resilience of infrastructure against geotechnical challenges, contributing significantly to the development of better and more effective construction methods in the future.

2. Materials and Methods

2.1. Materials

The soil anchor must be made of a material with sufficient tensile strength to withstand the expected loads and be resistant to corrosion, especially in aggressive environments such as acidic or alkaline soils. Commonly used materials for soil anchors include steel coated with zinc or other protective coatings to enhance corrosion resistance. For steel anchors, the material must have high tensile strength and the ability to withstand the given loads. Selecting the right material for soil anchors contributes to the overall safety, reliability, and longevity of the structure. Therefore, considerations such as material strength, corrosion resistance, cost, and material availability are crucial. The fold anchor model to be used in this study is a double fold anchor, with two layers of leaves at the end and middle of the anchor as shown in Figure 1. This represents a development from previous single-fold anchor models at the end, and the star-shaped model that was developed is still in the form of plates.

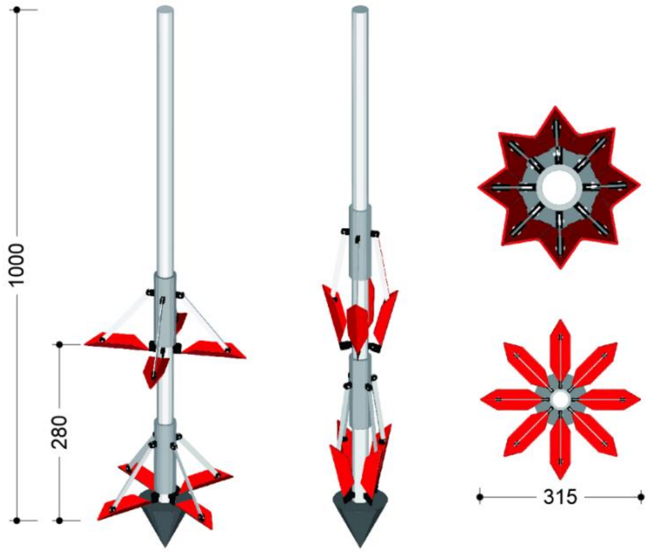


Figure 1. Illustration of double folding anchor (unit in mm)

In Figure 2, the design dimensions of an anchor with specific details for each component are as follows: The anchor consists of a 1-meter-long rod, equipped with 32 anchor hinges measuring 10×10 mm and 8 anchor leaf supports measuring 120×15 mm. There are also 2 vertical-moving steel pipes with a diameter of 40 mm, anchor leaves made of L-shaped steel plates measuring 120 mm × 20 mm, and a cone with a diameter of 100 mm and height of 100 mm. This design provides detailed specifications of the components used in the double-fold anchor, which is an enhancement of the previous model to increase the capacity and efficiency of the anchor structure.

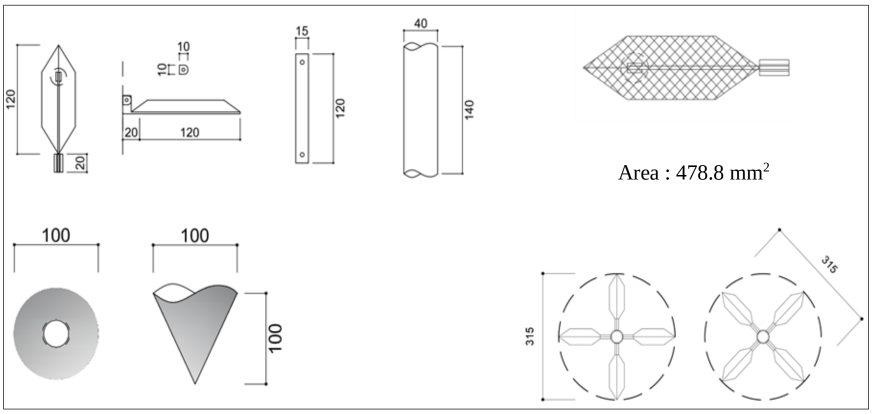
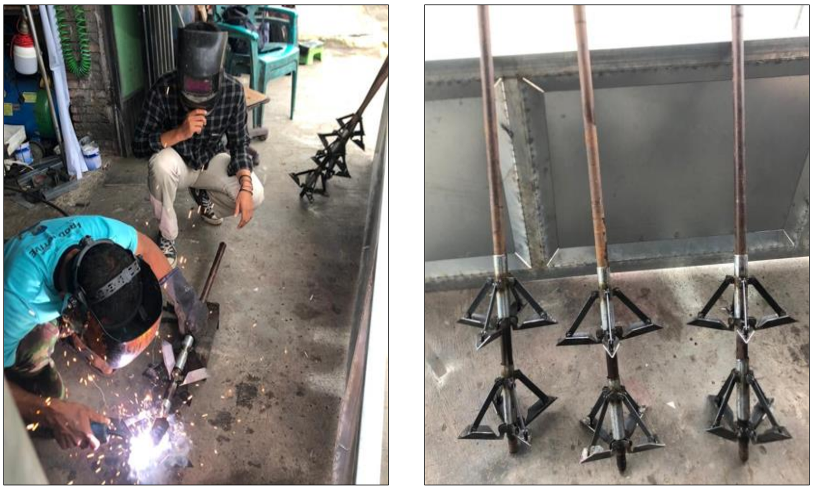


