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# A Comparative Analysis of Fly Ash Enhanced Micropiles in Sustainable Foundation Systems

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## Abstract

The construction industry is increasingly pressured to adopt sustainable practices that reduce environmental impact while ensuring structural integrity. This study investigates the comparative performance and sustainability of micropiles constructed with fly ash-enhanced grout mixtures (MFA) and conventional micropiles (MC). Fly ash, an industrial by-product is incorporated into the grout mixture to improve sustainability and enhance soil-structural stability. Comprehensive site investigations and numerical simulations were conducted to evaluate critical performance metrics, including Factor of Safety (FoS), deformation, settlement, and strain distribution, during pre- and post-construction phases. The results demonstrate that MFA systems exhibit superior performance, characterized by a higher FoS reaching ~3.0, reduced deformation (less than 3.0 m), and minimized settlement (maximum of -4.2 m compared to -14.6 m in MC). These findings indicate that MFA delivers structural benefits and contributes to sustainability by utilizing waste materials. The study underscores the potential of MFA as a viable alternative to traditional micropile systems, offering significant environmental and performance advantages. Further research is recommended to assess MFA systems' long-term performance and scalability in diverse geotechnical applications.

**Keywords:** Fly Ash Micropiles, Geotechnical Engineering, Numerical Simulations, Structural Stability, Sustainable Foundation Systems

## Introduction

The construction industry is increasingly driven by the imperative to adopt sustainable practices that minimize environmental impacts while maintaining structural integrity and performance. Traditional foundation systems, such as shallow footings and driven piles, often prioritize immediate cost-efficiency and structural stability over long-term sustainability and resilience [1-3]. These conventional approaches heavily rely on materials like Ordinary Portland

Cement (OPC), which contribute significantly to greenhouse gas emissions [4-6] and face durability [7-9] challenges in aggressive environmental conditions. As global efforts intensify to reduce the carbon footprint of construction activities, the demand for innovative and sustainable foundation solutions has grown significantly.

Micropiles have emerged as an effective and versatile foundation solution for addressing various geotechnical challenges, including underpinning existing structures [10,11], stabilizing slopes [12-14], and supporting significant loads [15,16]. These small-diameter piles, typically ranging from 100 mm to 300 mm [17,18], are particularly advantageous in urban areas due to their minimal noise and vibration during installation and their adaptability to restricted access or challenging terrains [19]. Despite these benefits, conventional micropiles (MC) predominantly rely on OPC-based grout, which limits their environmental sustainability and resilience in aggressive environments.

Integrating industrial by-products, such as fly ash, into micropile grout mixtures offers a promising alternative for enhancing both performance and sustainability. Fly ash, a by-product of coal combustion, is known for its ability to improve the mechanical properties [20,21] and durability of cementitious materials while reducing their environmental impact [22,23]. Recent studies have highlighted the potential of fly ash-enhanced micropiles (MFA) to achieve superior resistance to deformation [24,25], settlement [26,27], and environmental degradation [28,29] compared to conventional counterparts.

This study aims to conduct a comparative evaluation of the mechanical and sustainability performance of micropiles enhanced with fly ash against conventional micropiles. The study seeks to determine the feasibility, efficiency, and environmental advantages of incorporating fly ash in micropile systems for foundation applications. This study focuses on evaluating the performance of MFA in comparison to MC using a combination of site investigations and advanced numerical simulations. Key performance indicators, including the Factor of Safety (FoS), deformation, settlement, and strain distribution, are assessed to quantify the benefits of MFA systems. By emphasizing both structural performance and environmental sustainability, this research contributes to the growing body of knowledge in sustainable geotechnical engineering and highlights the potential for integrating industrial by-products into foundation systems.

## Materials and Methods

### Geotechnical Characterization

A detailed site investigation was conducted at SMK Taman Ria, Sungai Petani, Kedah, Malaysia, to evaluate subsurface conditions critical to foundation design. The site was selected due to its known soft subsoil profile and embankment instability, making it a relevant location for evaluating micropile performance. The investigation comprised four boreholes and fifteen Mackintosh probes, with soil samples collected for laboratory analysis. On-site classification identified the dominant soil type as sandy silt, a fine-grained material characterized by low shear strength and high compressibility. Laboratory tests confirmed the

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geotechnical properties, including unsaturated unit weight ($\gamma_{unsat}$ = 17.00–18.50 kN/m³), saturated unit weight ($\gamma_{sat}$ = 20.00–21.70 kN/m³), and internal friction angle (φ' = 24°–32°). The high susceptibility of sandy silt to deformation under load necessitated specialized foundation solutions to mitigate settlement and instability risks.

