Civil Engineering and Architecture 14(3): 1533-1542, 2026 http://www.hrpub.org
DOI: 10.13189/cea.2026.140311

Experimental Investigation of Bamboo Micropiles to Increase the Bearing Capacity of Shallow Foundations with Variation of Undrained Cohesion

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Received November 3, 2025; Revised March 4, 2026; Accepted March 26, 2025

Cite This Paper in the Following Citation Styles

(a): *[1] Isnaniati, Putu Tantri Kumala Sari, Muhammad Farid Fakhruddin , "Experimental Investigation of Bamboo Micropiles to Increase the Bearing Capacity of Shallow Foundations with Variation of Undrained Cohesion," Civil Engineering and Architecture, Vol. 14, No. 3, pp. 1533 - 1542, 2026. DOI: 10.13189/cea.2026.140311.*

(b): *Isnaniati, Putu Tantri Kumala Sari, Muhammad Farid Fakhruddin (2026). Experimental Investigation of Bamboo Micropiles to Increase the Bearing Capacity of Shallow Foundations with Variation of Undrained Cohesion. Civil Engineering and Architecture, 14(3), 1533 - 1542. DOI: 10.13189/cea.2026.140311.*

Abstract Undrained cohesion (c_u) is an important parameter to determine the bearing capacity of the sub-base, especially in soils with low permeability, such as soft clay. Low c_u values result in low shear strength and low bearing capacity, thus requiring soil strength to increase its bearing capacity. This experimental study examines the extent to which the ultimate bearing capacity of shallow foundations reinforced with bamboo micropiles increases compared with unreinforced conditions at different c_u values. Laboratory shear failure tests were conducted on soft clay c_{u1} and medium clay c_{u2}, with and without bamboo micropiles reinforcement. A rectangular shallow foundation (B= 0.075 m) was modeled using variations in the length ratio L/B, diameter ratio d/B, and installation configuration (K= 0.67B). The test results are expressed as an increase in the ultimate bearing capacity ratio ($Rq_{ult\text{-}empirical} = q_{ult\text{-}empirical}/q_{ult\text{-}Terzaghi,LSF}$). The results show that $Rq_{ult\text{-}empirical}$ increases with the increase in both L/B and d/B. The larger L/B value results in a significant increase in $Rq_{ult\text{-}emp}$, with a very strong coefficient of determination R^2 for c_{u1} and c_{u2}. The increase in d/B also increases $Rq_{ult\text{-}emp}$ to an optimum point at d/B = 0.04, then tends to stabilize with a very strong R^2 value for c_{u1} and c_{u2}. Overall, the average increase in bearing capacity (Rq_u) ranges from 147–166% in c_{u1} soil and 170–172% in c_{u2} soil. The most effective increase in $Rq_{ult\text{-}emp}$ in soil consistency levels c_{u1} and c_{u2}, occurs at a diameter ratio d/B = 0.04 and L/B = 2.13.

Keywords Experimental, Bamboo Micropiles, Bearing Capacity of Shallow Foundations, Undrained Cohesion

1. Introduction

In this study, the term micropile refers to small-diameter reinforcing elements beneath shallow foundations. Unlike conventional micropiles made of concrete or steel, bamboo micropiles were chosen due to their abundance, low cost, and environmentally friendly nature, making them suitable for small- and medium-scale projects.

Undrained cohesion (c_u) occurs when the soil cannot drain water freely, leading to increased pore water pressure under load. This is a key parameter for foundation stability, as higher c_u results in greater soil shear resistance and bearing resistance. The shear strength of undrained soil (undrained cohesion) is the most important parameter in evaluating the bearing capacity of undrained soil [1]. By knowing the undrained cohesion value, an engineer can design a foundation safely and economically. If undrained shear strength values are low, the soil has insufficient bearing capacity, which necessitates reinforcement measures such as the installation of bamboo micropiles.

Other research on undrained cohesion states that increasing undrained cohesion (c_u) in very soft soil significantly increases the ultimate bearing capacity of shallow foundations and the increase is more optimal with the presence of reinforcement (geogrid). This is because reinforcement helps distribute the load more evenly and increases the stiffness of the soil system with the foundation, so that the contribution of clay soil cohesion to foundation stability becomes more effective [2]. Other research occurred in normally consolidated clay (NC), where undrained cohesion increased linearly with depth directly, so that there was an improvement of shallow foundation bearing capacity due to reinforcement [3], [4].

Research on micropiles in sandy and clay soils shows that soil bearing capacity experiences an increase after installing the Micro-Pile Group (MPG) system, which is greater than the Single Micro-Pile (MPS) system [5], [6]. Other researchers have also proven that the presence of micropiles as reinforcement can increase the shear strength of soil on slopes [7], and micropiles are effective in reducing settlement and increasing shear strength in layered soil [8], and increase stability and ultimately increase the bearing capacity of the soil [9].