Figure 2. Design dimensions of double folding anchor (unit in mm)

The anchor model used is a fold-type soil anchor consisting of 4 leaves and 2 layers, as shown in Figure 3-b, made from high-quality steel and designed to be flexible, capable of opening and closing like an inverted umbrella. The anchor specifications for this study include leaves (elements) made of L-shaped iron with BJ.37 high-grade hardened steel, 4 mm thick. The leaves/elements are designed to be flexible (non-rigid), allowing them to open and close during field installation. The rod pipe is made of hardened steel with a diameter of 22 mm. The piercing cone is made sharp from a steel plate shaped like a cone. Welding is used to connect each anchor element, ensuring a solid and strong unit. Welding ensures that all components, such as leaves, rods, and other fastening elements, are well-connected to evenly distribute tensile forces throughout the structure as shown in Figure 3-a.



(a) (b)

Figure 3. Pull-out and pull-up capacity test double fold anchor in Sungai Kariango, (a) pull-out capacity, (b) pull-up capacity

2.2. Testing Methods

Figure 4 illustrates the research flow for this study. As a preliminary step, a literature review was conducted to determine effective designs and materials for ground anchors. The next step involved performing cone penetration tests to determine the embedment depth of the anchors. Following that, pull-out and tensile capacity tests were conducted to assess the deformation and maximum capacity of the ground anchors under tensile load.

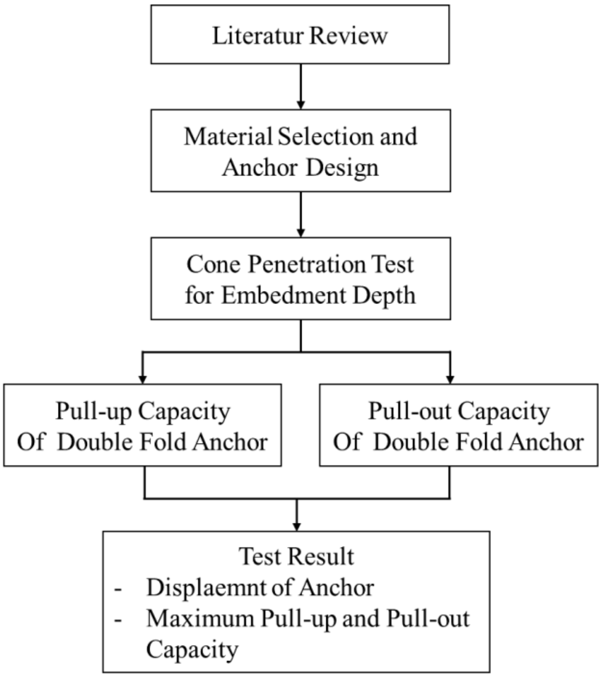
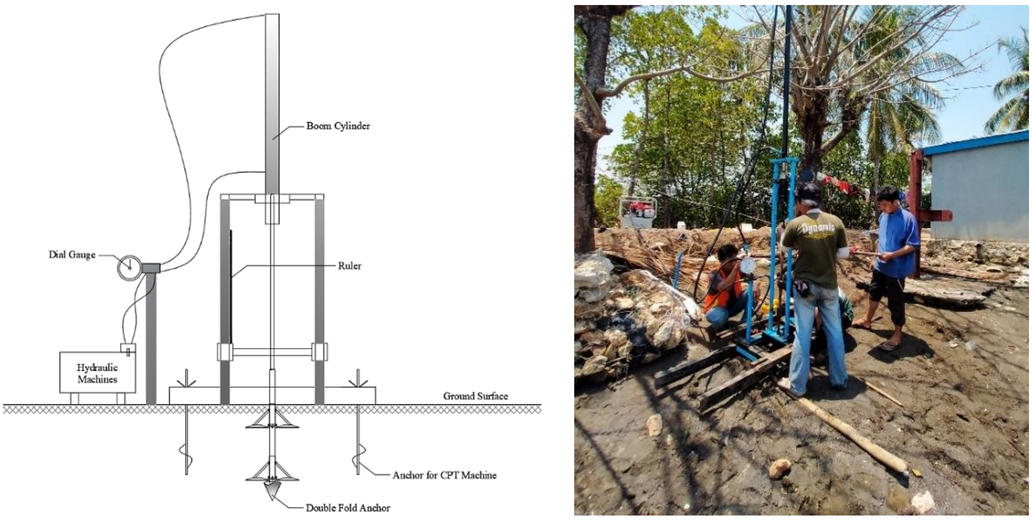


