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Enhancing the performance of boundary footing of a renovated building using micropiles: Numerical and Site Visual Assessment

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ABSTRACT

Reconstruction and building extensions have become popular trends, even being recognized as one of the most appropriate options for homes, especially in high population density areas or crowded cities. Due to the changes in the size of buildings (by applying additional loads), the existing foundations themselves are incapable of resisting extra stresses. Therefore, it is imperative to increase the bearing capacity as well as the overall stability of existing foundations. The paper aims to present a numerical case study on the use of micropile elements for enhancing the performance of the boundary footing of a renovated building in terms of bearing capacity and stability. Moreover, the effect of cohesionless soil types on the bearing capacity of boundary foundations was presented. Numerically calculated results show that the stability of the boundary footing, presented in terms of the safety factor, was increased as strengthened by micropiles. The bearing capacity ratio (BCR) of the boundary footing was significantly improved when the relative distance (S) between the micropile and the boundary footing decreased, and the length of micropiles (L) increased; however, the BCR rose as the micropile's angle (β) with respect to the vertical increase. In other words, the performance of the foundation underneath the boundary footing was significantly affected by some micropile parameters, including length, inclination, and the distance between the micropile and the boundary footing. These crucial factors must be carefully examined during the design of the micropiles' configuration for strengthening the boundary footing. Lastly, the load-carrying capacity improvement of the loose sand using micropiles was found to be more significant than that of denser ones.

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1. Introduction

Micropile technique was originally used to strengthen building's foundations in the 1950's in Italy (Bruce et al., 1997). To date, this technique has been widely used as supporting structural elements that receive applied loads directly, or as load-bearing elements to strengthen the ground in situ. The wide use of the micropile techniques, especially in increasing soil bearing capacity as well as the overall stability of foundations, is because of their minimum interference to existing structures, and their small diameter which enables them to be placed or 're-cast on substrates with better characteristics' through the inside of the old building, their low levels of vibration which allows them to be conducted via the old structure (Bhattacharjee et al., 2011; Bruce et al., 1997). These advantages have increased the adoption of the micro piling technique in the renovation, and rehabilitation work on old buildings in recent years. The only drawback of the micro piling technique is its relatively high cost as compared to other conventional piling systems (Bruce et al., 1997; Juran et al., 1999).

In Vietnam, the micro piling technique has mostly been used for the deep foundation, wall retaining, slope stabilization, and rehabilitation of bridges (Vietnam Ministry of Transport, 2016; Xiang et al., 2015). However, the use of micro piling technique in restoration work on old buildings is still rare. This will unable us to preserve the old buildings or heritage, and protect them from harmful activities, such as dynamic loads, and upgrading the size of the building. The present work is designed to assess a practical case of the use of micro piles in enhancing the performance of boundary footings, which is presented in terms of bearing capacity and overall stability of the foundation of an old building while renovated.

2. Presentation of case study

The present investigation was conducted on a selected storey building located in Halong city, Quang Ninh province. The building was constructed in 2000 and initially reached 12 m height above the ground. One new storey was added in 2020, giving the building 16 m in height. The building's original structural elements were strengthened to be able to carry the additional load of the new storey. The present study was carried out to evaluate the new foundation design approach, in which the micropiles were used to improve the bearing capacity of and the overall stability of the boundary footings. Additionally, the effects of micropile foundation parameters and soil types were examined using numerical approach.

2.1. Soil characteristics

The ground condition was investigated using the standard penetration (SPT test) with a borehole length of 16.5 m (from a surface level of 44.50÷28.00). Due to small areas with limited access and low headroom interiors, the SPT test was carried out in the vicinity of the study building with the location of the borehole of 2 m far from the building. According to soil investigation report (Report on soil investigation., 2019), within 10 m depth under the footing, the average SPT value of soil mass was 20, and the soil was found to be mainly firm clay with its frictional angle of 20^0, unit weight of 19.6 kN/m^3, and void ratio of 0.63 as summarized in Table 1. The geotechnical investigation also found that there was no groundwater table below the boundary footings by the time of the investigation.