### *Foundation System Design*

In this case study, the design of the MC followed standard engineering practices and guidelines for micropile foundation systems, as shown in Figure 1. Conversely, the MFA design incorporated fly ash into the grout mixture to enhance performance and sustainability. Micropiles are commonly used in foundation systems to stabilize embankments and earth slopes. MC typically uses Ordinary Portland Cement (OPC) in their mix. However, integrating fly ash into micropile designs offers potential advantages in terms of durability, sustainability, and overall performance.

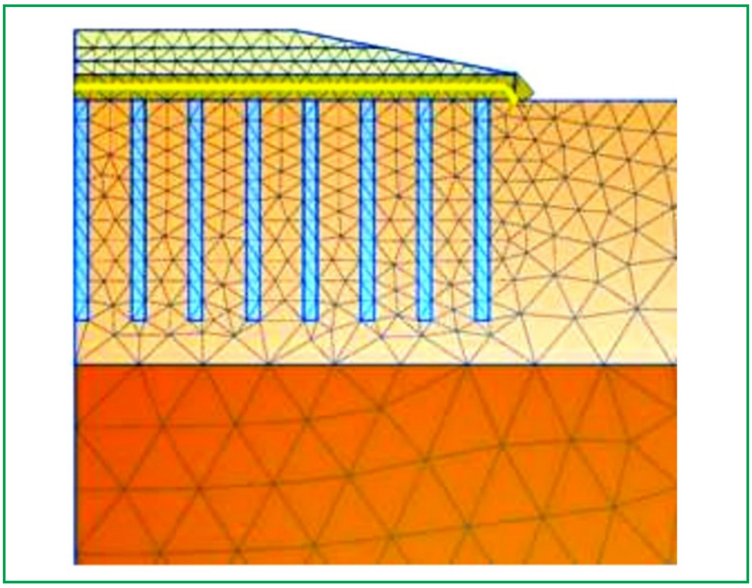

**Figure 1.** 2D numerical design of embankment with micropiles

MFA offers enhanced durability and performance, particularly in aggressive environments. The resistance to sulfate attack and improved pullout capacity makes them a superior choice for challenging soil conditions and aggressive environments, as supported by recent studies [28]. The use of fly ash contributes to sustainability goals by reducing the reliance on OPC and minimizing environmental impact. This aligns with modern construction practices that emphasize reducing carbon footprints and using sustainable materials.

While the initial cost of MFA may be higher due to material costs, the long-term benefits such as increased durability and reduced maintenance can lead to overall cost savings. Improved performance in aggressive soils and environments can further offset initial expenses [30,31]. The MFA design offers several advantages over MC, including increased durability, better performance in aggressive conditions, improved pullout capacity, and sustainability benefits.

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These improvements make the MFA design a compelling choice for enhancing embankment stability and addressing the challenges posed by soft soils and aggressive environments.

### Numerical Simulation Framework

Numerical simulations were conducted using PLAXIS 2D, a well-established finite element software for geotechnical analysis. The simulation aimed to model the embankment behavior under both pre-construction and post-construction phases over a duration of approximately 9,130 days (~25 years). Table 1 summarizes the properties of embankment soil modeled using the Mohr-Coulomb model under drained conditions. This includes critical parameters such as unit weight, stiffness, cohesion, and internal friction angle, all essential for capturing slope and foundation behavior under load.

**Table 1.** Embankment parameter properties

| Soil Model | Drainage Type | $\gamma_{unsat}$ (kN/m³) | $\gamma_{sat}$ (kN/m³) | $E'_{ref}$ (kN/m³) | $\nu$ | $C'_{ref}$ (kN/m$_2$) | $\varphi'$ (º) |
|---|---|---|---|---|---|---|---|
| Mohr- Coulomb | Drained | 18.28 | 23.5 | 6.51 x $10^6$ | 0.35 | 14 | 31.9 |