Figure 4. The Flowchart of Research

The testing was conducted at 3 locations with 4 test points: the first location had 1 test point, the second location also had 1 test point, and the third location had 2 test points. The testing was initiated with a Cone Penetration Test (CPT) to assess soil stratigraphy and bearing capacity in the pull-up capacity test area. The CPT was performed according to the applicable procedural standards [20]. Based on previous research, the embedment depth of the ground anchor is determined by soil layer consistency (Maming et al. [19]). For soils with medium to stiff consistency where the cone resistance is > 30 kg/cm², the fold anchor will have difficulty penetrating and may become constrained. Therefore, the CPT is very useful in planning the anchor embedment depth. The testing scheme is as shown in Figure 5-a. The soil layers or stratigraphy obtained from the CPT results [21] were used as a reference to determine the depth for the pull-out capacity test. The method for testing pull-out capacity and installing the anchor began with setting up the CPT-hydraulic tool as a mechanical pusher and puller for the anchor, placing the sample (fold anchor) at the test points, digging approximately ± 50 cm for anchor placement, and ensuring the anchor was in the closed position. The anchor was then inserted into the ground by pushing the driving shaft to a certain depth and connecting the rod bar. This process was repeated until the desired depth or until the anchor encountered difficulty penetrating the ground. Subsequently, the pull-out capacity test was conducted by pulling the connecting rod and reading the tension gauge. Tension readings were taken meticulously every 1 cm. This frequent measurement allowed for a detailed understanding of how tension varied as the anchor was subjected to increasing loads. As testing progressed, readings were taken at broader intervals, every 10 cm, once the tension reached higher levels or showed consistent increases, and tension readings continued until the anchor was pulled out or the soil failed, as shown in Figure 5-b.



(a) (b)

Figure 5. Pull-out and Pull-up Capacity Test double fold anchor, (a) testing scheme, (b) testing process

3. Result and Discussion

3.1. Results of The Cone Penetration Test (CPT) are Used to Determine The Soil Profile

The Cone Penetration Test (CPT) and soil anchor testing offer several advantages by providing continuous data on soil characteristics and depth, which aid in understanding the soil profile in detail and identifying soil types such as clay, silt, or sand based on cone resistance (qc) and shear resistance (fs). Based on Tables 1 to 3, the CPT results show the soil layer profiles from three test locations. These profiles are identified based on the Soil Behavior Type (SBT) charts referenced from source [21]. Soil profiles are crucial as they form the basis for pull-out and pull-up capacity testing at these locations. Understanding the soil characteristics at each site helps predict how the soil will react to pull-out and pull-up forces, ensuring more accurate and relevant test results aligned with field conditions.