Table 1. Physical and mechanical properties

Descriptions	Unit	Values
Specific gravity, Gs	kN/m^3	2.71
Void ratio, e	-	0.63
Saturated unit weight	kN/m^3	20.3
Dry unit weight	kN/m^3	19.6
Friction angle	Degree	20
Cohesion	kPa	18
Deformation Modulus, E	kN/m^2	6E+4
Poisson's ratio	-	0.25

2.2. Primarily bearing capacity assessment

The isolated footing was initially designed for the boundary foundation of the study building with its size of (1.8x1.8) m. According to inspection data on the renovated building, the magnitude of load on the most heavily loaded footing was about 550 kN, hence the ground under the footing was subjected to a pressure of 137.5 kPa. However, after reconstructed and renovated, the maximum load was about 650 kN (162.5 kPa in pressure), whereas the average safe bearing stress of the ground estimated based on Terzaghi and FEM methods was about 130.0 kPa, corresponding with the required factor of safety for reconstructed stage of 3.0 (Terzaghi et al., 1996) as shown in Figure 1.

In addition, due to the changes in size of ground conditions, the boundary of the study building was both narrowed and lowered from the current level of +44.5÷+42.00 as shown in Figures 2a, b. Accordingly, the boundary footings of the reconstructed building required strengthening, even under the current loads. The plan of the foundation of the study building and typical cross-section of boundary footings using micropile is shown in Figures 2a and 2b.

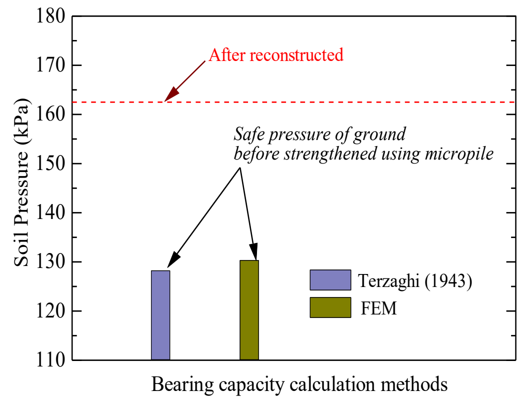

Figure 1. Soil pressure under the boundary footing before and after reconstructed.

2.3. Design method for stability analysis

To strengthen the boundary footings of the building, micropile elements were applied. The micropiles were designed with a 220 mm in diameter using 4D18 solid steel bars. Neat cement