Laboratory research on bamboo micropiles as soft soil reinforcement in shallow foundations has shown that installing micropiles is effective in increasing the bearing capacity of shallow foundations in soft soils, especially through the correct number and installation configuration [10]. This research is supported by other research findings that micropiles are effective in increasing the bearing capacity of shallow foundations in soft clay soils when installed under the foundation in a square-shaped foundation area and research that proves that micropile reinforcement is effective in reducing foundation settlement and increasing soil bearing capacity in soft soils, thus improving structural stability [11].

Micropiles using bamboo material are based on numerous studies that state that bamboo not only has the potential as an environmentally friendly building material, but also as an innovative structural and geotechnical element, including the development of bamboo micropiles to improve the bearing capacity and performance of foundations in soft soils [12]. Other research results state that all bamboo species show higher strength values than other woods, so bamboo has great potential as an alternative construction material to replace wood [2]. Abdul Karim's research states that the tensile strength of bamboo is within the tensile strength range of light steel reinforcement, so bamboo has the potential to be used as a partial replacement or alternative to steel in reinforced concrete systems. These findings strengthen the basis for utilizing bamboo as reinforcement in shallow foundations and micropile systems, especially in soft soils, where increasing bearing capacity and controlling deformation are key aspects in foundation planning [13].

This study examines the mechanism of soil-bamboo interaction in soft soil and evaluates the effectiveness of bamboo as an environmentally friendly micropile foundation element, assuming the soil used behaves undrained. The results of this study prove that bamboo as a micropile can work effectively in soft soil, proving that bamboo micropiles are able to increase the bearing capacity and control the deformation of soft soil through the mechanism of blanket friction and soil mass stiffening [14].

Waruwu researchers tested the effect of bamboo micropiles on bearing capacity, subgrade reaction modulus, and settlement in soft soil (peat), which is known to have low bearing capacity and high settlement. The study found that bamboo micropiles are functionally capable of increasing the bearing capacity of peat soil close to concrete, so that bamboo is a potential reinforcement alternative for soft soil [15]. Research on foundations using bamboo as a cheaper, local, and environmentally friendly alternative reinforcement material states that bamboo can function as an alternative reinforcement in concrete foundations, providing load-bearing capacity and collapse mechanisms equivalent to those of foundations with steel reinforcement [16].

Based on the above background, further research is needed to evaluate the effect of undrained cohesion (c_u) on the ultimate bearing capacity of shallow foundations after micropile installation. This study considers variations in the micropile length ratio (L/B) and diameter ratio (d/B), with a micropile configuration of K/B = 0.67 and the number of micropiles of n = 16 [4], [10], [17]. The objective of this study is to assess the magnitude of improvement in the ultimate bearing capacity of shallow foundations resulting from micropile installation, as quantified by the increase in the ultimate bearing capacity ratio when the settlement is 0.1B ($Rq_{ult\text{-}mp} = q_{ult\text{-}empirical} / q_{ult\text{-}Terzaghi,\ local\ shear}$) at different undrained cohesion (c_u) [18]. By using laboratory modeling through shear failure testing on soil samples of soft clay consistency level (c_{u1}) and medium clay consistency level (c_{u2}) before installing micropiles and after installing micropiles with variations of "L/B" and "d/B", the $q_{ult\text{-}empirical}$ value was obtained. Meanwhile, the magnitude of the ultimate bearing capacity was calculated using the Terzaghi formula in local shear failure conditions ($q_{ult\text{-}Terzaghi,\ local\ shear}$) from the Terzaghi failure model, as illustrated in Figure 1 and based on the results of previous research tests [10].

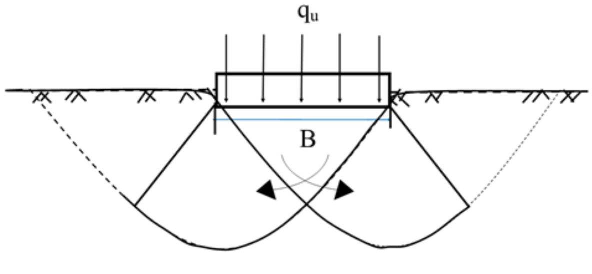

Figure 1. Graphic illustration of local shear failure [19]

2. Materials and Methods

To evaluate the influence of undrained cohesion on the improvement of the ultimate bearing capacity of shallow foundations reinforced with micropiles, laboratory testing was conducted using a 1:30 scale from the field scale [20]. The shallow foundation is made of a square iron plate with a thickness (t = 0.003 m), width / side (B = 0.075 m), working on soft soil reinforced with bamboo micropiles. The micropiles beneath the shallow foundations were installed as a group of micropiles with an edge-to-edge spacing of (K = 0.67B) and a total number of micropiles (n = 16) [10], [21]. Variations in micropiles use the ratio of the variation in micropile diameter d/B (= 0.027; 0.04; 0.067) and the ratio of micropile length to footing width L/B (= 1.333; 1.733; 2.133), with the following completion stages [22].

