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Strengthening AL-Kadhimin Tilted Minaret by Using a System of Micro-piles

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Abstract In this study, a strengthening system to control a tilt of about 80cm from vertical axis in the northeast minaret of AL- Kadhimin shrine that is located in the city of Baghdad, Iraq is proposed. The shrine consists of four minarets with two domes inside a big courtyard. Due to uncontrolled dewatering process inside the shrine, the four minarets have tilted in different angles, but the most severe tilt occurred in the northeast minaret. The dewatering well that operated near the minaret is causing water table level to decrease and effective stresses of the soil to increase. This results in a differential settlement of the minaret foundation. In order to protect the minaret's foundation from potential lateral loads, a group micro-piles have been proposed around the minaret. A Three-dimensional numerical analysis is used to analyze this problem by using PLAXIS 3D model. Different diameters, depths, angles of inclination were used to simulate the performance of single-row and double-row micro pile systems. The simulation results showed that the proposed micro pile system is an effective solution in resisting lateral loads and controlling the tilt that occurred in the minaret.

Keywords Minaret, Micro-pile, Tilting, PLAXIS 3D, Lateral Load

1. Introduction

Historical buildings and structures may belong to the national cultural heritage of a specific country or to both national and international heritages. The value of these buildings reaches the highest levels when it is linked to the connotations and contents of folk and religious heritage. Old mosques and churches are categorized as historical religious buildings and a large number of these buildings can be found in Europe and the Middle East. Shapes of the minarets found with mosques and churches are either cylindrical or prismatic as shown in Figure 1. Historical minarets are tall slender structures which are usually built either from stones or bricks. However, many others are constructed from wood. Minarets are vertical landmarks that are considered as a medium between earth and heaven, man and Minarets are one of the specific and important structural elements which are indispensable elements of the Islamic city skyline [1,2]. The height of most minarets in Turkey ranges from 20-38 m [3].

Earthquakes, strong wind and activities nearby construction sites may cause damage to the old minarets. Because of the earthquakes, 115 minarets were reported to have collapsed in Düzce, Turkey alone. Also, it was observed that approximately 70% of the RC and masonry minarets surveyed in Düzce sustained severe damage or collapsed [4-6]. Throughout its history, 10 minarets and church towers with historical and cultural heritage (located in the Mediterranean region of Turkey) have experienced significant damages or even collapse [7]. The ancient monument Al-Hadba' minaret is located in the city of Mosul, Iraq and it was constructed in 1173 with a total height of 47m. Two building materials were used in the construction of the minaret and these were stones and mud bricks. The stucco-lime was used as a mortar (Figure 2). The soil problem, the climatic conditions, and the weakness of the building materials caused the minaret leaning and warned of massive risk [8].

a. Cylinderical shape minaret b. Prismatic shape minaret

Figure 1. Different shapes of minaret in historical buildings (Amir, 2014)

Figure 2. Al-Hadba minaret before and after its massive devastation in 2017 [9]

However, it did not fail during the monument life, but it was destroyed by ISIS in 2017. Reference [8] reviewed soil layers, underground water condition, description of the minaret parts, and providing the solutions and propositions for future reconstruction works of the minaret after it was blown up by ISIS.

Different methods were used to strengthen the foundations of leaning structures and these methods are underpinning of the foundations, compaction grouting, and soil extraction. More information about the above mentioned methods can be found in published studies [10-12].

In Cairo, Egypt, restoration of some Mamluk minarets was carried out over a century, between the mid-1800s and mid-1900s [13].

In Bosnia and Herzegovina, there are 36 mosques with domes and stone minarets and 786 mosques with wooden minarets [14]. The architectural design of these minarets is similar to the ottoman classical minaret shape. Restoration of these two types of minarets is significantly different, mainly due to the nature of the material itself [15].

Structurally, minarets can be described as slender cantilevers with irregular mass distribution along their heights and this makes them more exposed to damage during ground movement. Therefore, many tower-type masonry structures were completely or partially destroyed due to major earthquakes, strong winds, or suddenly without any indication [14].

The advancement in mathematical modeling and computer technology helps the engineers to employ the mathematical modeling in the restoration of the minaret. Based on solid finite elements approaches, macro-modeling that considered the bricks and mortar layer as a homogenous continuum was used to predict the seismic behavior of historic masonry minarets in Antalya, Turkey. The three-dimensional (3D) model of the historical minarets was created using solid elements by SAP2000 software [3].

The historical minarets were created using solid elements by SAP2000 software. The numerical models were applied to check the safety of historic masonry minarets against earthquakes and winds [16-22]. In addition, numerical modeling was used to investigate the effect of vertical ground motion on damage propagations of historical masonry slender tall rectangular stone minarets [23, 24].

In the current study, the 2020 version of PLAXIS (3D) was used to simulate the behavior of a historical leaning minaret located in Baghdad, Iraq when a group of micro-piles were used around it in order to protect the minaret foundation from any lateral loads and to ensure the stability of the soil-foundation. The proposed micro pile system is mainly to retrofit the foundation and to stop any future increase in the leaning of the minaret due to wind load or earthquake.

2. Description of the Minaret and Site Survey

2.1. The Leaning of the Historical Minaret of Al-Kadhimin Mosque

Baghdad is an ancient city distinguished by its historical and archaeological buildings and mosques. Among the most prominent of these mosques is the Al-Kadhimin mosque, which consists of two large domes and four minarets around them. One of these minarets (the northeast minaret) was constructed 500 years ago and it is the oldest one. During recent years, an inclination was observed in the oldest minaret (the northeast minaret, NEM). The tilting of the minaret from vertical axis measured from the highest point is about 80 cm. This inclination is quite visible from the courtyard of the holy shrine as shown in Figure 3. The minaret was built from bricks and plaster with a total height of 41.5 m. The minaret superstructure can be divided into three sections; the first section represents the height of the minaret from the ground to the slab floor, which is about 11.2 m with a diameter of 3.4 m. The second section has a height of 18.8 m and a diameter of 3.2 m which extends from the slab floor to the top of the balcony. The third and last upper section extends up to the top. The height of the section is 11.5 m and a diameter of 2.6 m. The minaret below the ground has diameters of 3.6 m, 6 m and 8 m which extend to a depth of 2.5 m, 4 m and 6 m, respectively. The foundation is surrounded by 1 m thick walls that are extended to a depth of 4 m below the ground. Figure 4 shows the dimensions of the minaret and its foundation.