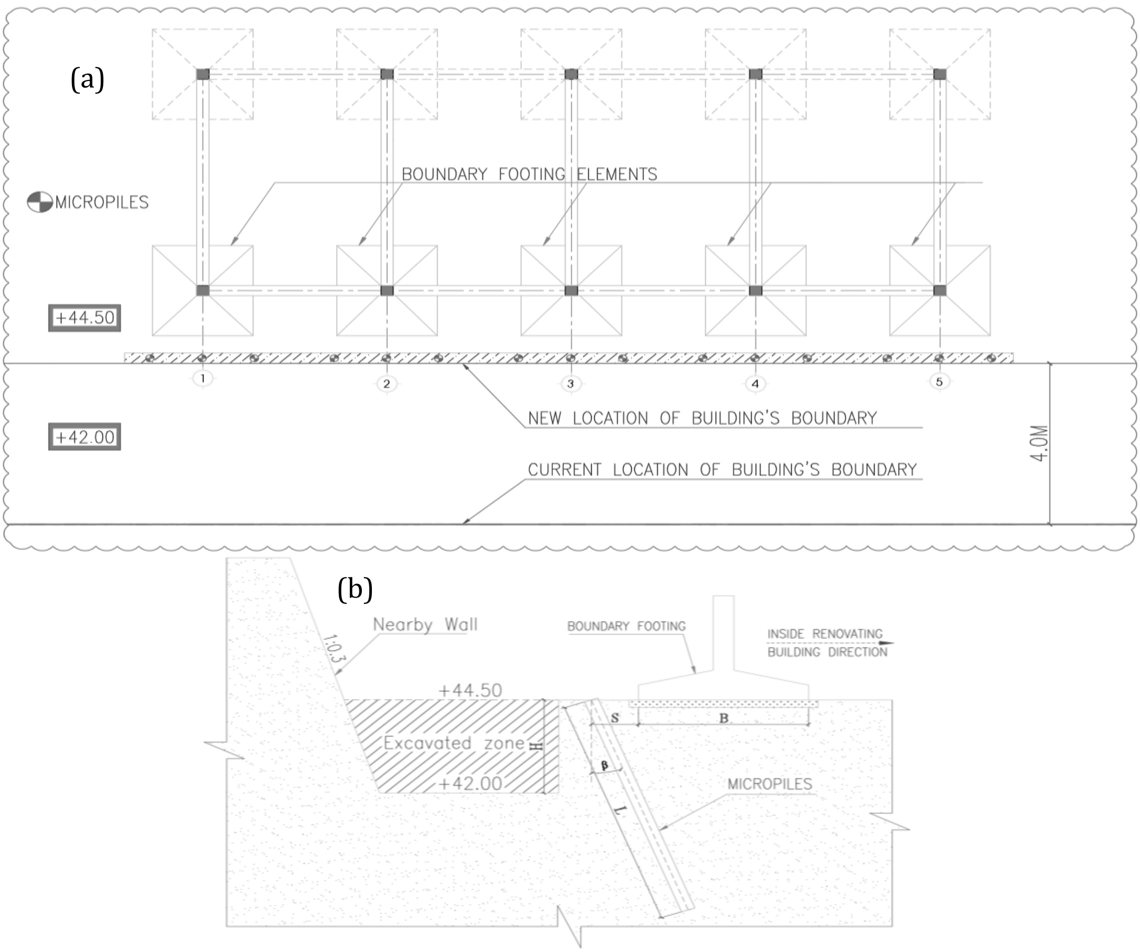

Figure 2. (a) Layout plan of foundation; (b) Cross-section of boundary footing after strengthened.

grout with its ratio of water to Portland cement of 0.4 by weight was injected into the drilled hole under a gravity head. A capping beam made of reinforce concrete was designed to tie all the micropile elements together, to prevent or inhibit lateral displacement of the installed retaining piles (or known as "thin-wall (Liu et al., 2021; Momeni et al., 2015)) during the excavation process nearby the boundary footings. From this design concept, the effects of several key factors on the performance of reinforced foundation below the boundary footings were analyzed. Figure 3 presents the details of micropiles and construction activities of micropiles in the study building.

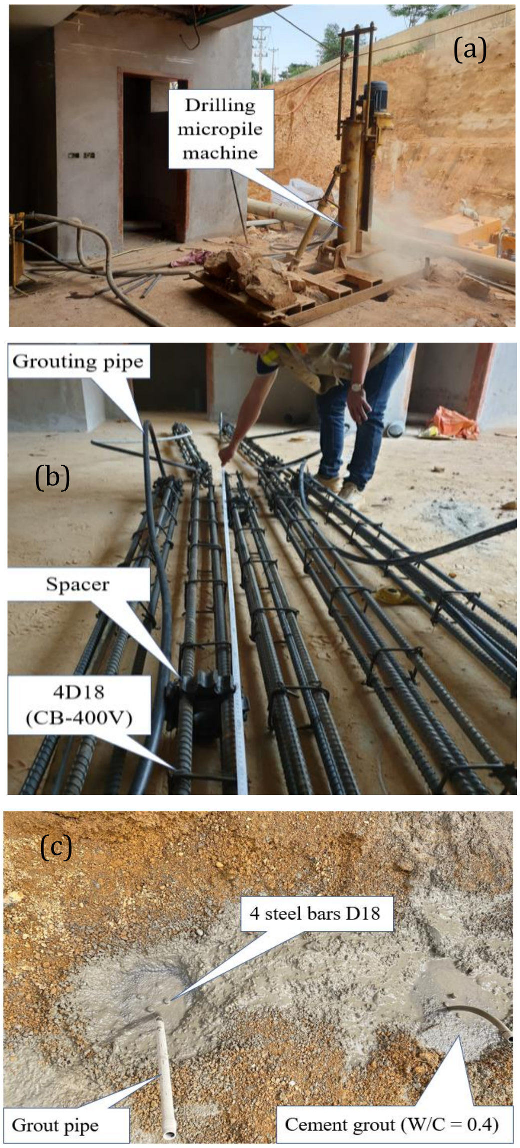

Figure 3. Design and construction of micropiles at the study building.