**Table 2.** Soft soil parameter properties

| Layer | Soil Model | Drainage Type | $\gamma_{unsat}$ (kN/m³) | $\gamma_{sat}$ (kN/m³) | $\lambda^*$ | $k^*$ | $C'_{ref}$ (kN/m$_2$) | $\varphi'$ (º) |
|---|---|---|---|---|---|---|---|---|
| 1 | Soft Soil | Undrained | 17 | 20 | 0.12 | 6 x $10^{-3}$ | 20 | 24 |
| 2 | Soft Soil | Undrained | 18.5 | 21.7 | 0.12 | 6 x $10^{-3}$ | 25 | 32 |

Numerical simulations were conducted using PLAXIS 2D, a well-established finite element software for geotechnical analysis. The simulation aimed to model the embankment behavior under both pre-construction and post-construction phases over a duration of approximately 9,130 days (~25 years). Table 1 summarizes the properties of embankment soil modeled using the Mohr-Coulomb model under drained conditions. This includes critical parameters such as unit weight, stiffness, cohesion, and internal friction angle, all essential for capturing slope and foundation behavior under load.

**Table 3.** Micropiles parameter properties

| Improvement method | Soil Model | Drainage Type | $\gamma_{unsat}$ (kN/m³) | $\gamma_{sat}$ (kN/m³) | $E'_{ref}$ (kN/m³) | $\nu$ |
|---|---|---|---|---|---|---|
| Conventional | Linear Elastic | Non-porous | 24.5 | 24.5 | 24 x $10^6$ | 0.2 |
| Innovation | Linear Elastic | Non-porous | 14.4 | 14.4 | 24 x $10^6$ | 0.4 |

Table 4 outlines the properties of the sand cushion layer, which plays a key role in load distribution between the embankment and the micropile elements. The Mohr-Coulomb model was used here as well, with drained conditions applied to simulate realistic pore pressure dissipation during loading.

The innovative micropiles were modeled using an elastic soil model with axial stiffness (EA) of 700 kN/m, indicating their high resistance to deformation

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**Table 4.** Sand cushion parameter properties

| Soil Model | Drainage Type | $\gamma_{unsat}$ (kN/m³) | $\gamma_{sat}$ (kN/m³) | $E'_{ref}$ (kN/m³) | $\nu$ | $C'_{ref}$ (kN/m$_2$) | φ′ (º) |
|---|---|---|---|---|---|---|---|
| Mohr- Coulomb | Drained | 17 | 20 | 13 x $10^3$ | 0.3 | 1 | 31 |

under axial loads. The EA value indicates the micropile's rigidity in resisting deformation under axial loads. Figure 2 shows the numerical simulation flow. First, the project parameters, such as model dimensions and unit system, were defined according to the project specifications. At the same time, material properties were configured accurately to ensure the simulation closely replicated real-world behaviour, thus providing reliable results.

Based on data collected from various research studies, two soil layers were created in the model, and the input of relevant soil properties for each layer was used. Moreover, materials for the geotextile, MC, MFA, and sand cushion had been defined with specific properties such as stiffness and unit weight. The geometry model had been constructed to include the embankment, micropiles, geotextile, and sand cushion layers, followed by meshing to capture the foundation system's details. Boundary conditions had been applied, with fixed boundaries simulating bedrock and roller boundaries allowing vertical movement. Initial stresses had been generated based on soil properties.

Flow conditions had been set to establish initial groundwater levels and pore pressure distribution. During construction, flow conditions had been adjusted for temporary changes due to drilling and grouting. In the loading phase, applied loads and resulting pore water pressures were considered, which helped evaluate micropile performance. Furthermore, long-term analysis assessed the foundation system's behaviour under sustained loads and environmental conditions, focusing on groundwater flow and the chemical stability of the fly ash-improved grout mixture. The simulation accurately predicted the performance and durability of the fly ash-improved micropiles. Finally, results were analyzed for displacement, stress distribution, and safety factors under applied loads.

The proposed foundation systems underwent evaluation and were compared to MC using established criteria, including stability analysis, deformation analysis, consolidation analysis, and cartesian strains. Numerical simulations were employed to analyze the performance metrics of both systems. This included graphical representations of the safety factor before and after construction for both MC and MFA methods. Besides, displacement analysis involved observing both models' values along the x-axis- and y-axis. In a long-term assessment over 25 years, minimum and maximum displacements were recorded for both MC and MFA methods to determine which model better-controlled displacement. In addition, cartesian strains pre-construction and post-construction were compared, along with major and minor strains, focusing on lower strain magnitudes between the MC and MFA methods. The total stress under applied loads and pore pressure management effectiveness before and after construction were also compared between the two methods.