2.1. Formation of Soft Clay and Medium Clay Samples

The purpose of sample formation is to determine the effective vertical stress (σ'_v) and undrained cohesion (c_u) for soft and medium clay soil consistency levels. The (σ'_v) and c_u results were then used as a reference for creating each test specimen for soil shear failure testing. The soft and medium clay soil sample formation process involves a compression stage, as shown in Figure 2, and a shear strength test.

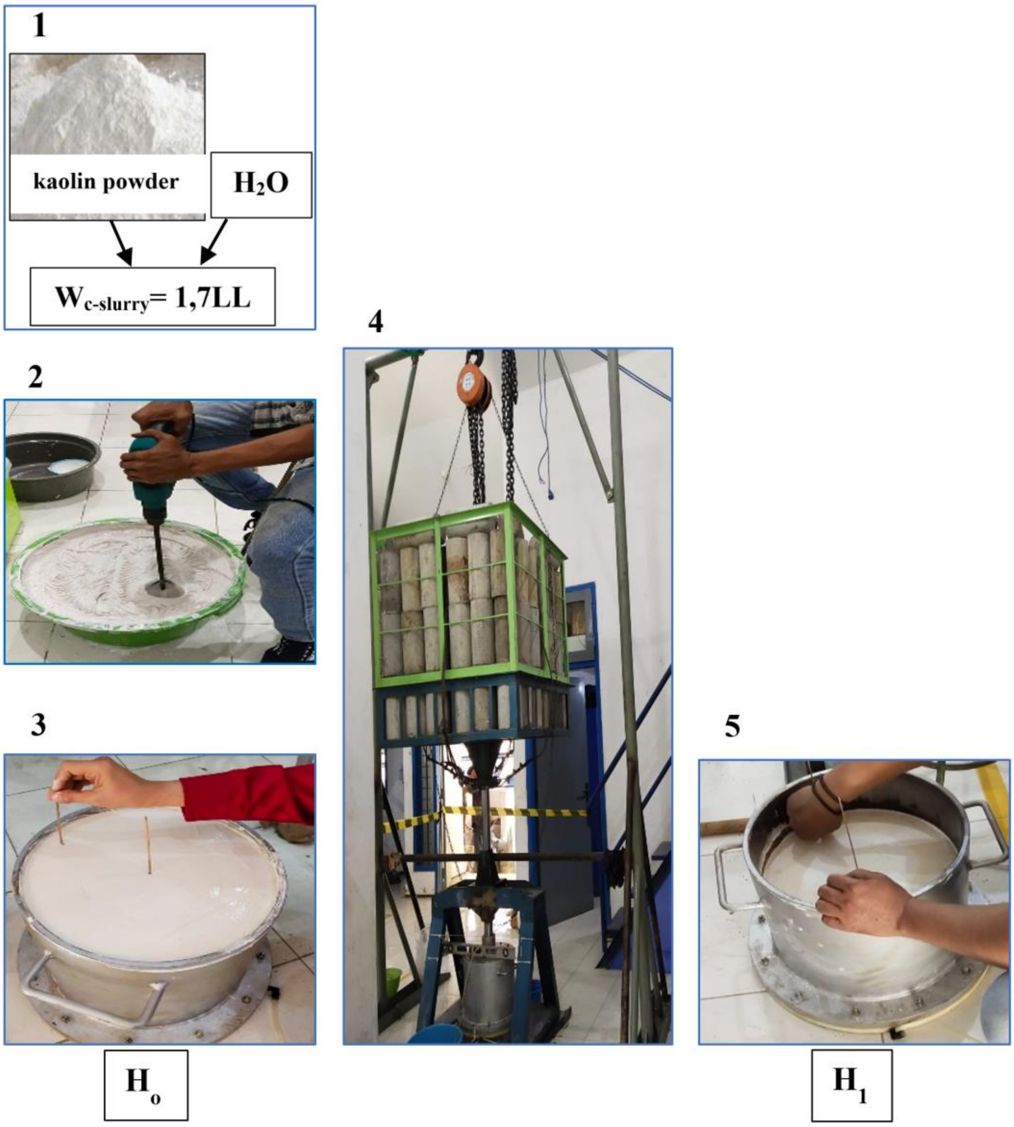

Figure 2. Slurry compression stages of soft clay-medium clay soil samples

Slurry sample compression is a method to obtain undisturbed soil, as shown in Figure 2, with the following sequence:

1. Make a slurry from kaolin powder with a water content (w_c = 1.7xLL) [23].
2. Mix with a mixer for approximately 15 minutes until the mixture resembles a paste.
3. Pour into a slurry mold with a diameter (d = 0.33 m) and an initial height (H_o = approximately 0.28 m).
4. Compress with an effective vertical stress load of σ'_v = 114.149 kN/m^2 for soft clay and σ'_v = 195.054 kN/m^2 for medium clay. The loading time (t) is carried out at a degree of consolidation (U) of 95% to 100% for 5 to 7 days using the formula [19].

$$t_{U\%} = \frac{T_{v,U\%}\left(\frac{H_{dr}}{2}\right)^2}{C_v} \qquad (1)$$

where,

H_{dr} = initial sample thickness (H_o), double drainage conditions

$Tv_{99\%}$ = time factor at $U_{99\%}$

C_v = consolidation coefficient

At the $U_{99\%}$ consolidation level, the soil is considered to have reached hydrostatic pore water pressure ($u = u_o$).