3. Finite Element Analysis (FEA)

The footing and proposed micropiles were modeled for the purpose of estimating the bearing capacity improvement of the boundary footing, and the stability of foundation below the footing as surface ground outside the building was lowered from level of +44.50÷+42.00. The computer program Plaxis 2D was used in the analysis, a two dimensional plane strain model was implemented with fifteen nodes of triangular elements. Geometry model, mesh generation and boundary conditions are displayed in Figure 4; in which, the average element size was 612.95*10^{-3}m and default boundary conditions were automatically applied. The micropile behavior was assumed to be linear elastic and the soil behavior was described by the Mohr-Coulomb model. Table 2 lists the parameters that were used for the boundary footings and the micropiles. In the FEA, the footing and micropile were modeled as plate elements and these plates were capable of resisting moment and shear forces based on their flexural rigidity (EI).

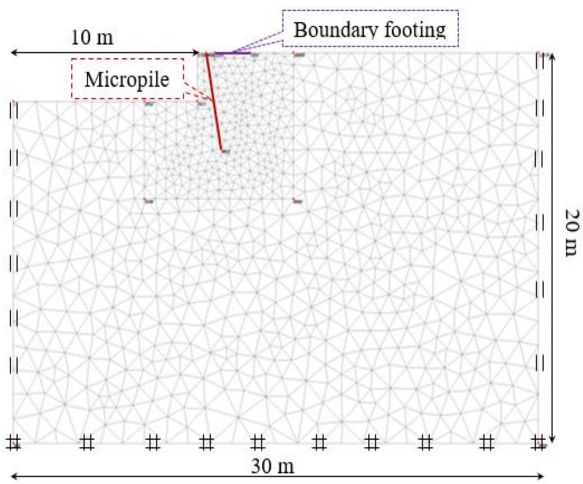

Figure 4. Geometry model, mesh generation, and boundary conditions.

Table 2. Materials properties of structural elements used in FE analysis.

Materials	EA (kN/m)	EI (kNm^2/m)
Micropile (D220)	3.8E+5	1.15E+3
Footing	3.4E+5	8.5E+3

4. Results and Discussions

To assess the effective installation of micropiles in enhancing the performance of the boundary footings, both bearing capacity improvement and overall stability of foundation were taken into account, because these two aspects are the major concerns of any geotechnical engineering project, especially in ground improvement using micropiling technique and the foundation placing nearby a vertical cut slope (Bhattacharjee et al., 2011; Esmaeili et al., 2013). A non-dimenional parameter of bearing capacity improvement ratio, says BCR, is widely used to investigate quantitative analysis. BCR is defined as ratio of bearing capacity of reinforced foundation, Q_r, to that of unreinforced foundation, Q_0, (Bhattacharjee et al., 2011; Hwang et al., 2017):

$$BCR = Q_r/Q_0 \qquad (1)$$

4.1. Bearing capacity improvement analysis

The assessment of load-carrying capacity of foundation is an imperative factor in the design of any structures, especially for the case in which shallow foundation rests on slope or near the proposed excavation (Raj and Bharathi, 2013). As the study building is adjacent to a sloping ground, consequently, the bearing capacity analysis was firstly estimated. Figure 5 shows the effect of excavation and micropile installation on the bearing capacity of boundary footings.

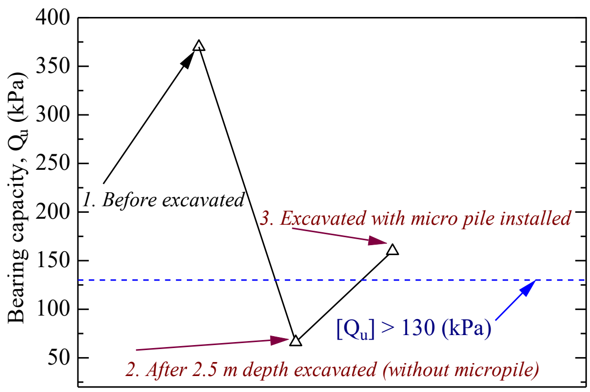

Figure 5. Effect of excavation and micropile installation on bearing capacity.