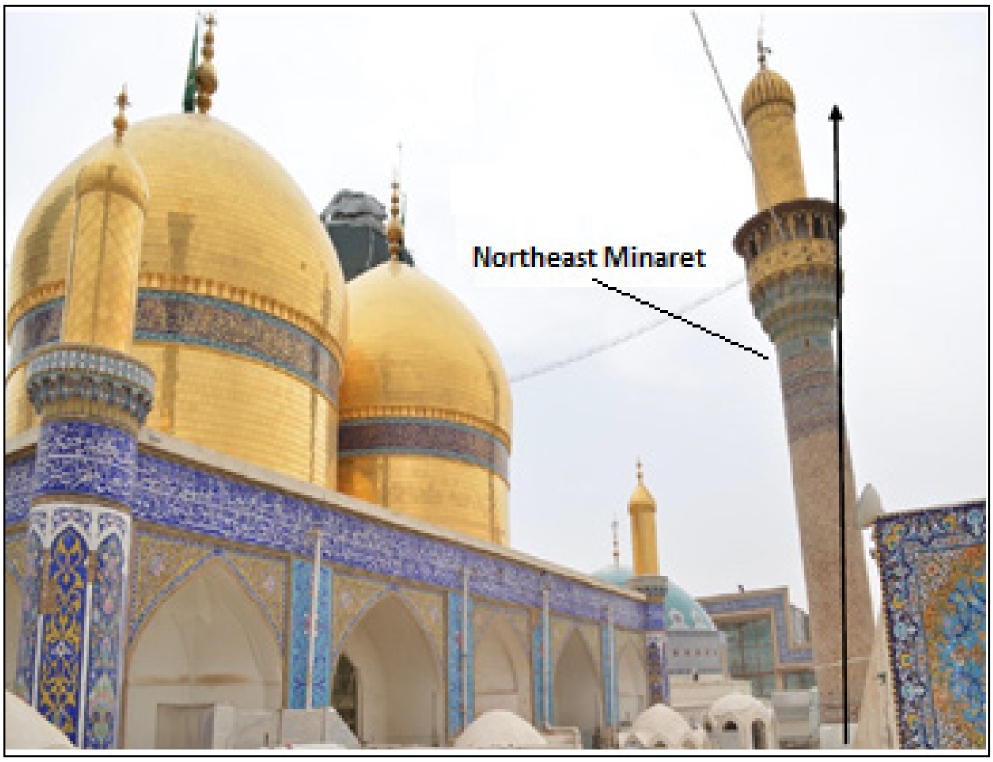

Figure 3. The leaning northeastern minaret

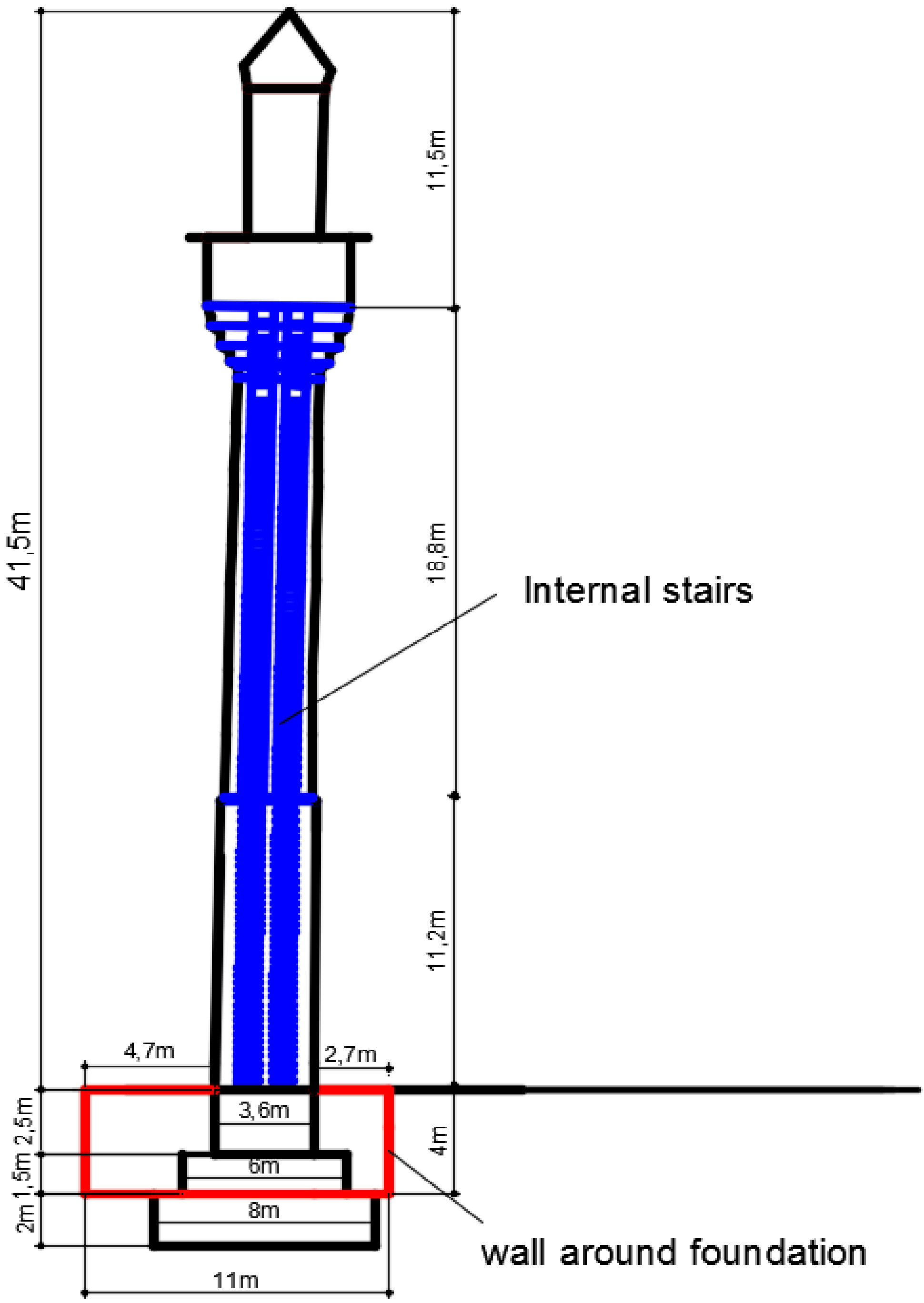

Figure 4. The dimensions of the minaret and its foundation

However, the leaning of the other three minarets of the Al-Kadhimin mosque was measured and found to be 30 cm. After many site visits, uncontrolled dewatering wells were found inside the main courtyard of the Al-Kadhimin mosque near the northeast minaret. After the dewatering process and lowering the water table near the minaret foundation, leaning of the minaret with cracks were observed. The dewatering near the minaret foundations caused a differential settlement, increase in effective stresses, leaning of the minaret and cracks [4, 14]. The continuous pumping of water from the wells caused migration of soil particles and formation of cavities [5]. The micro-piles are widely used for structural underpinning and in situ reinforcement due to its quick installation, and high bearing capacity [25-28]. The change of the center of gravity of the leaning minaret, leads to instability due to the generation of moment on the foundation. This decreased the stability of the minaret, particularly when it exposed to the lateral loads resulted from either wind or earthquake or any other source of lateral load such as any construction activities near the minaret in the near future. Therefore, after determining the cause of the leaning of the minaret, the first measures that were taken was to stop the dewatering from all wells around the foundation of the minaret with continuation survey. The results of the monthly survey showed that the tilting of the northeast minaret is completely stopped at 80 cm. This indicates that the dewatering is the main reason for the minaret leaning.

2.2. The Site Investigation

The stratification of soil layers below the ground surface at the site of the (NEM) is shown in Figure 5. The cohesive soil of brown to grey clay is the most abundant soil at the site.

According to USCS; the cohesive soil can be classified as Fat Clay (CH) to Lean Clay (CL). It is followed by poorly graded sand (SP) interbedded with well graded sand (SW) and silt. Soil properties under the minaret are shown in Table 1. The depth of water table near the foundation of the minaret was found to be 4.20 m. The soil to a depth of (9-10 m) is characterized by low seismic wave's velocities (low rigidity modulus) which indicate weak zones underneath the foundation and its surrounding wall (Figure 4). Based on site investigation report, the weakness was encountered at depth of 3.0-5.0 m below ground level.