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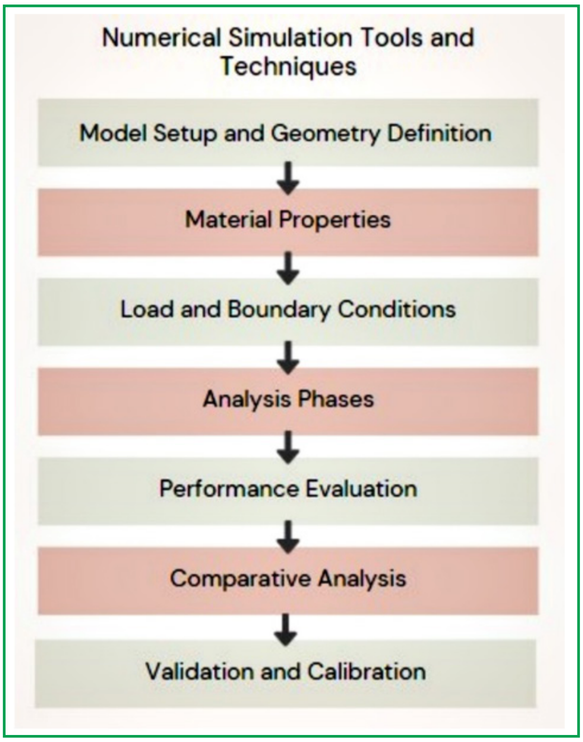



**Figure 2.** Numerical simulation procedures

## Results and Discussion

### Factor of Safety Analysis

The FoS serves as a fundamental criterion in evaluating the stability and reliability of micropile foundation systems. As illustrated in Figure 3, the pre-construction phase exhibits a generally higher FoS for conventional micropiles (MC) and fly ash-enhanced micropiles (MFA). Notably, MFA demonstrates superior and more consistent safety margins compared to MC, with peak values reaching approximately 3.0.