Numerical calculation results indicate that the load bearing capacity of foundation below the boundary footing remarkably decreased as the original plain ground was lowered by 2.5 m in depth. The value of bearing capacity of foundation before and after excavated were 370 kPa, and 66.5 kPa, respectively. The value of 66.5 kPa is much less than the required safe one, [Qu], of 130 kPa. The decrease in bearing capacity is accredited to the size of passive resistance zone. As excavated, the zone of passive resistance is reduced, and hence, less resistance towards failure may be offered by the soil mass located towards the retaining wall face (Acharyya and Dey, 2017). However, as the micropile element is vertically installed beside the boundary footing, the bearing capacity improves and reaches a value of more than 160 kPa which meets the safe design value. The improvement of bearing capacity of foundation as micropile installed is attributed to the formation of a thin-wall made of micropile elements with average design spacing of 2.5D where D is micropile diameter. This numerical calculation result is supported by previous studies which found that providing thin walls for shallow foundations could increase bearing capacity of the foundation by an improvement factor in the range of 11.2% to 70%, also raise the entirety depth of failure, failure pattern, and mobilize more shear strength (Al-Aghbari and Dutta, 2008; Al-Aghbari and Mohamedzein, 2004; Momeni et al., 2015).

The following subsections are designed to assess the effects of ratios of S/B, L/H, and inclination of micropiles on the changes in bearing capcity of the foundation below the boundary footings; where S, B, L are shown in the Figure 2b, H is the depth of excavation of the boundary excavated wall.

4.1.1. Influence of distance, S

Figure 6 exhibits the numerical analyses of bearing capacity improvement at different ratios of S/B, where S is the distance from the boundary footing to the micropile, B is the width of boundary footing. The calculated results show that the smaller values of S/B were , the higher bearing capacity achieved, and the maximum value of the bearing capacity was found at the S/B ratio of 0.25. The tendency of increasing in bearing capacity is accredited to the soil confining effect as the micropile was installed close to the boundary footing. Conducting an experimental

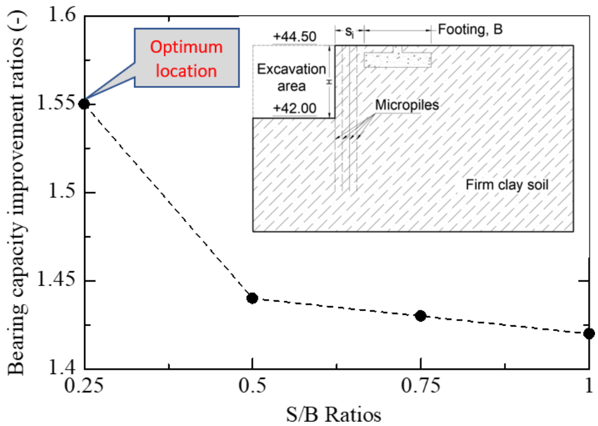

Figure 6. Effect of S/B on BCR.

research to examine the improvement of square footing using micropile, Bhattachrjee et al in 2011 have found that once the micropiles were installed next to a footing, the lateral movement of soil mass below the footing was resisted, which increased the nearing capacity of improved soil mass underneath the footing (Bhattacharjee et al., 2011).

4.1.2. Influence of the micropile inclination

Comparing to conventional piling works, micropile could be installed at various angle (Juran et al., 1999), so this section is designed to estimate the effect of micropile slope on the improvement of foundation below the boundary footing. The angles of micropiles were 0, 15, 30, and 45 degrees; meanwhile the distance between piles and the boundary footing (S parameter) was 1.0 m (S/B ratio of 0.25 yields the maximum value of bearing capacity improvement) as shown in Figure 7a. It can be seen from Figure 7b that the improvement in bearing capacity increases as the micropile inclination increases. This result is accredited to the fact that as micropile is inclined, it can carry more loads because of the downward component of the pile's axial force.