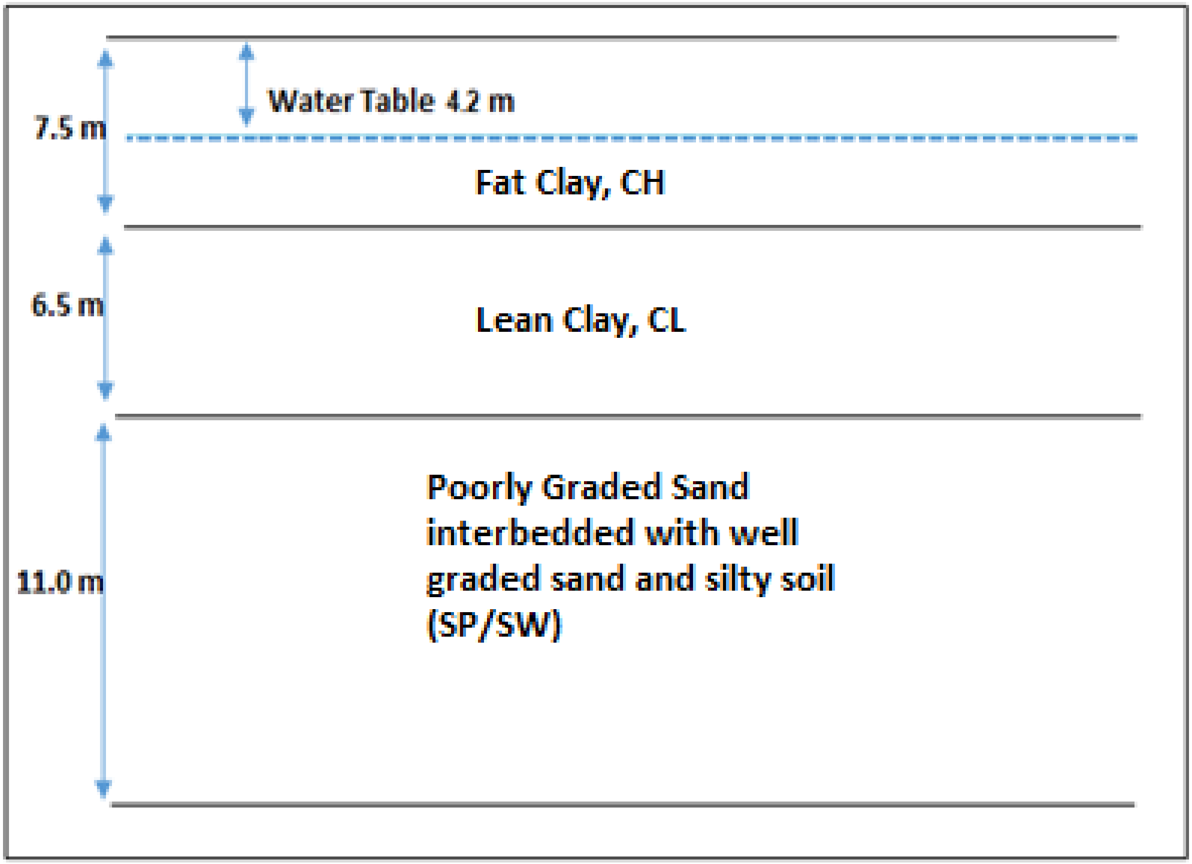

Figure 5. Soil profile at the minaret foundation

Table 1. Soil properties for modeling

Description	Fat Clay, CH	Lean clay, CL	Sand, (SP/SW) interbedded with silty soil
Unit weight, (KN/m^3)	20	20	20
Modules of elasticity, (KN/m^2)	4000	6000	10000
Poison ratio	0.3	0.3	0.3
Cohesion, (KN/m^2)	50	60	10
Internal angle, $\phi°$	8	10	35

2.3. The Proposed Strengthening System

This part gives a detailed description of the proposed system for maintaining the minaret's foundation. As previously discussed, the minaret was tilted from the vertical axis by about 80 cm, which leads to a change in the center of gravity and generates a moment on the foundation.

This means that the minaret foundation in the current state is in an unstable when exposed to external loads such as seismic loads, wind loads, explosions, etc. The current study aims to eliminate the movement of the foundation for any potential loads by constructing a system of micro piles around the soil surrounding the minaret foundation. In order to ensure the effectiveness of the micro-pile system around the foundation, PLAXIS 3D was used as a tool for analyzing this problem and showing the effect of the proposed system in the soil on the stability of the minaret foundation. Concerning the proposed micro-piles system, the studied variables are micro-pile depth, diameter of micro-pile, angle of installation of micro-pile, and finally the effect number of rows around the soil as shown in Figures 6 and 7.

2.4. The Numerical Simulation

PLAXIS 3D (2020) program was used to analyze the proposed micro-pile system around the minaret foundation. The dimensions of the model were used are 200 m in length and width, and the depth of the soil in the model is 25 m, which represents the depth of the borehole from site investigation. The boundary condition of the model was used similar to the previous studies where the bottom boundary was fixed against the movement, while the right and left side were allowed to move in the vertical direction only [29,30].

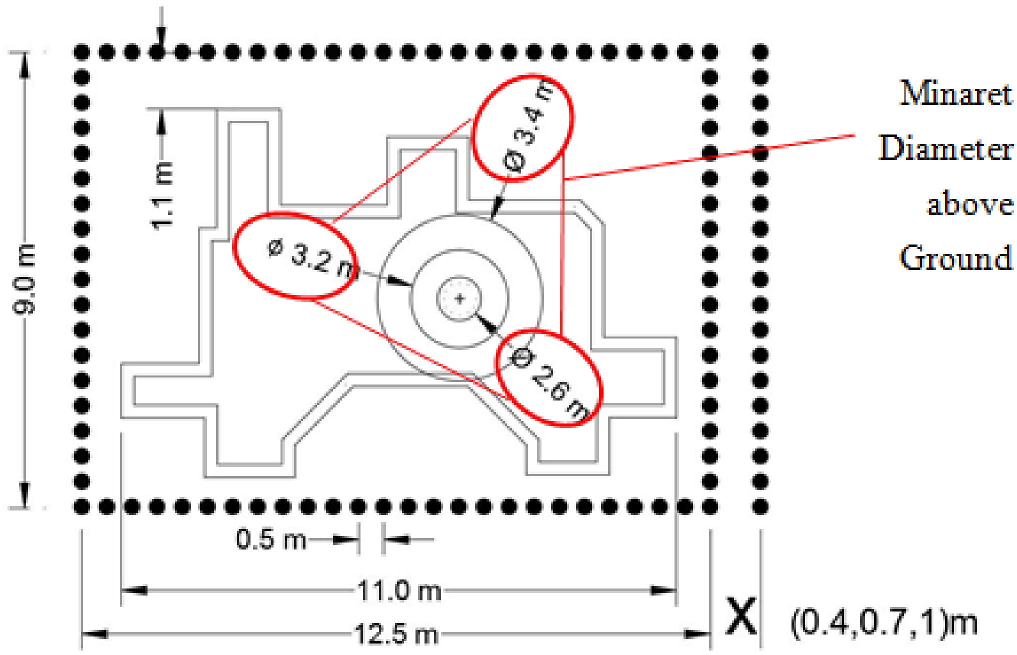

Figure 6. Proposed system of micro-pile around the minaret including minaret diameters above ground level