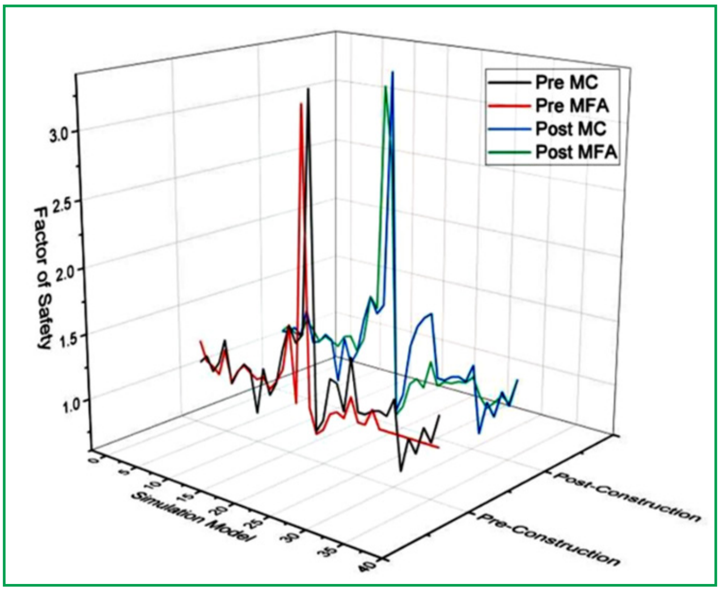


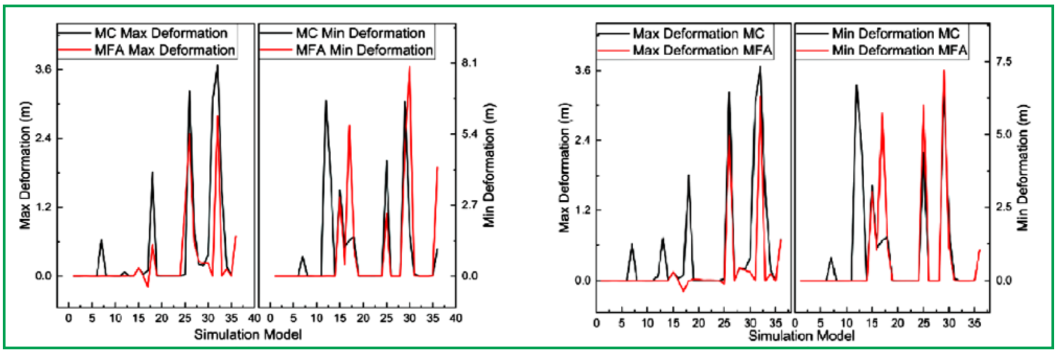

**Figure 3.** FoS of MC and MFA at pre-construction and post-construction

Following construction, both systems experience a reduction in the FoS; however, MFA maintains a slightly higher and more stable safety factor relative to MC. This trend indicates that while structural safety diminishes post-construction due to imposed loads and settlement effects, MFA provides enhanced resilience and stability over time. These findings underscore the structural advantages of incorporating fly ash into micropile designs, particularly in applications where long-term safety is critical.

### *Deformation Analysis*

Structural deformation is a key indicator of foundation performance. Figure 4(a) presents deformation trends during the pre-construction phase, revealing that MC exhibits significantly higher maximum deformation values than MFA. Peaks exceeding 3.0 meters are observed in MC models, suggesting greater susceptibility to structural displacement. In contrast, MFA micropiles demonstrate a more stable deformation profile with reduced maximum displacement, reinforcing their potential for enhanced structural integrity.

In the post-construction phase, depicted in Figure 4(b), both micropile types experience increased deformation due to load application and settlement. However, MFA consistently shows lower and more uniform deformation values, minimizing risks associated with excessive movement [24]. The reduced variability in MFA deformation highlights their effectiveness in mitigating structural instability, particularly in challenging soil conditions.




(a) (b)

**Figure 4.** Deformation analysis at (a) pre-construction and (b) post-construction

### *Settlement Analysis*

Settlement behavior is another critical factor influencing the long-term stability of foundation systems. Figure 5(a) presents settlement trends during the pre-construction phase, indicating that both MC and MFA undergo settlement. However, MFA exhibits lower settlement values across all measured parameters, suggesting improved load distribution and soil reinforcement.

In the post-construction phase, illustrated in Figure 5(b), MC experiences pronounced settlement variations, with maximum settlement values reaching approximately -4.2 meters and minimum settlement exceeding -14.6 meters. Conversely, MFA demonstrates significantly reduced settlement magnitudes and

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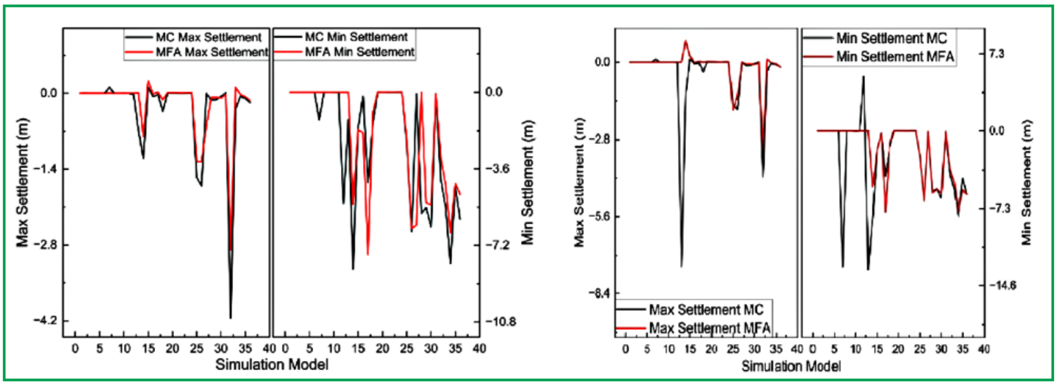