Table 1. Soil Behavior Type Based on CPT in Sungai Kariango

Location	Depth (m)	qc_{Ave} / Pa	Rf_{Ave}	Soil Behavior Type
Sungai Kariango	0.00 - 2.40	5.94	4.33	Organic Soil - Clay
	2.40 - 3.00	21.02	2.70	Silt mixtures - clayey silt to silty clay

Table 2. Soil Behavior Type Based on CPT in Sungai Maros

Location	Depth (m)	qc_{Ave} / Pa	Rf_{Ave}	Soil Behavior Type
Sungai Maros	0.00 - 1.80	5.39	2.12	Clay - silty clay to clay
	1.80 - 3.40	7.46	1.88	Silt mixtures - clayey silt to silty clay
	3.40 - 6.00	5.37	6.13	Clay - silty clay to clay
	6.00 - 7.00	7.69	5.82	Clay - silty clay to clay

Table 3. Soil Behavior Type Based on CPT in Sungai Cenranae

Location	Depth (m)	qc $_{Ave}$ / Pa	Rf $_{Ave}$	Soil Behavior Type
Sungai Cenranae	0.00 - 2.60	1.55	4.19	Organic Soil - Clay
	2.60 - 3.60	21.44	1.70	Silt mixtures - clayey silt to silty clay

At the first testing location at Sungai Kariango, the Cone Penetration Test (CPT) results showed that at a depth of 3 meters, a soil layer with cone resistance (qc) > 30 kg/cm^2 was encountered, with an average cone resistance (qc) in this layer measured at 21.02 kg/cm^2. Therefore, this depth of 3 meters is the planned depth for anchor installation.

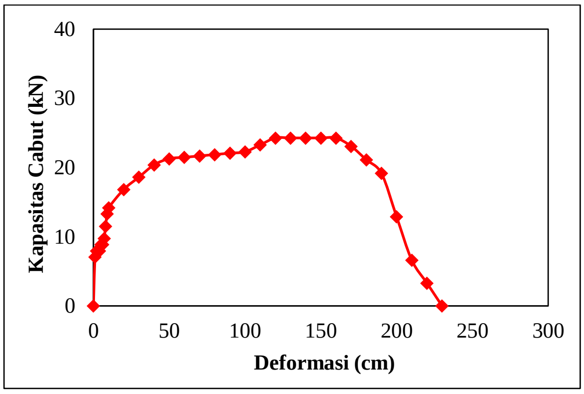
Table 2 shows the results of soil layer classification at the testing location in Sungai Maros. Based on the Cone Penetration Test (CPT) results at a depth of 7 meters, the cone resistance (qc)>10 kg/cm^2, with an average cone resistance (qc) in this layer measured at 7.69 kg/cm^2. Therefore, the planned depth for anchor installation at this location is 7 meters.

At the testing location of Sungai Cenranae, which is the third location, the Cone Penetration Test (CPT) results for assessing soil consistency show that at a depth of 3.60 meters, a soil layer with cone resistance (qc) > 30 kg/cm^2 has been encountered. Between depths of 2.60 – 3.60 meters, the average cone resistance (qc) in this layer is 21.02 kg/cm^2. Therefore, at this location, the planned anchor installation depth is 3.60 meters.

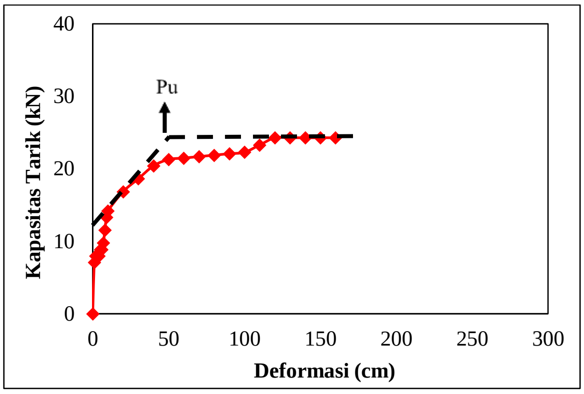
3.2. Results of The Pull-out and Pull-up Capacity of Double Fold Anchor

The pull-out capacity and pull-up capacity of soil anchors are two critical parameters that determine the load-bearing capacity and stability of anchors in supporting structures such as retaining walls or building foundations. Pull-up capacity refers to the maximum tensile force that an anchor can withstand before experiencing significant deformation or failure. On the other hand, pull-out capacity is the maximum force that causes the anchor to completely pull out from the soil. Testing for both capacities is conducted by applying tensile forces gradually to the anchor and recording the force values and displacements that occur, which are then presented in a graph showing the relationship between force and displacement.