5. Measure the height of the compacted soil sample (H1-sc for soft clay and H1-mc for medium clay).

Soil Shear Strength Testing Stage.

The soil shear strength test uses the Unconfined Compression Test and the Vane Shear Test. The purpose of this test is to verify whether the undrained cohesion (c_u) value obtained by compressing the soil under load (σ'_v) remains within the soil consistency limits of c_u = 12,258–24,516 kN/m^2 for soft clay, and c_u = 24,516–49,033 kN/m^2 for soft clay [24].

2.2. Soil Shear Failure Testing, with q_{ult} Results

The foundation used is a square shape with a width of B = 0.075 m, the applied number of micropiles (n = 16), and this ratio of the micropile installation configuration (K/B = 0.67), where K/B is the ratio of the micropile installation span from end to end [25].

1. **Sample without a micro-pile:** analysis is based on Terzaghi's theory of local shear failure conditions (c = 2/3c_u) at foundation depth (D_f = 0), saturated clay soil (ϕ = 0°) and square foundation, so that the formula was obtained as below [26]

$$q_{ult} = 4{,}94.\ c_u \qquad (2)$$

where,

q_{ult} = ultimate bearing capacity

c_u = undrained cohesion

2. **Sample with micro-pile reinforcement:** the same conditions were used for analysis as for samples without micro-pile with variations in micro-pile,
   - using the L/B ratio (= 1.333; 1.733; 2.133).
   - using the d/B ratio (= 0.027; 0.04; 0.067)

The test sample without a micro-pile refers to a shallow foundation, which is tested under initial conditions (without a micro-pile), as shown in Figure 3 below.

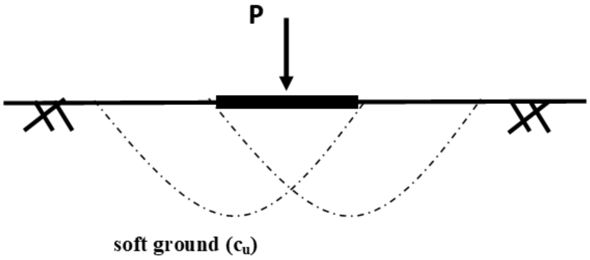

Figure 3. Shallow foundation without reinforcement on soft soil

The sample installed with a mi means a shallow foundation with micro-pile reinforcement, as in Figure 4, as follows:

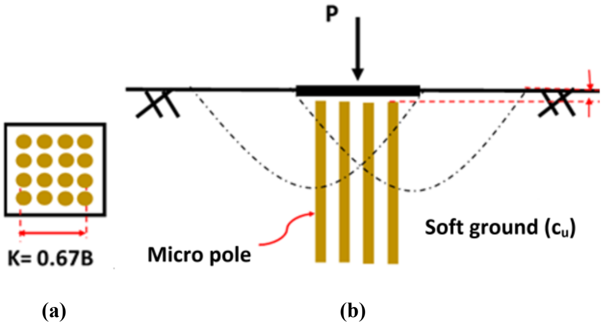

Figure 4. Shallow foundation with micropile reinforcement with n = 16 and K = 0.67B, a) Top view of the bamboo micropile installed under the shallow foundation, b) Sectional view of the bamboo micropile installed on soft soil (cu)

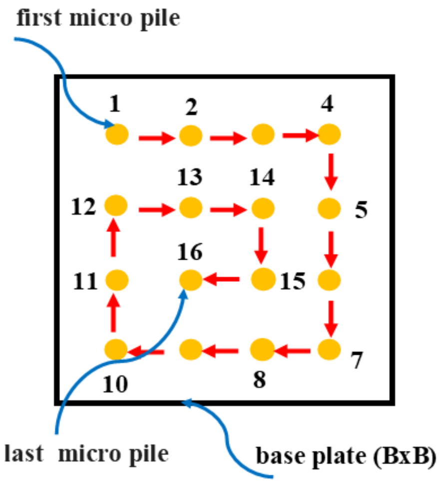

Figure 5. Micropiles installation direction for n= 16

Before conducting the shear failure test, consideration should be given to the installation of the bamboo micropiles to optimally increase the ultimate bearing capacity (q_{ult}).

Micropile installation is illustrated in Figure 5 (installation sequence) and Figure 6 (final configuration). Sixteen bamboo micropiles (n=16) were installed vertically at spacing K = 0.67B [27]. The installation sequence (Figure 5) is carried out so that the excess pore water pressure formed due to the installation of the micropile does not flow out. Meanwhile, the waiting period is carried out after the micropiles have been installed (Figure 6), so that the condition of the soil due to damage from the installed micropiles can be assessed.