Another reason which contributes to the increase in bearing capacity is due to the confining effects (Bhattacharjee et al., 2011). To be more specific, the bigger slopes of pile is, the more restrained the settlement of footing and subsequently enhance the bearing capacity of micropiled footing system.

4.1.3. Influence of micropile length

Figure 8 presents the improvement the in bearing capacity of the foundation under the boundary footings with the increase in the length of micropile (at S/B = 0.25) . The results indicate that the use of longer piles (or higher value of L/H) yielded higher value of BCR, however, after the L/H reached values of larger than 2.5, the improvement was found not to be significant. This is because the longer piles generate a more horizontal restrain effects comparing to shorter ones (Hwang et al., 2017; Lee et al., 2016). It is noted that once the pile reaches maximum value of its length, the increase in length will not contribute much on the bearing capacity of the foundation.

4.2. Safety Analysis

Because the current level of ground around the boundary footings was lowered by 2.5 m in depth, so it is necessary to estimate stability of the foundation. From the calculated safety factor, it can be stated that the value of factor safety after excavation without using micropile of just about 1.2 was less than the recommended value of 1.5 Thus, the analysis was continued by considering the use of micropile to achieve the recommended safety factor.

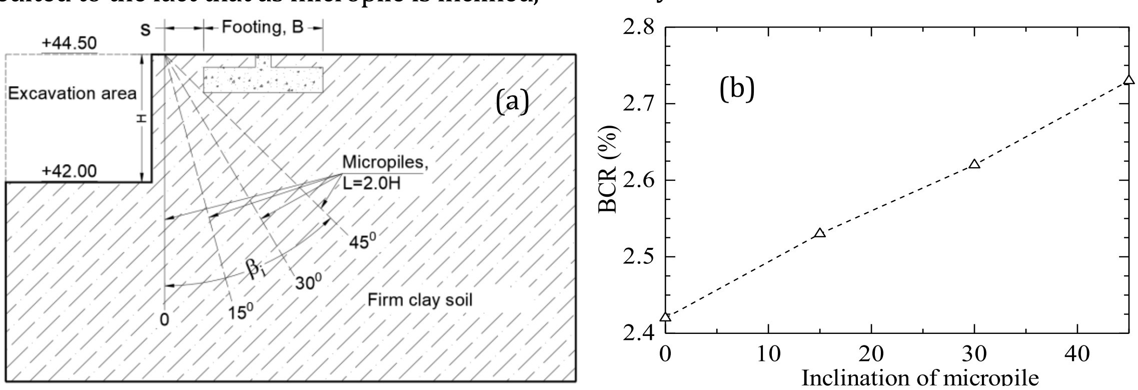

Figure 7. Effect of pile slopes on BCR.

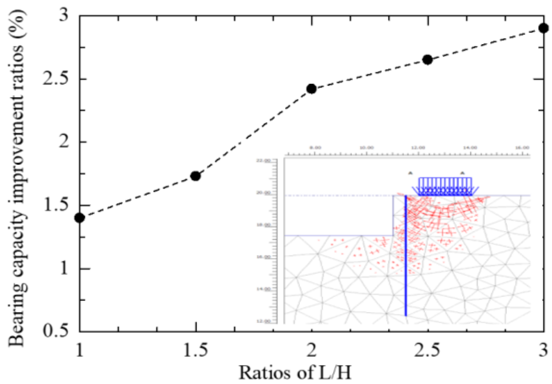

Figure 8. Effect of pile length on BCR.

The numerical outputs in the Figure 9a show that the safety factor of the foundation before excavation was 3.5; however, it significantly decreased after being narrowed and lowered. To specify, the values of FS were 1.15 and 1.75 for the cases of without and with micropile support, respectively.

Figures 9b and 9c indicate the failure mechanism of foundation on horizontal ground surface (before excavated) and on vertical slope (the state of boundary footing after being narrowed and lowered). The former one shows that the foundation was found to undergo general shear failure under the action of vertical loading applied on the boundary footings. However, an asymmetric failure mechanism in the side of boundary footing was found in the latter one, which resulted in a reduced stability of the foundation below the boundary footing. It is worth to note that the outward movement of the shear failure in the case of having micropile is restricted, this phenomena leads to the soil below the boundary footing to be compacted as shown in Figure 9d.