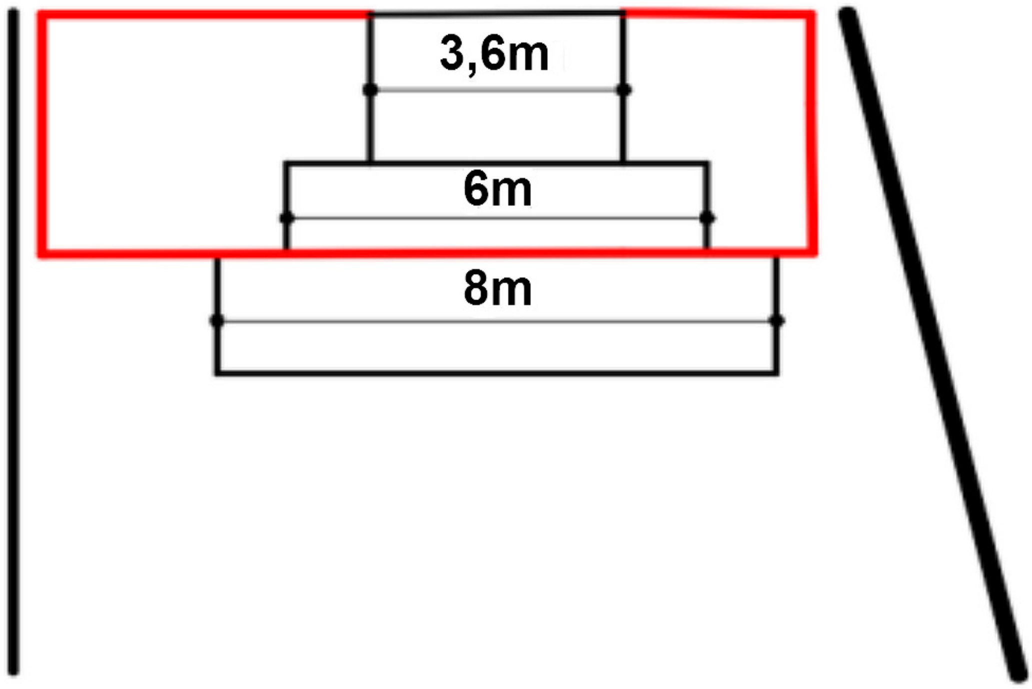

Figure 7. Inclined micro-pile from the tilting side of the minaret

The interface element was used to represent the interaction between the soil and the brick foundation. The mesh size was chosen a fine based on the convergence analysis that was conducted for several cases to ensure that the obtained results are independent of the mesh size. The micro-pile surrounding the minaret foundation was modeled using a linear elastic model with grout properties. Several depths were used for the micro-pile with different diameters. The interface element between soil and micro-pile was also used to ensure the interaction between them. In the study, the linear elastic material is considered to perform practical analysis. For this reason, the variation in stiffness due to mortar has been neglected in brick joints for minaret and walls. Also, geometric quadratic effects were not considered in the analyses. The minarets that interact with the adjacent mosque walls were ignored and the bottom knitting knots were fixed to the ground. Soil properties that are used in numerical analysis are shown in Table 1 while the properties of the micro-pile and the bricks are shown in Table 2. The important part of this study is to check the effect of the micro-pile surrounding the foundation of the minaret under the expected lateral loads such as wind loads, seismic loads, and construction process near the minaret. Initially, the minaret was modeled in the current state with a tilt of 80 cm from the vertical axis by analyzing the weight of the minaret into two components, horizontal and vertical forces, and applied on the foundation. So that the foundation tilts from the beginning and then the body of the minaret is modeled until it reaches the top of the minaret with a tilt of 80 cm. After that, lateral loads were applied on the base of the minaret, and the 10 cm tilt criterion was adopted. This is because the current situation has been observed spread of cracks in the body of the minaret, and it is expected that the future tilt of 10 cm will cause an increase in cracks and structural problems of the minaret, so the value of lateral resistance was calculated in the numerical analysis at a tilt of 10 cm. Figure 8 shows a three-dimensional model of the minaret surrounded by micro-pile and a lateral force is applied on the foundation.

Table 2. Properties of micro-pile and brick

Properties	Micro-pile	Brick
Unit weight, (kN/m^3)	24	17
Elastic modulus of the grout of micro-pile, E_g (kN/m^2)	14.2*10^6	5.6*10^6
Poisson's ratio, ν_c	0.2	0.2

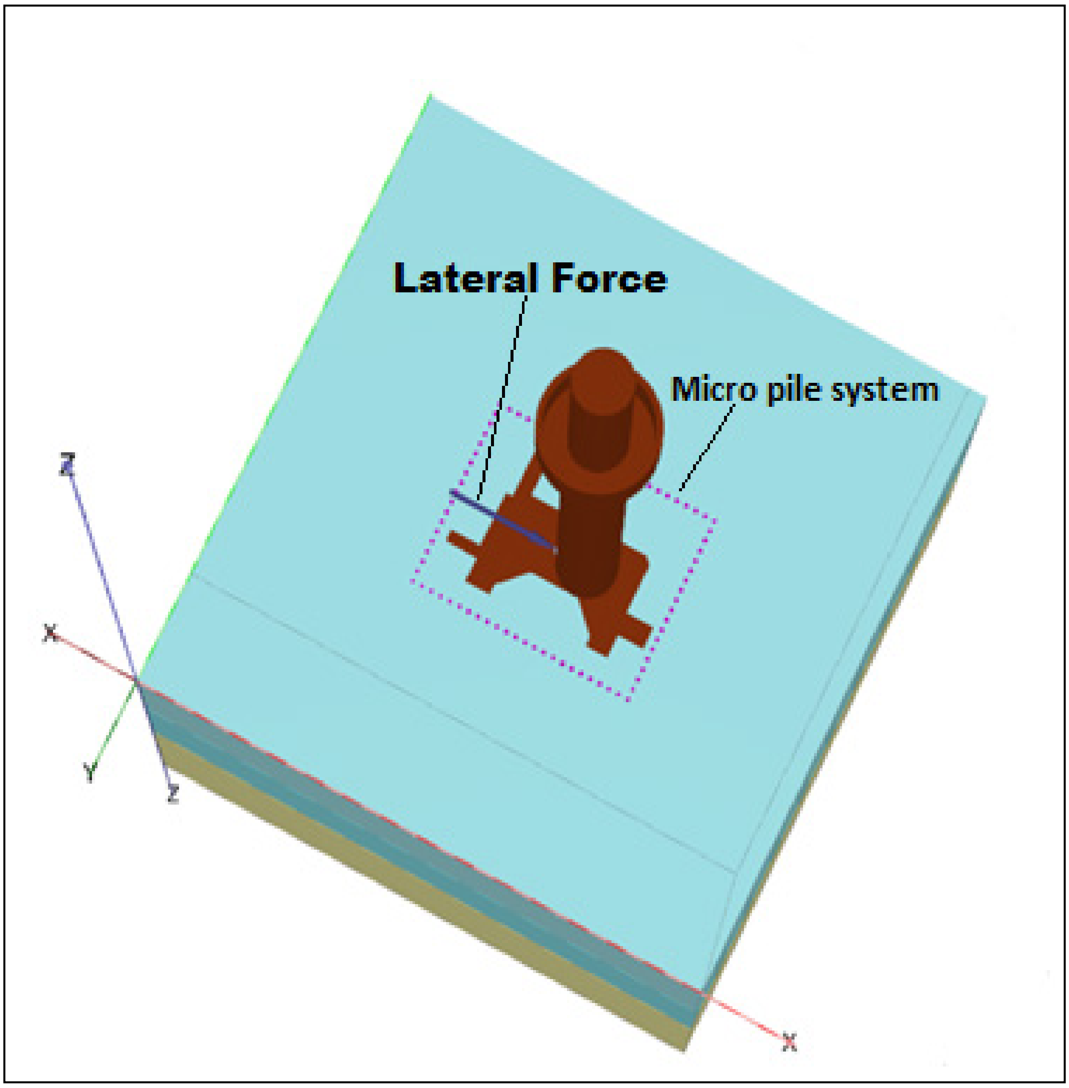

Figure 8. Three-dimensional model of the minaret with proposed micro-pile system

3. Analysis of the Results

3.1. Effect of Micro-Pile Depth

This part deals with the effect of the micro-pile depth with a diameter of 10 cm on the lateral resistance of the foundation. Three depths used in the study; 8 m, 12 m, and 15 m. It is observed that the value of lateral resistance of foundation increases when the depth of the micro-pile increases, as shown in Figure 9. The percentage increase in the lateral resistance has been calculated for each case using Eq. (1), to enable direct understanding of the effect of the micro-piles around the minaret foundation.

$$\mathbf{P_{in} = \frac{Lrp - Lrf}{Lrf} \times 100} \quad (1)$$

where Pin percentage increase of the lateral resistance of the minaret foundation, Lrp

Lateral resistance of foundation-micro-pile system at 10 cm minaret tilt, L_{rt} lateral resistance of foundation only at 10 cm minaret tilt. The percentage increment of lateral displacement resistance increment percentage is remarkably influenced by the depth of the micro-piles and it is clear that the percentage increases of lateral resistance increases as the depth of the micro-pile increases as shown in Figure 10. It is predicted that the percentage of increase of the lateral resistance is about 16.1%, 25.5%, and 32.95% for the micro-pile depths of 8 m, 12 m, and 15 m, respectively. The results of the study show that the increase of micro-piles depth is resulting in an increase in the lateral resistance capacity for the minaret foundation. Figure 11 shows the general state of deformation of the minaret under the influence of the lateral load and results show that the top lateral displacement is 10 cm.