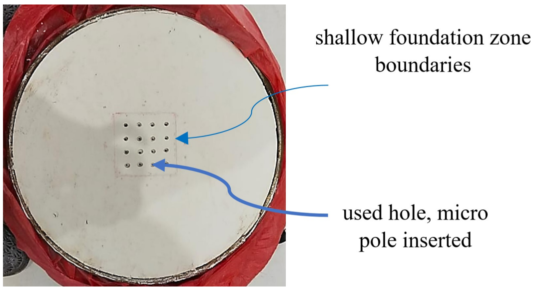

Figure 6. Micropiles installed, n= 16 with K= 0.67B

This test on soil shear failure is conducted to identify the allowable bearing capacity for samples reinforced with micro-piles ($q_{ult,mp}$) and those without (q_{ult}), as shown in Table 1.

Table 1. Overview of the number of test samples for soft clay (c_{u1}) and medium clay (c_{u2}) in the micro-pile installation configuration (K=67B)

Micro-pile length ratio	Number of test object samples		Micro-pile diameter ratio
	Undrained cohesion (c_u)		
	c_{u1}	c_{u2}	
L_o	1	1	d_o
L_1/B	1	1	d_1/B
L_2/B	1	1	d_1/B
L_3/B	1	1	d_1/B
L_3/B	1	1	d_2/B
L_3/B	1	1	d_3/B

From Table 1, soil shear failure testing was carried out to obtain the ultimate bearing capacity (q_{ult}) value using a loading speed of 15 mm/minute [28], with testing as shown in Figure 7.

Figure 7. Soil shear failure test (q_{ult}) on soft clay soil

Figure 7 shows a shear failure test with bamboo micropile reinforcement using an ASTM-based apparatus to obtain q_{ult} [28]. Tests were conducted on soft (c_{u1}) and medium clay (c_{u2}) samples (ds = 0.33 m) with 16 specimens: 2 unreinforced at Lo/B and do/B, and 14 reinforced at L_i/B and d_i/B (see Table 1).

3. Results and Discussion

Results and their discussion are shown in Figure 8 and Figure 9. The figures are the results of laboratory tests that investigate the effect of the length and diameter of the cone on the increase in the maximum bearing capacity ratio at the time of settlement is 0.1B ($Rq_{ult-mp} = q_{ult-empirical} / q_{ult-Terzaghi, LSF}$) in clay soil with soft to medium consistency (c_u). Soft consistency clay soil with undrained cohesion (c_{u1}) and medium consistency clay soil with undrained cohesion (c_{u2}) were installed with micro-pile reinforcement using the cone installation configuration (K = 0.67B). Based on the test results, the bearing capacity improvement ratio is reviewed when the settlement is 0.1B [18]. The test results before the installation of the micro-pile obtained Rq_{ult-mp} = 1.123 for soil with undrained cohesion (c_{u1}) and Rq_{ult-mp} = 0.953 for soil with undrained cohesion (c_{u2}), as shown in Figures 8 and 9. These results indicate a match between the results of laboratory (experimental) tests without a micro-pile and Terzaghi's theory on local shear failure. This finding is also supported by previous research [18], [21].

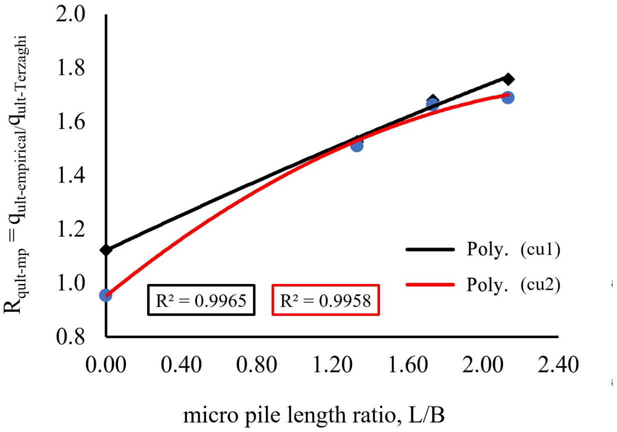

Figure 8. Relationship between "L/B" and "Rq_{ult-mp}" for n= 16; d_1/B= 0.03; K/B=0.067; with variations in c_u

Figure 8 shows a graph of the test results of the relationship between the ratio between the length of the micro bamboo pile and the width of the foundation (Li/B) to the increase with respect to the ratio of ultimate bearing capacity ($Rq_{ult-mp} = q_{ult-empirical} / q_{ult-Terzaghi,LSF}$) for the ratio of the diameter of the bamboo micropile (d1/B= 0.03), the number of bamboo micropiles (n= 16) with variations in undrained cohesion (c_u). At the same ratio of the length of the bamboo micropile (L/B) and different undrained cohesion (c_u), it can be seen that before the bamboo micropile is installed (L/B= 0) the Rq_{ult} value on the undrained cohesion soil c_{u1} is greater than Rq_{ult} on c_{u2} while when the bamboo micropile is installed the value of bearing capacity ratio at ultimate state (Rq_{ult}) on the undrained cohesion c_{u1} and c_{u2} is practically almost the same. This phenomenon is consistent with previous research, which stated that the contribution of clay soil cohesion (c_u) to foundation stability makes it more effective [29], [30].