Figure 10 shows the site visual assessment of the stability of the building after its ground level was narrowed and lowered. This presents the effectiveness of the stability method for the foundation under the boundary footings. Some key details of the design method for improving the performance of the foundation underneath the boundary footings in this study are L=5.0 m, S=1.0 m, and β=0.

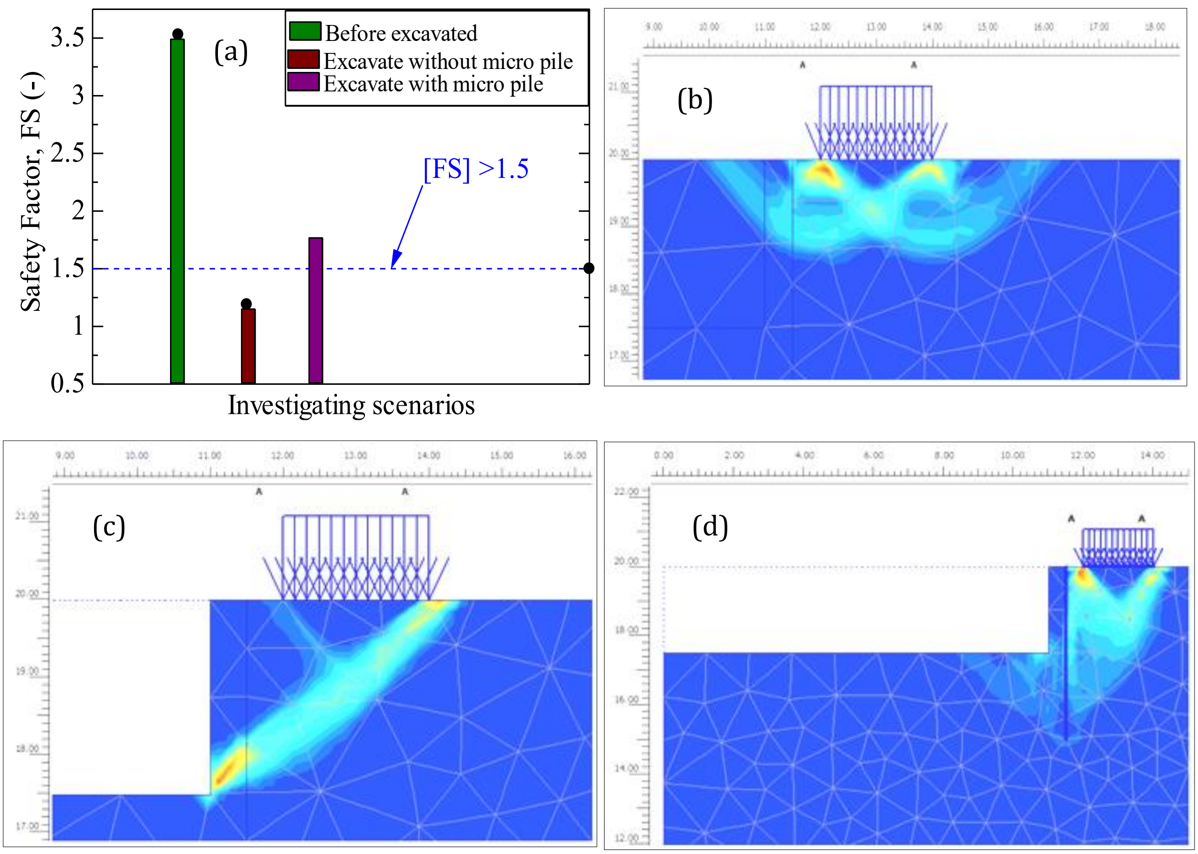

Figure 9. Stability analysis result of the foundation below the boundary footing.

4.3. Influence of stiffness of soil mass below the footing

According to the results of the numerical analyses shown in Figure 11, the influence of the improvement using micropile seems to be more considerable for soil with E of (10÷20) MPa.