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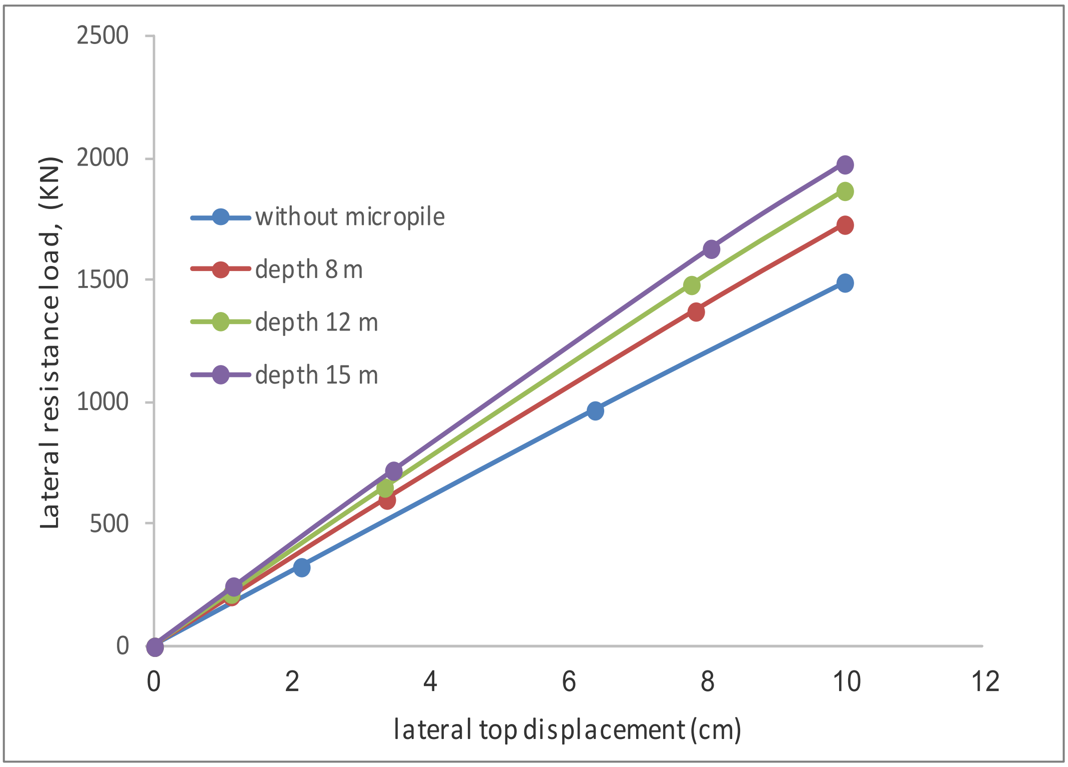

Figure 9. Variation of lateral load resistance with the displacement

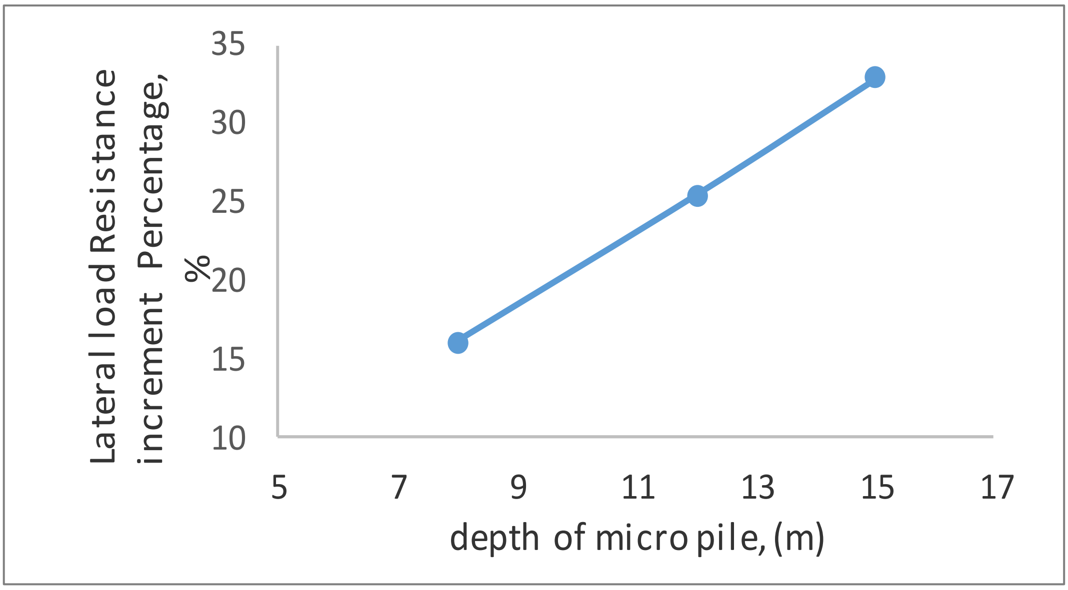

Figure 10. Lateral load resistance increment percentage of the minaret foundation vs. the depth of micro-pile