From Figure 8, it can also be explained that the increasing length of the micro-pile (L/B) results in a larger $Rq_{ult\text{-}mp}$ for both soils with undrained cohesion c_{u1} and c_{u2}. This is because the larger "L/B" increases the area of lateral resistance, the ability to withstand lateral forces increases, so that the total soil resistance to shear also increases. It ultimately has an impact on increasing its ultimate bearing capacity ($q_{ult\text{-}empirical,\,0.1B}$) and increasing its ultimate bearing capacity ratio ($Rq_{ult\text{-}mp}$). This finding is consistent with previous studies indicating that micropile length significantly influences the increase ($Rq_{ult\text{-}mp}$) [7], [21], [31], [32].

Beyond the observed trend, the results demonstrate that bamboo micropile reinforcement alters the governing failure mechanism of shallow foundations. The increase in the L/B ratio enlarges the confined soil zone beneath the footing, thereby limiting lateral deformation and promoting a more uniform stress distribution. This confinement effect reduces the influence of undrained cohesion on bearing capacity improvement, as reflected by the convergence of $Rq_{ult\text{-}mp}$ values for different c_u conditions. Such behavior is characteristic of reinforced-soil systems, where the behavior of the foundation depends more on soil–reinforcement interaction than on the inherent soil strength, which is consistent with reinforced footing and geobag studies reported in the literature.

In Figure 9, the test results are shown, which are the micro-pile diameter ratio (d/B) to the improvement in the maximum bearing capacity ratio ($R_{qult\text{-}mp} = q_{ult\text{-}empirical}/q_{ult\text{-}Terzaghi,LSF}$) for the micro-pile length ratio (L3/B= 2.13), the total count of micro-piles (n= 16) with variations in undrained cohesion (c_u). At the same bamboo micropile diameter ratio (d/B) and different undrained cohesion (c_u), experimental results reveal that before installing the micro-pile (do/B= 0) and after installing the micro-pile, the $Rq_{ult\text{-}mp}$ value on the undrained cohesion soil c_{u1} is always greater than $R_{qult\text{-}mp}$ on c_{u2}. The enhanced maximum bearing capacity ratio ($Rq_{ult\text{-}mp}$) after the micro-pile is installed is greatest in the soil with undrained cohesion c_{u2} than in the soil with undrained cohesion c_{u1}. These results corroborate previous studies demonstrating that the contribution of clay soil cohesion (c_u) to foundation stability makes it more effective [29].

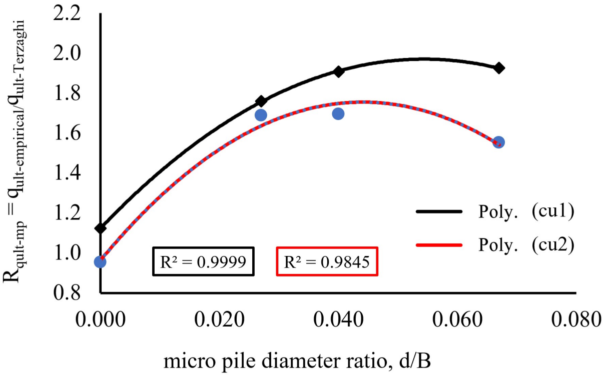

Figure 9. Relationship between "d/B" and "$Rq_{ult\text{-}mp}$" for n= 16; L_3/B= 0.03; K/B=0.067; with variations in c_u

Figure 9 shows that increasing the micro-pile diameter (d/B) results in an increase in the ratio of ultimate bearing capacity (Rq_{ult}). Nevertheless, this most optimal increase in $Rq_{ult\text{-}mp}$ occurred at a micropile diameter equivalent to 0.04B, while d > 0.04B resulted in an insignificant increase in $Rq_{ult\text{-}mp}$. However, the most optimal increase in $Rq_{ult\text{-}mp}$ occurs when the bamboo micropile diameter is 0.04B, while d > 0.04B results in an insignificant increase in $Rq_{ult\text{-}mp}$. This is because the diameter exceeds 0.04B; the micropile becomes too strong so that the shear failure is chiefly dictated by the soil's strength parameters. This phenomenon is in accordance with research results stating that micropiles are proven to promote higher ultimate bearing capacity of shallow footings over soft clay soils when the number, length, diameter, and installation position are optimized [21].