A similar result was found with other cases using different sandy soil types with their typical properties shown in Table 3, such as loose sand, medium sand, and dense sand. The bearing capacity improvement ratios for loose, medium, and dense sand were 1.45, 1.15, and 1.1, respectively.

Table 3. Properties of sandy soils using in FEA.

Factors	Unit	Loose	Medium	Dense
γ_sat	g/cm3	1.97	2.1	2.2
γ_dry	g/cm3	1.53	1.75	2.1
φ	Degree	25	30	36
c	kPa	7	7	7
E	kPa	$2x10^4$	$4x10^4$	$8x10^4$

From these numerical results, it could be stated that the improvement of the soil using micropiles is more effective for weak soil layers. In other words, the soil reinforcement using micropiles is beneficial for weak and soft subgrade soils supporting the footing loads. This finding is similar to what has been reported by several research works (Hwang et al., 2017; Juran et al., 1999; Shah et al., 2021)

5. Summary and Conclusions

This paper presents the results of numerical analysis and site visual assessment of the performance of a boundary footing reinforced with micropiles.

The primary findings of the research are summarized as follows:

First, the placement of a micropile row along the boundary footings could enhance the performance of the foundation below the boundary footings, such as their general stability and bearing capacity;

Second, the improvement of bearing capacity of foundation strengthening by micropiles is

Figure 10. Site visual assessment of stability of the building after excavated.

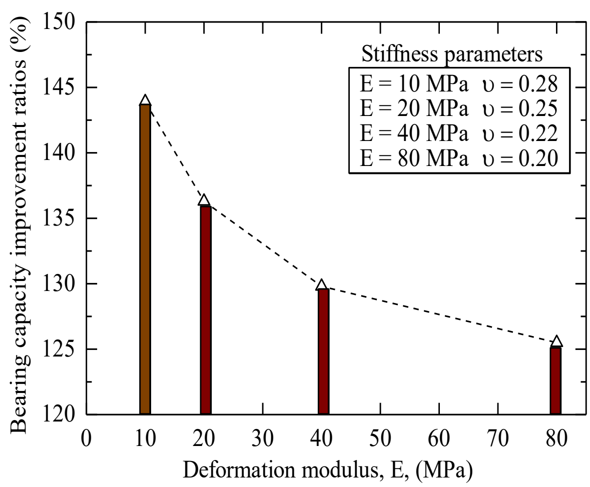

Figure 11. Effect of stiffness parameters on BCR.

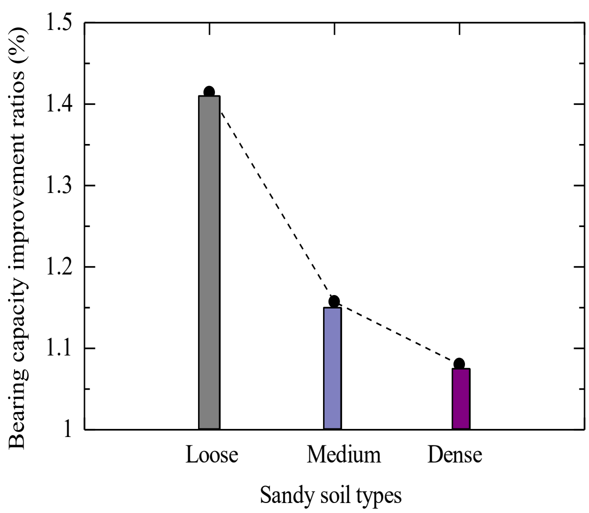

Figure 12. Effect of soil types on BCR.

found to be more effective for weaker soils than stiffer ones;

Last, the enhancement in the bearing capacity is a function of several factors, such as length, inclination, and the distance between the micropile pile, and the boundary footing. Care should be paid to these parameters once using micropiles to strengthen the boundary footings.

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Author contributions

Bui Van Duc - propose idea, conception, data analysis and draft the article; Manh Van Nguyen, Nhan Thi Pham, Thang Anh Bui, Trong Dang Nguyen - methodology and give a critical review during writing the first draft; Piotr Osinski, Benedic Tatiana - collected documents, data. All authors declare no conflict of interest

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