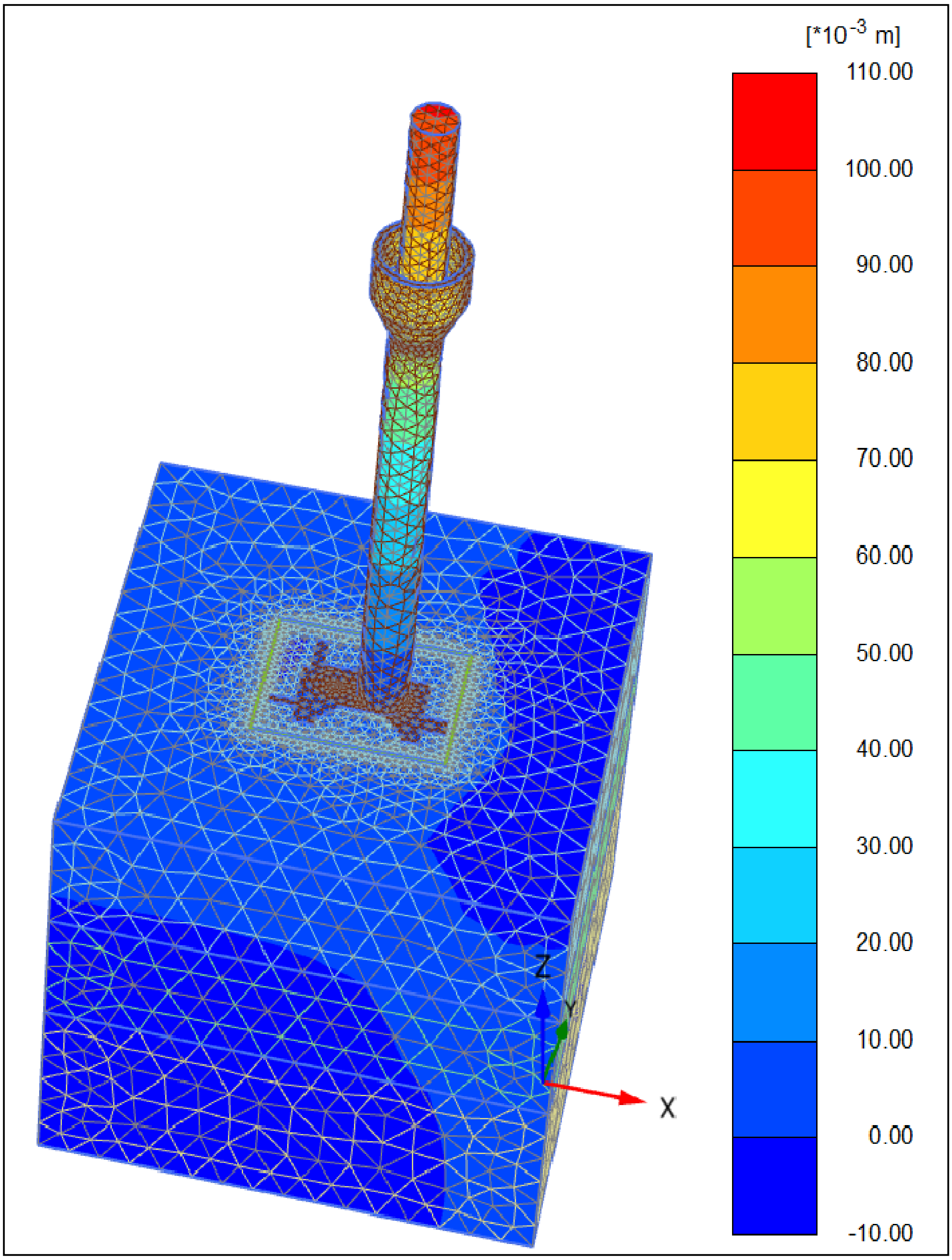

Figure 11. General state of deformation mesh for the minaret

3.2. Effect of Micro-Pile Diameter

The effect of micro-pile diameter on the lateral resistance of the foundation was simulated. For micro-piles depth of 12 m, micro-piles of various diameters (10 cm, 15 cm and 20 cm) were investigated. The results showed that the increase in micro-piles diameter leads to an increase in the lateral resistance of foundation as shown in Figure 12. The effect of diameter on the percentage increase in lateral resistance of the foundation is shown in Figure 13. The percentage increase in the lateral resistance of the minaret foundation is found to be 25%, 29%, and 32% for micro-pile diameters of 10 cm, 15 cm, and 20 cm, respectively.

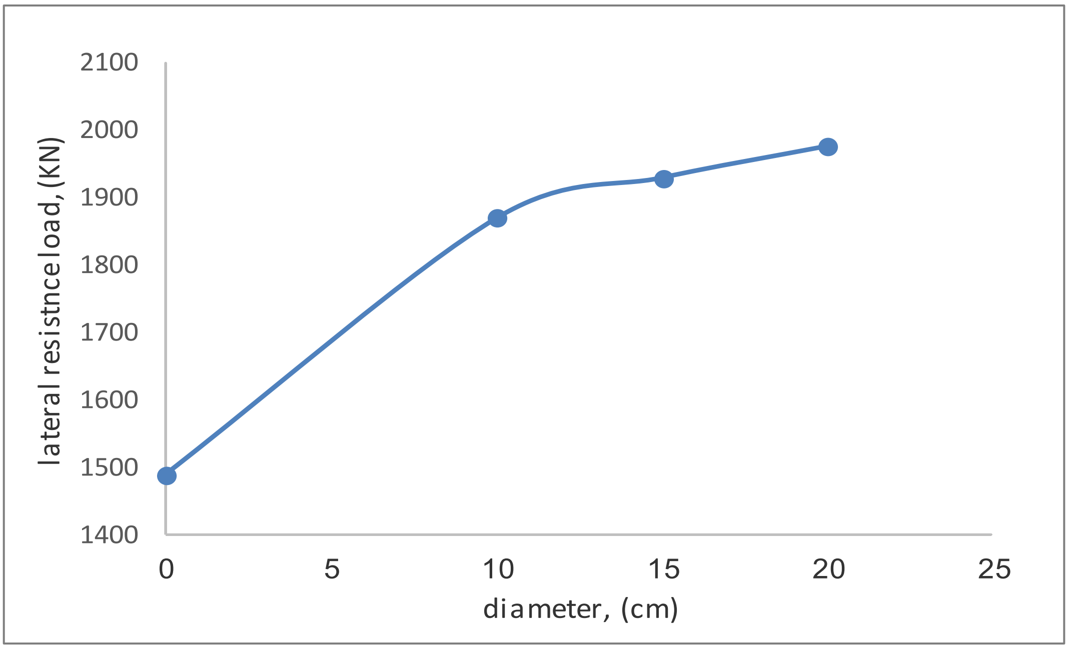

Figure 12. Relationship between diameter and lateral resistance for micro-pile 12 m in depth

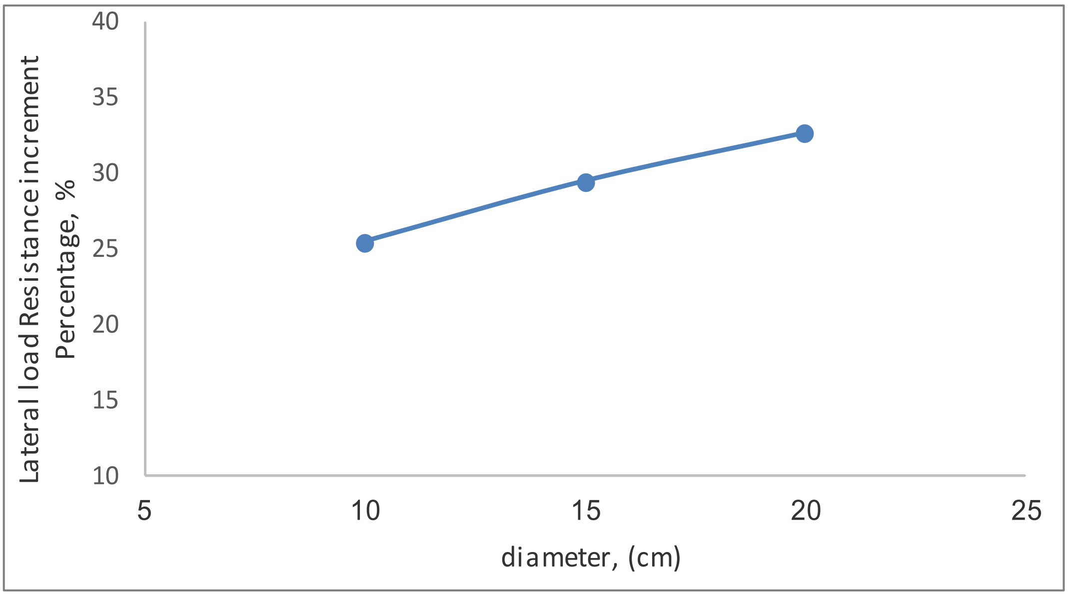

Figure 13. Lateral displacement resistance increment percentage for minaret foundation vs. diameter for micro-pile 12 m in depth

3.3. Effect of Micro-pile Angle

In this section, the effect of the micro-pile inclination angle on the lateral resistance of the minaret foundation is studied. The performance of strengthening system with micro-piles of inclination angles of 10°, 20°, and 30° located at the inclined side of the minaret was studied and compared with strengthening system of vertical micro-piles used at the other surrounding sides of the minaret. The adopted depth and diameter of the micro-piles were 12 m and 10 cm, respectively. The simulation results are shown in Figure 14. Simulation results showed that by using inclined micro-piles with angles of 10°, 20° and 30°, the value of the lateral load increased slightly and lateral resistance of the minaret foundation was increased only by 1%, 2%, and 4%, respectively as shown in Figure 15.