This study aims to understand the behavior of the double-folded anchors under tensile and pull-out loads and their relationship with displacement. Figure 6 shows the results of pull-out and pull-up capacity testing at Sungai Kariango, point 1. The anchor's pull-out capacity occurred at a displacement of 230 cm at a depth of 3 m where the anchor was embedded. The maximum pull-up capacity (Pu) of the anchor was 24.28 kN at a displacement of 120 – 160 cm, after which the tensile force decreased until the anchor finally pulled out. The soil failed in this condition, indicating that the soil above the anchor could no longer support the tensile stress nearly reaching the ground surface.



(a)



(b)

Figure 6. Pull-out and pull-up capacity test double fold anchor in Sungai Kariango, (a) pull-out capacity, (b) pull-up capacity

At testing point 2 in the Maros River location, the anchor was installed to a depth of 7 meters, followed by pull-out and pull-up capacity testing. The pull-out capacity occurred with a displacement of 650 cm. The pull-up capacity obtained at testing point 2 was 20.39 kN at a displacement of 140 – 240 cm. After reaching the maximum load, the tensile force decreased, indicating that the soil around the anchor had exceeded its bearing capacity and started to undergo plastic deformation. This significant deformation suggests that the soil had softened and could no longer support additional loads, eventually leading to the anchor pulling out. The results of the pull-out and pull-up capacity testing at point 2 are shown in Figure 7.

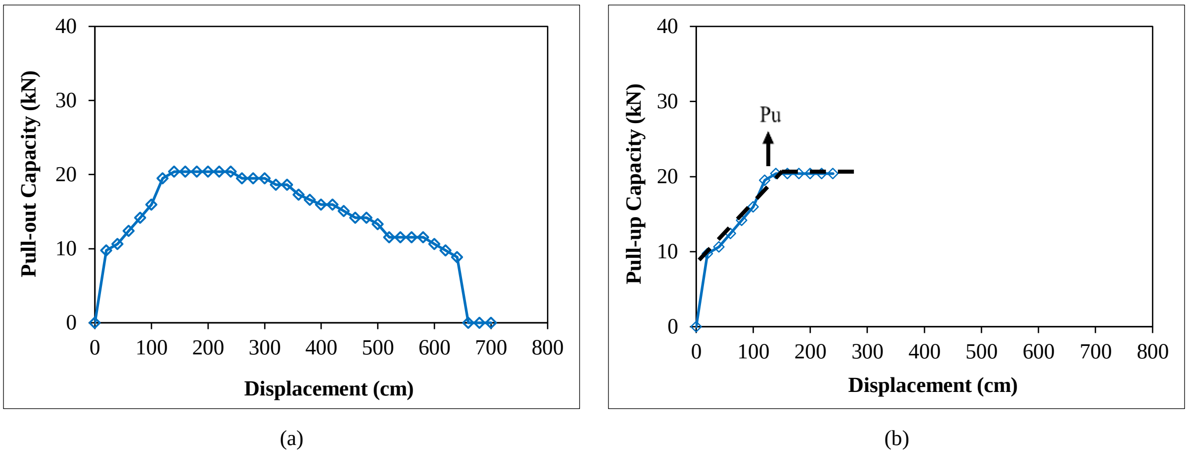


Figure 7. Pull-out and pull-up capacity test double fold anchor in Sungai Maros, (a) pull-out capacity, (b) pull-up capacity

In Figure 8, the graph depicts the behavior of the double-fold anchor in terms of pull-out and pull-up capacity, based on testing results obtained at location Sungai Cenranae, point 3. At this point, the anchor was installed to a depth of 3 meters. The pull-out capacity occurred with a displacement of 130 cm. The significant displacement at the pull-out capacity indicates that the soil around the anchor experienced significant shifting, reflecting plastic deformation or even loss of its bearing capacity.