From a mechanistic perspective, the existence of an optimum micropile diameter reflects the interaction between soil confinement and stress redistribution beneath the shallow foundation. At smaller diameter ratios, increasing d/B enhances lateral confinement and mobilizes additional shaft resistance, resulting in a substantial increase in $R_{qult\text{-}mp}$. However, once the micropile diameter exceeds the critical value of approximately 0.04B, the governing failure surface develops predominantly within the surrounding soil mass rather than at the soil–micropile interface. This is in line with the results of research [33]. Consequently, further increases in micropile diameter do not significantly alter the failure mechanism or the extent of the confined soil zone. Similar behavior has been reported in reinforced foundation systems, where increasing reinforcement stiffness beyond an optimal level leads to diminishing improvements in bearing capacity because soil strength controls the ultimate failure response. This finding highlights that the bearing capacity improvement achieved by bamboo micropiles is governed by soil–structure interaction rather than by micropile strength alone.

To find out how much the increase was after the micropile was added, a comparison percentage was made between the q_{ult} ratio during the i-th test (before and after the cerucuk) with the q_{ult} ratio during the test without the micropile, as shown in Figures 10 and 11. The variation of L/B in each undrained cohesion (c_{u1} = 20,692 kN/m^2 and c_{u2} = 38,932 kN/m^2) is shown in Figure 10, and the variation of d/B in each undrained cohesion (c_{u1} and c_{u2}) is illustrated in Figure 11.

Figure 10 illustrates the relationship between the micro-pile length ratio (L/B) and the increase in the q_{ult} ratio during the i-th test (pre and post installation of the micropile) with the q_{ult} ratio when testing without the micropile in the form of % (Rq_u). As shown in Figure 10, the micropile diameter is d = 0.03B, the number of micropiles is n = 16, and the micropile configuration is K = 0.67B for both c_{u1} and c_{u2}.

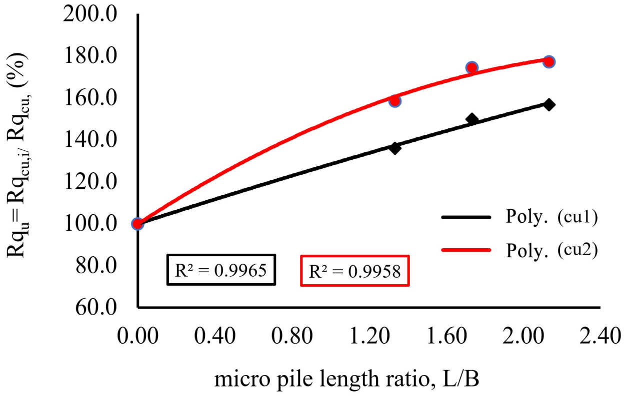

Figure 10. Relationship of L/B ratio to Rq_u, at c_{u1}; c_{u2} for d= 0.03B; n=16; K/B=0.067

In Figure 10, it can be seen that the larger L/B provides a significant improvement in the ultimate bearing capacity ratio (Rq_u). The Rq_u value at L/B = 1,3 increases to about 136% for c_{u1} soil and about 158% for c_{u2} soil, while Rq_u at L/B = 2,13 increases to about 157% for c_{u1} soil and about 177% for c_{u2} soil. This is because the longer the cone length (L/B), the wider the cone influence zone under the foundation, so that the interaction between the cone and the soil increases. However, after a certain point (L/B > 2), the improvement of foundation bearing capacity begins to slow down because the effect of increasing length is no longer significant on the shear mechanism of the soil under the foundation. From the percentage of Rq_u in the L/B variation, an average increase in Rq_u for c_{u1} is 147% and an average increase in Rq_u for c_{u2} is 170%.

The research results show that extending the foundation length relative to its width (L/B) has a direct effect on increasing the ultimate capacity up to a certain limit [34]. These findings align with previous studies on shallow foundations reinforced with bamboo micropiles, where increasing L/B will increase the maximum bearing capacity ratio (Rq_{ult}). The analysis confirms that variations in foundation geometry and the L/B ratio are key parameters that determine the effectiveness of increasing bearing capacity. Thus, in both rock and soft soil, there is an optimum limit to the length of the vertical element, where further extension no longer provides a significant increase in the bearing performance of the foundation.

Another study, based on the findings of Pham et al. [35], through three-dimensional (3D) numerical modeling of a geosynthetic-reinforced embankment system supported by piles (GRPS) system, found that soil cohesion plays a significant role in load transfer governed by soil–reinforcement interaction. A similar trend is also seen in the shallow foundation system with micro-pile reinforcement in this study, where increasing undrained cohesion causes a more even stress distribution under the foundation and a substantial enhancement in foundation load-bearing efficiency. Thus, the concept of soil-reinforcement interaction described by Pham and Dias can be used to explain the mechanism of increased bearing capacity due to increased undrained cohesion, even though the system configurations studied are different (embankment vs shallow foundation) [35].

The increase in Rq_u with increasing L/B occurs because longer micropiles enlarge the stress bulb beneath the foundation and enhance soil-pile interaction. Results from this study indicate that the maximum bearing capacity ratio (Rq_u) is presented in percentage form and calculated as the ratio of the maximum bearing resistance of shallow foundations without and using micropiles compared to that of foundations with no micropiles. Therefore, an Rq_u value greater than 100% indicates an increase in load-bearing capacity caused by the installation of micropiles. However, when L/B exceeds approximately 2, the rate of increase in Rq_u becomes smaller, indicating that the optimal micropile length has been achieved. In addition, higher undrained cohesion (c_{u2}) consistently results in higher Rq_u values due to more effective stress transfer and confinement around the micropiles.