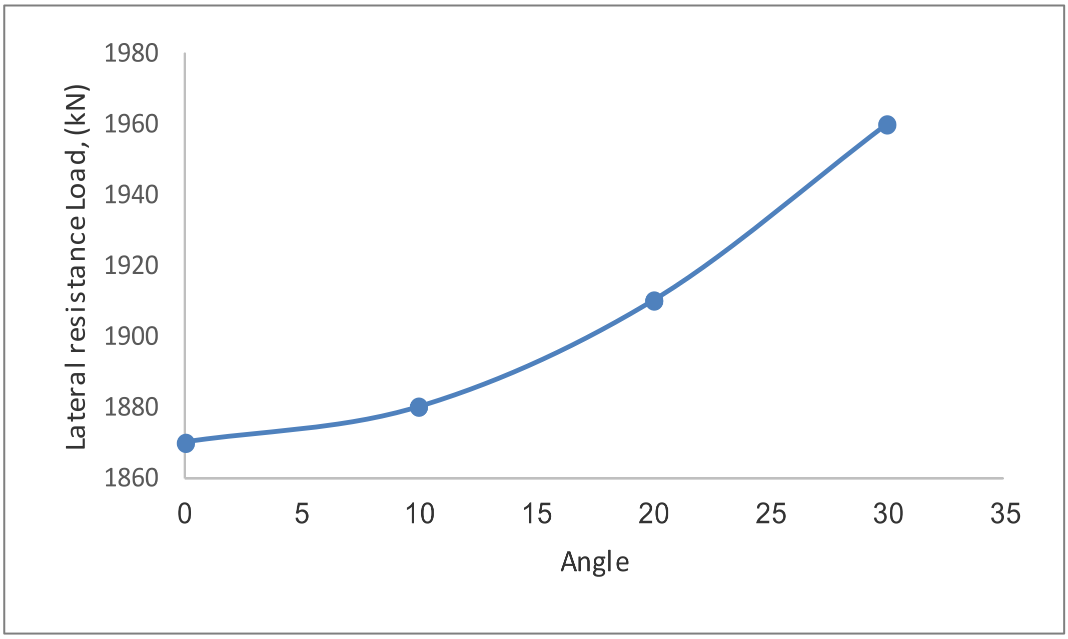

Figure 14. Impact of micro-pile inclination with the lateral resistance for 12 m depth of micro-pile and 10 cm in diameter

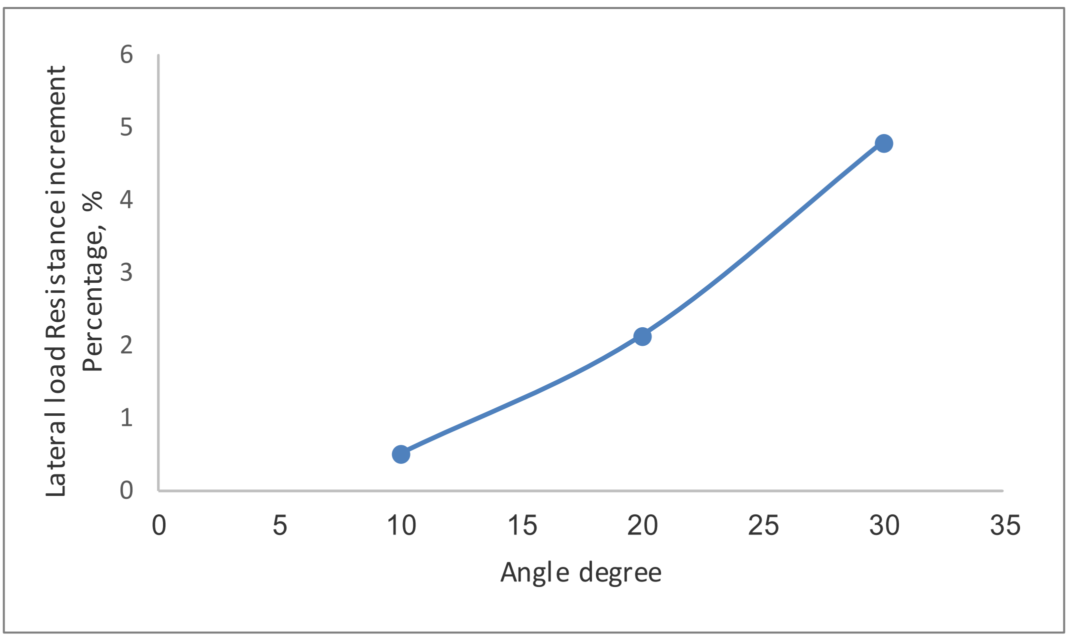

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Figure 15. Percentage increment of lateral displacement for inclined micro-pile of 10 cm and 12 depth

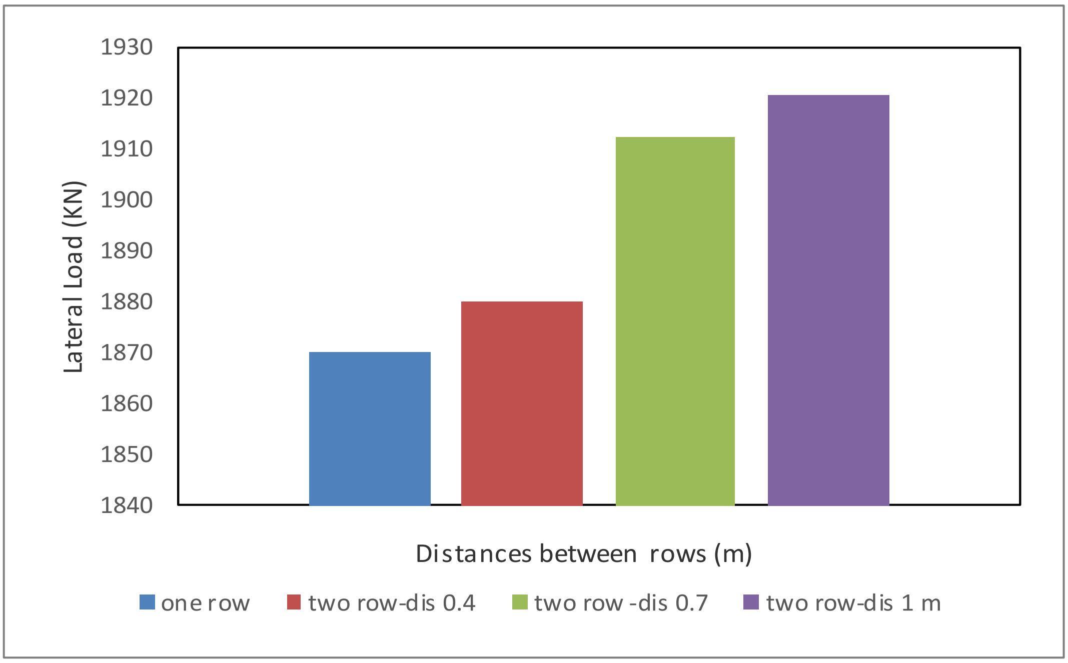

Figure 16. Impact of an additional row of micro-piles with 10 cm diameter and 12 m depth on lateral resistance