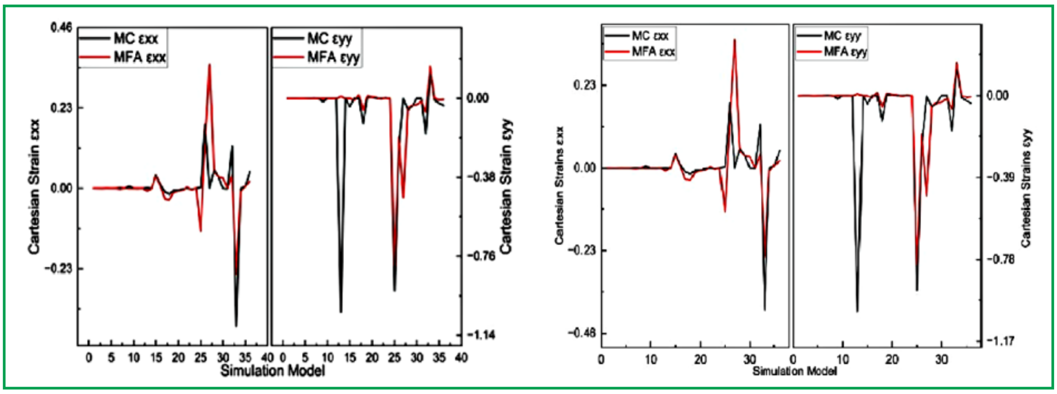

(a) (b)

**Figure 5.** Settlement analysis at (a) pre-construction and (b) post-construction

more consistent behavior. This suggests that fly ash incorporation enhances the micropile's capacity to counteract soil displacement, ultimately reducing the likelihood of differential settlement and associated structural damage.

### *Cartesian Strain Analysis*

Cartesian strain distribution offers insight into the internal stress behavior of micropiles. Figure 6(a) illustrates strain variations during the pre-construction phase, revealing that MFA maintains lower and more stable strain values than MC. This trend is particularly evident in the εyy component, where MC exhibits substantial fluctuations, reaching strain magnitudes below -1.14 [32]. The increased strain concentration in MC may indicate localized stress accumulation, which could compromise long-term structural performance.




(a) (b)

**Figure 6.** Cartesian strains analysis at (a) pre-construction and (b) post-construction

Post-construction strain distributions, depicted in Figure 6(b), reinforce these observations. MFA continues to demonstrate reduced strain variability, minimizing stress concentrations and enhancing overall load-bearing efficiency. The consistent strain response observed in MFA suggests improved adaptability to external forces, further validating their superiority in maintaining foundation stability.

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### Comparative Analysis

The simulation results emphasize the structural and sustainability advantages of MFA compared to conventional MC. Notably, MFA exhibits a consistently higher and more stable FoS, ensuring greater structural reliability and reducing the likelihood of failure [28]. Additionally, the reduced deformation observed in MFA indicates superior resistance to displacement, thereby enhancing overall structural integrity under varying load conditions [24]. The minimized settlement further reinforces their effectiveness in mitigating excessive ground subsidence, critical for maintaining long-term foundation stability. Moreover, the improved strain distribution, characterized by lower strain magnitudes, highlights the enhanced durability and optimized stress management offered by MFA.

These findings collectively establish MFA as a structurally viable and sustainable alternative to conventional micropile systems. The incorporation of fly ash enhances mechanical performance and aligns with environmentally sustainable construction practices by promoting waste utilization and reducing reliance on conventional materials. This dual benefit positions MFA as a promising innovation for resilient foundation systems, offering a practical solution that integrates enhanced geotechnical performance with sustainability objectives.

## Conclusion

This study compares MFA against MC in foundation engineering, emphasizing structural integrity and sustainability. The main conclusion are as follows:

1. MFA micropiles demonstrated higher and more stable FoS compared to conventional micro piles.
2. Deformation and settlement were significantly reduced in MFA systems.
3. Cartesian strain analysis revealed enhanced load distribution in MFA designs.
4. Integration of fly ash contributes to durability and sustainability.
5. MFA systems align with environmental objectives by utilizing industrial by-products.

Considering the current cost of fly ash (often being a by-product), its increasing availability, and the adaptability of micropile construction techniques, the MFA system presents promising scalability for large infrastructure projects. However, regional availability and the need for quality control in fly ash composition should be accounted for. With appropriate training and guidelines, the implementation can be carried out efficiently using existing geotechnical engineering expertise.

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## Conflicts of Interest

The authors declare no conflicts of interest.

## Author Contributions

**Rufaizal Che Mamat:** conceptualization, methodology, supervision. **Azuin Ramli:** data curation, writing-original draft preparation. **Abd Hakim Abd Aziz:** visualization, investigation. **Muhammad Daniel Hakim Azhari:** software. **Angelyna Jackson:** software, validation, writing-reviewing and editing.

## Data Availability Statement

The data used to support the findings of this study are included within the article.

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