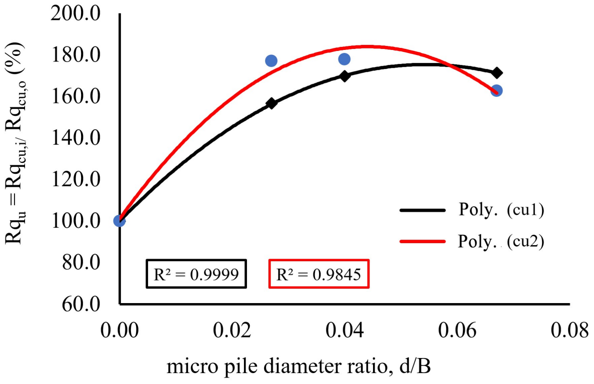

Figure 11. Relationship of d/B ratio to Rqu, at c_{u1}; c_{u2} for L= 2.13B; n=16; K/B=0.067

Figure 11 shows the relationship between the ratio of micropile diameter (d/B) and the increase in the q_{ult} ratio during the i-th test (before and after installing the micropile) with the q_{ult} ratio during the test without the micropile in the form of % (Rq_u). As shown in Figure 11, the length of the micropile is L= 2.13B, the number of micropiles is n= 16, and the micropile configuration is K= 0.67B for c_{u1} = 20,692 kN/m^2 and c_{u2} = 38,932 kN/m^2.

In Figure 11, the results indicate that when $d/B \leq 0.04$, a substantial enhancement in the maximum bearing capacity ratio occurs (Rq_u) in all c_u. However, when $d/B > 0.04$, the increase in Rq_u decreases gradually. At d = 0.04B, the Rq_u was obtained at 170% for c_{u1} and 178% for c_{u2}. When d = 0.067B, the increase in c_{u2} decreases with the Rq_u value obtained at 171% for c_{u1} and 163% for c_{u2}. Overall, c_{u2} has an average Rq_u value greater than Rq_u in c_{u1}, namely with an average Rq_u = 166% for c_{u1} and Rqc_u = 172% for c_{u2}. This phenomenon is in line with research results, which state that an increase in undrained shear strength (c_u) in cohesive soil causes a proportional increase in the ultimate load capacity of single and group micropile foundations [36], [37].

Other supporting research states that increasing undrained shear strength (c_u) can increase the bearing capacity (up to ~1.5–2 times) depending on the micropile configuration and the number of micropiles installed [38]. Experimentally, through centrifugal model tests, a similar pattern was also found, namely a rise in bearing capacity reaching about 1.8 times compared to without reinforcement [8]. This correlation strengthens the results of Figure 11, where the trend of increasing the Rq_u ratio nonlinearly follows a pattern similar to the experimental results of Li et al. [8].

Figure 11 illustrates a nonlinear dependency between the micropile diameter, the d/B ratio, and the increase in bearing capacity, which is well represented by the second-order polynomial regression curve. The high coefficient of determination (R^2= 0.9999 for c_{u1} and R^2= 0.9845 for c_{u2}) indicates that the variation of Rq_u is greatly influenced by the micropile diameter ratio, which confirms d/B as a key parameter affecting the effectiveness of micropile reinforcement.

4. Conclusions

The increase in the bearing capacity ratio ($Rq_{ult\text{-}emp}$) shows an increasing trend as the cone length ratio (L/B) increases. This indicates that the greater the L/B value, the more significant the increase in $Rq_{ult\text{-}emp}$, both in soft clay (c_{u1}) and medium clay (c_{u2}). This relationship is strengthened by the very high coefficient of determination (R^2) values, with R^2 = 0.9965 for c_{u1} and R^2 = 0.9958 for c_{u2}, respectively, thus indicating a very strong correlation between the variables. In addition, the increase in the cone diameter ratio to the foundation width (d/B) also causes an increase in $Rq_{ult\text{-}emp}$ until it reaches an optimum point at d/B = 0.04. After that, the increase tends to stabilize or slightly decrease, with R^2 values of 0.9999 for c_{u1} and 0.9845 for c_{u2}, confirming the reliability of the observed relationship. Overall, the mean percentage increase in load-bearing capacity (Rq_u) due to L/B variation is 147% in soft clay soil (c_{u1}) and 170% in medium clay soil (c_{u2}), while in d/B variation, the increase reaches around 166% for soft clay soil (c_{u1}) and 172% for medium clay soil (c_{u2}). Thus, the average value of the increase in bearing capacity (Rq_u) in L/B and d/B variations is in the range of 147–166% for soft clay soil (c_{u1}) and 170–172% for medium clay soil (c_{u2}). This shows the effectiveness of increasing the dimensions of the cerucuk on the ultimate capacity of shallow foundations in both soft and medium soils.

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