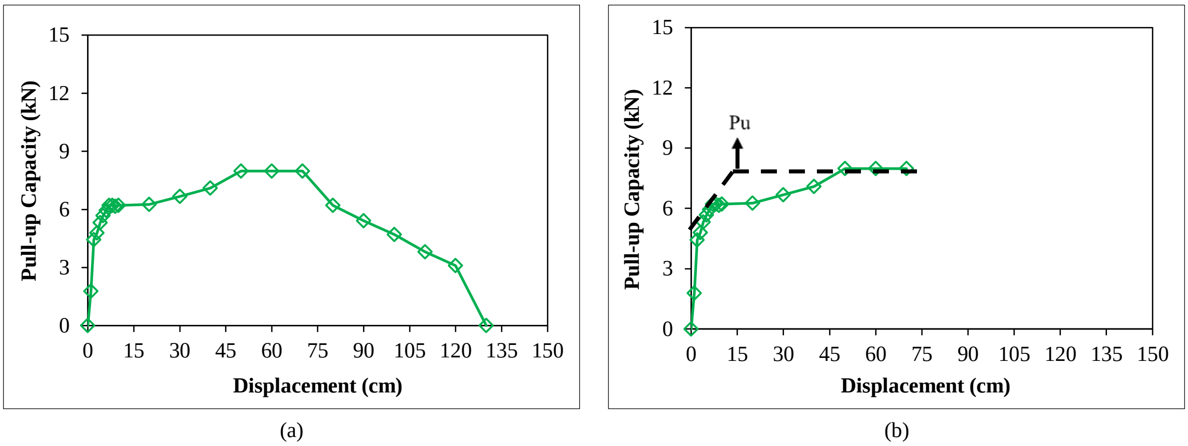


Figure 8. Pull-out and pull-up capacity test double fold anchor in Sungai Cenranae, (a) pull-out capacity, (b) pull-up capacity

The results of the pull-up capacity testing show that the maximum pull-up capacity of the anchor was 7.98 kN at a displacement of 50 – 70 cm. This indicates that the anchor could withstand a certain tensile load before reaching failure. After reaching the maximum load, the tensile force on the anchor decreased, indicating that the soil had exceeded its elastic limit and started to undergo permanent deformation. This deformation is a result of the tensile stress reaching or approaching the surface of the soil, causing it to no longer support additional loads.

The final testing at point 4 in the location of Sungai Cenranae showed results that were roughly similar to point 3, with the anchor installed at a depth of 3 meters. The pull-out capacity of the anchor occurred at a displacement of 140 cm, indicating that the soil around the anchor had experienced significant shifting and had lost its bearing capacity.

The maximum pull-up capacity of the anchor was 7.09 kN at a displacement of 50 – 80 cm. After reaching the maximum load, the tensile force on the anchor decreased because the soil around it had exceeded its elastic limit and started to undergo permanent deformation. This phenomenon occurs when the tensile stress applied to the anchor reaches or approaches the soil surface, causing the soil to no longer support additional loads while maintaining its original conditions, the results of the pull-out and pull-up capacity testing at point 4 are shown in Figure 9.

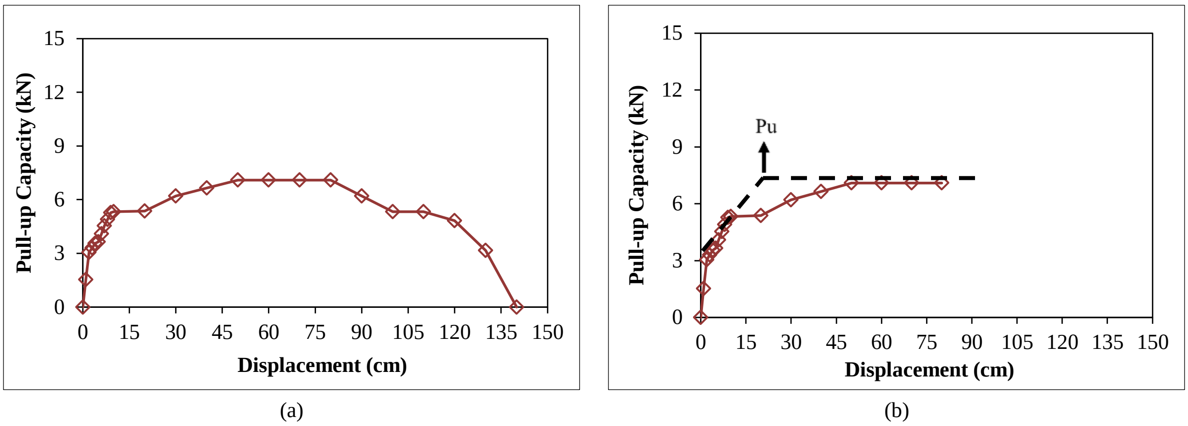


Figure 9. Pull-out and pull-up capacity test double fold anchor in Sungai Cenranae, (a) pull-out capacity, (b) pull-up capacity

3.3. Comparison of Maximum Pull-Up Capacity of Double Fold Anchor

Comparison of anchor pull-up capacities between different locations can vary significantly depending on the soil characteristics and the depth at which the anchors are installed at each testing location. Understanding the comparison of anchor pull-up capacities between one location and another can provide an insight into the maximum pull-up capacity of the double folding anchor in specific soil conditions and at specific depths of installation.