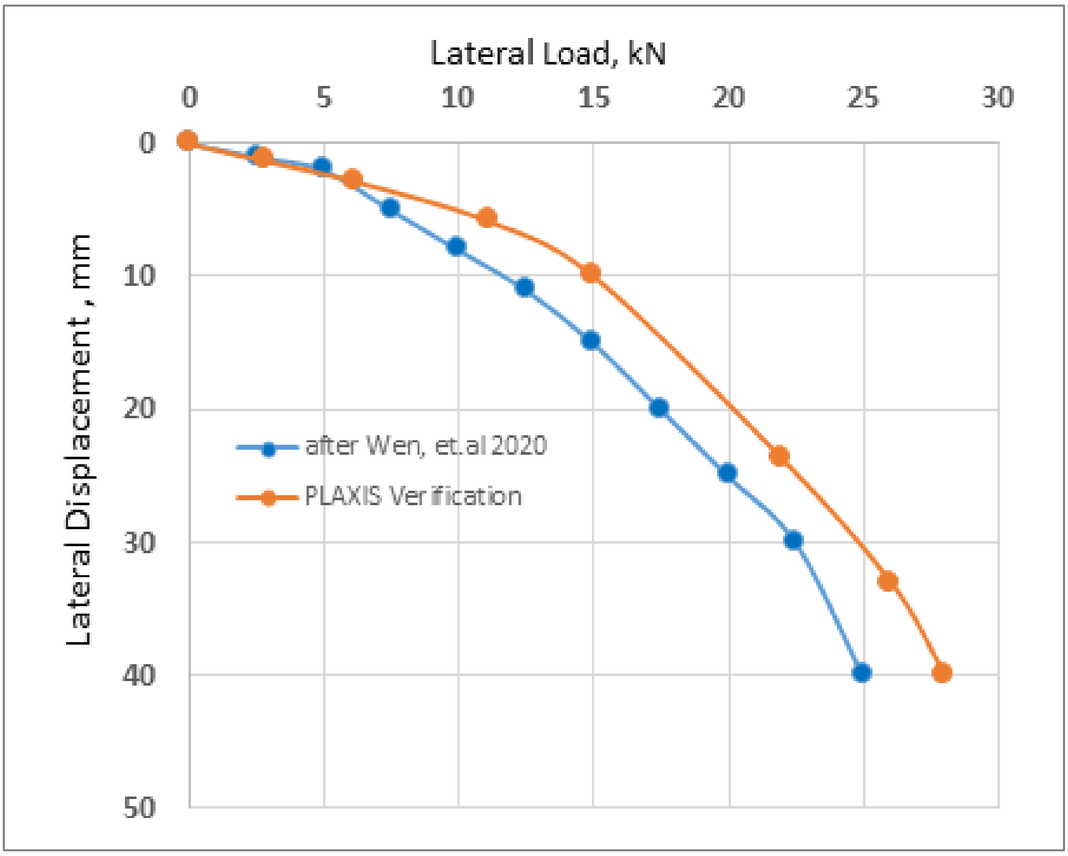

Figure 17. Compression between results of the present study with the

3.4. Effect of Additional Row

In this part of the study, another row of micro-pile was added vertically at the location of the inclined minaret. The second row of micro-pile was placed at different distances from the first row. Three distances used between the two rows of the micro-piles in the simulation were 0.4m, 0.7m, and 1m. The adopted depth and diameter of the micro-piles were 12m and 10cm, respectively. The simulation results are shown in Figure 16. It is noticed that by adding a row of micro-pile the increase in the value of lateral resistance was negligibly small. Only a 2% increase in the lateral resistance was obtained when a second row of micro-piles was placed at 1 m from the first row.

3.5. Accuracy of PLAXIS 3D Model

In this study, data on similar ranges of lateral loading and lateral displacement was used to check the accuracy of PLAXIS 3D model. The data was published by Wen et al. (2020) and the main objective of the comparison was to demonstrate the capability of the program in simulating the use of micro-piles under the influence of lateral loads. The study included the installation of a full scale model of the micro-pile under the effect of lateral load. The comparison is shown in Figure 17.

Although the simulation by PLAXIS 3D in the present study include grouted and non-grouted micro-piles under lateral loading, however, the simulation result on grouted micro-piles with diameter of 102 mm and a depth of 11.5 m were only used in the comparison. In the present study, the soil consists of several layers, the first is soft clay and mud clay extending from the surface to a depth of about 10 m, and the last two layers are from a depth of 10 to 15 which are silty and sandy clay soils. The coefficient of determination (R^2) for lateral displacements obtained from simulation by PLAXIS 3D model and that borrowed from literature where found in agreement as shown in Figure 18 [2]. The value of the R^2 was found to be 0.96.

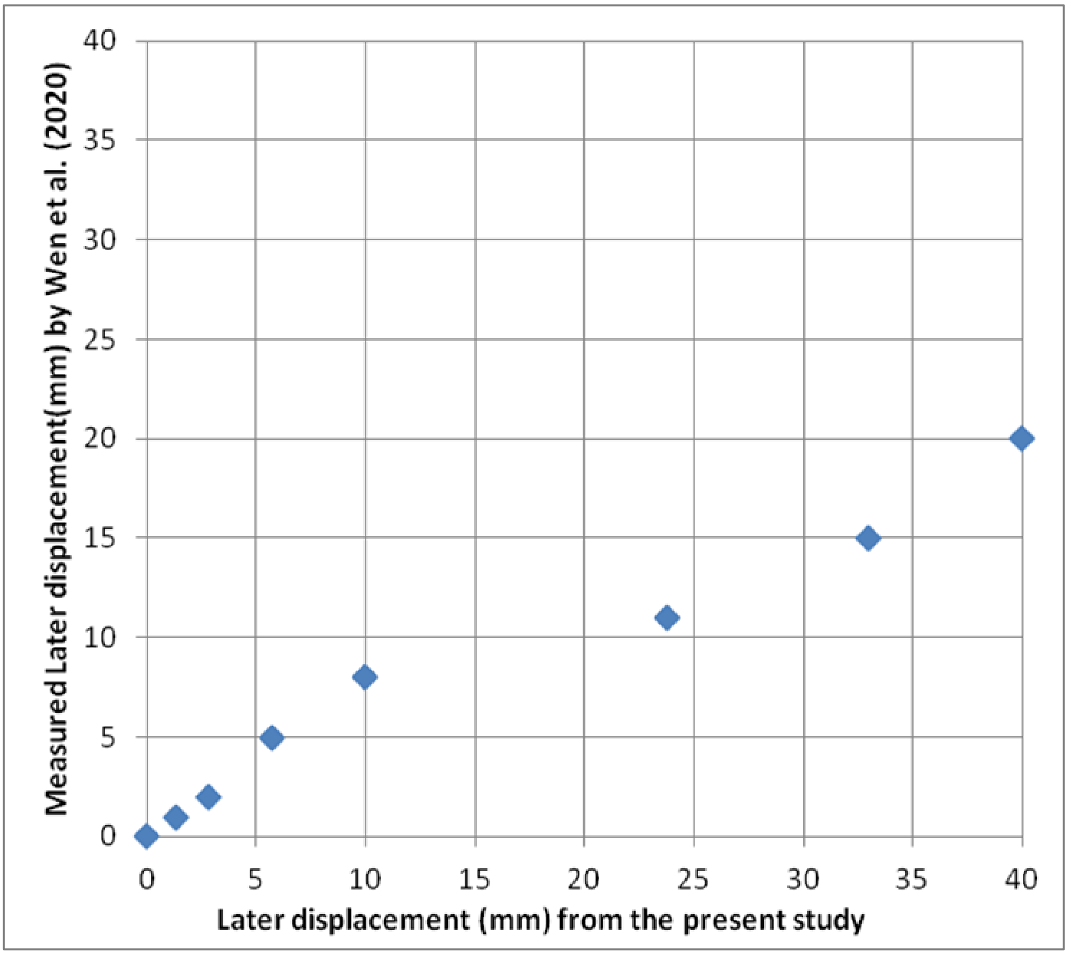

Figure 18. Comparison between results from PLAXIS 3D and that given by Wen et al. (2020)

4. Conclusions

The tilting of the minarets of AL-Kadhimin mosque is a serious problem that affects the safety of the crowded worshipers and a well-studied solution is required. Based on the site visits, site investigation, interviews, data collections, identification for the cause of minaret tilt, proposed solution and simulation output, the following conclusions can be drawn:

1. The simulation results showed that by enclosing the soil with a system of micro piles increased the lateral resistance of the minaret foundation under the effect of lateral loads.
2. The simulation results confirmed that the depth of the micro piles around the foundation of the minaret has a direct effect on the lateral resistance of the foundation. Results showed that by increasing the micro piles depth from 8 m to 12 m and then 15 m increased the lateral resistance of the foundation by about 16.1%, 25.5%, and 32.95%, respectively.
3. Simulation results showed that by increasing the micro-pile diameter from 10 cm to 15 cm and then to 20 cm, increased the lateral resistance of the foundation important. Where the percentage of increase is by about 25%, 29%, and 32%, respectively.
4. Simulation results showed that by adding another row of micro-piles at a distance of 1 m from the first row has a negligibly small increase in the lateral resistance of the foundation (2% only). Simulation results showed that by increasing the inclination angle of the micro-piles to 30°, lateral resistance of the foundation will increase by 4% only.
5. Based on the simulation results, the recommended strengthening system includes micro-piles with a diameter ranging from 10-20 cm and a depth exceeding the depth of the minaret foundation.

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