Figure 10 shows the comparison of anchor pull-up capacities at three different locations across four testing points. From the graph, it is evident that there is a significant variation in anchor pull-up capacities at each testing point. These differences can be attributed to various factors including soil type, its strength or bearing capacity, and the depth of anchor installation. The varying capacities underscore the importance of understanding the specific conditions of the location where the anchor will be placed and selecting an appropriate depth of installation to achieve optimal pull-up capacities to support the structure above.

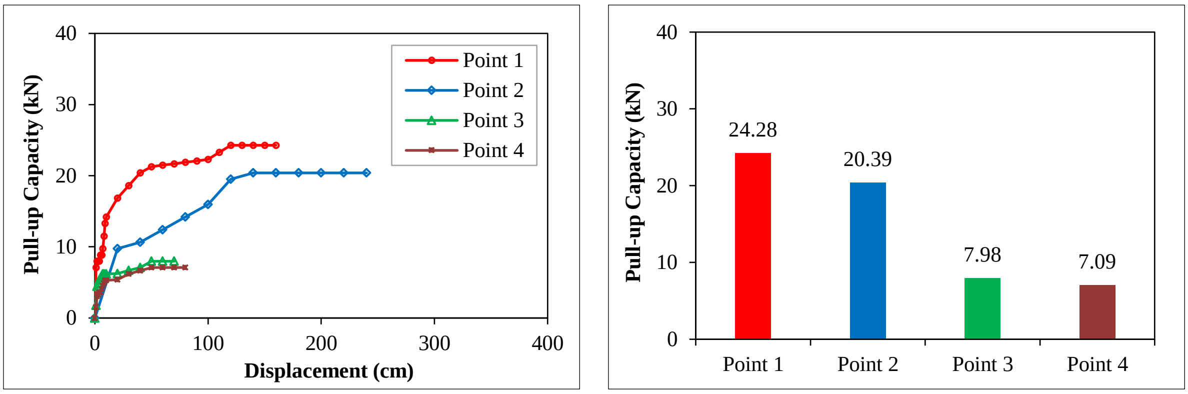


Figure 10. Comparison of Maximum Pull-Up Capacity of Double Fold Anchor

4. Conclusion

The results from the pull-out and pull-up capacity tests on the double-folding anchor reveal significant variation across different test locations, reflecting differences in soil characteristics at each point. At Point 1, located in Sungai Kariango, a significant pull-up capacity was recorded at a shallow installation depth. This can be attributed to the type of soil and its good bearing capacity at this location. With adequate bearing capacity at a relatively shallow depth, the anchor functions effectively even without being installed deeply into the ground. In contrast, at the second point, which is situated in an area with relatively soft soil, the pull-up capacity obtained was almost equivalent to that at the first point but required a deeper installation depth. This indicates that while the pull-up capacities at both locations might be similar, the installation depth must be adjusted according to the softer soil conditions to achieve optimal results.

At the final location, where two test points were conducted, the pull-up capacities obtained showed high consistency, indicating that the soil type and strength at this site are relatively uniform. This consistency suggests that the soil classification at this site is quite homogeneous, providing stable pull-up capacity results. Soil investigation using the Cone Penetration Test (CPT) provides additional insights by measuring cone resistance (qc), which has a significant impact on the pull-up capacity of the anchor. Higher qc values, reflecting better soil bearing capacity, are directly associated with greater achievable pull-up capacities. Therefore, a thorough understanding of soil characteristics through CPT is crucial for determining the design and depth of anchor installation. This ensures that the anchor can achieve optimal pull-up capacities, function effectively, and address geotechnical challenges that may be encountered in various soil types during construction.

5. Declarations

5.1. Author Contributions

Conceptualization, A.J.H. and T.H.; methodology, A.J.H. and T.H.; software, A.J.H.; validation, T.H., A.R.D., and A.B.M.; formal analysis, A.J.H.; investigation, A.J.H.; resources, A.J.H.; data curation, A.J.H.; writing—original draft preparation, A.J.H.; writing—review and editing, A.J.H.; visualization, A.J.H.; supervision, T.H., A.R.D., and A.B.M.; project administration, A.J.H.; funding acquisition, A.J.H. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Acknowledgments

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

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