

Ground Improvement of Dhu Al-Kifil Minaret Using Micropile and Cement Grouting

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Abstract. The Minaret of Dhu Al-Kifil Nabi (PBUH), located in the city of Kifil with a height of about 25 meters, is one of the historical monuments of Iraq. The 4.5 degree deviation of this Minaret has become a challenge for authorities in recent years. Various reasons, such as the old age of the building and manipulation of the soil of the minaret bed, damage the structure and have caused it to deviate from the vertical direction and form cracks at its height. A temporary metal retaining structure is currently constructed on the site to maintain the building in its current state. Still, in order to remove it and repair the body and foundation of the Minaret, the designs have been carried out by Iranian engineering groups. After that, its strengthening operations have also finished. In this article, after the introduction of the project, the analytical and numerical results of the bed improvement plan using the combination of inclined and vertical micropiles are presented. Finally, the reliability of the plan in controlling the heterogeneous settlement of the Minaret is assessed.

Keywords: Soil improvement, micropile, cement grouting, settlement, historical structure, Minaret of Dhu Al-Kifil Nabi (AS).

1. INTRODUCTION

Considering the importance of preserving the ancient monuments of any country, the improvement and restoration of historical structures is one of the disciplines that play a significant role in preserving historical records. Like other construction projects, strengthening such structures requires the three skills of architecture (repair), structure, and geotechnics. In any restoration project, the coordination of the above engineering groups is one of the most important things and plays a crucial role in improving the final quality of the project. The Minaret of Dhu Al-Kafel Nabi (PBUH), with a height of about 25 meters, is one of the historical monuments of Iraq. The studied site is located about 130 km south of Baghdad city, the distance between the city of Hillah and Najaf (30 km northeast of Najaf city) [1]. Also, this site is located about 350 meters east of the Euphrates River and inside the city of Keff (Figure 1). This Minaret is about 700 years old (13th century AH) and belongs to the Ilkhanian period, and its construction is attributed to Sultan Uljaito Muhammad Khodabandeh. The Minaret of Al-Nokhayleh Mosque is 35 meters from the shrine of the Prophet (PBUH), next to the wall of the western chamber.



Figure 1: Site location and a view of Minaret.

Among the characteristics of the studied masonry minaret are the 6-meter height of the base with a square section, the 14.5 m body of the Minaret with a circular section, and the head of the Minaret with a height of 4.10 meters (Figure 1). In the past decades, because of unknown reasons such as the passage of time, the age and archaism of the building, and manipulation of soil, deviations from the vertical direction have appeared in the height of the Minaret, which has caused serious concern among the residents and authorities. However, the exact time of the beginning of deviation movements in the Minaret has not yet been revealed to the researchers. Based on the studies conducted in the past years on the Minaret, two reports were published by Iraqi universities. In 1998, the Idrisi Center of the Ministry of Construction of Iraq declared the deviation of the Minaret to be 3.5 degrees. In 2008, the Engineering Consulting Center of Al-Qadisiya University announced a deviation of 4.56 degrees (Figure 2). For this reason, the management of the complex (Diwan Waqf Shia) decided to stabilize the Minaret to stop this deviation. For this purpose, steel elements were added to the Minaret in 2010. It believes that creating such a protective structure to prevent further deviation of the Minaret was considered a suitable solution. However, its implementation with such materials and in these dimensions has created many problems for the study and access to the Minaret (Figure 2).

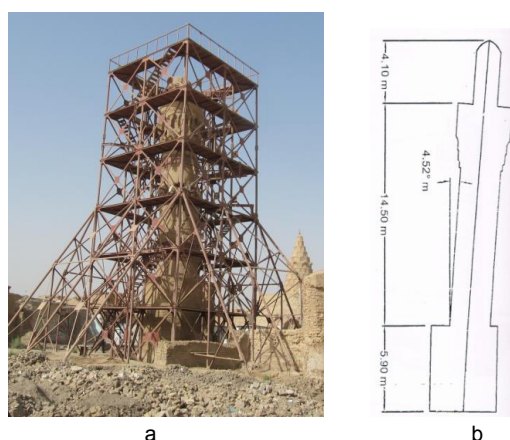


Figure 2: a) A view of the Minaret along with the steel retaining structure, b) The amount of eccentricity of the Minaret in height.

Engineering groups consisting of architectural and restoration, decoration, structural, and geotechnical working groups were engaged to find a practical solution for revitalizing and strengthening the mentioned site and Minaret. Various methods have been used to improve the soil in different parts of the world. Several researches have been done by Karam and colleagues in this field [2-5]. Previous studies show many cases in which the use of micropiles to control the settlement of existing structures has been very effective and successful. For example, Cadden [6] described the effect of using micropiles in some of the most well-known historical structures. AbdelSalam [7] described a micropile system for repairing a tilted building on deep soft clay in Alexandria, Egypt. The micropile system included 60 micropiles to stabilize the 16-story structure. Elgamal [8] and Bakr [9] presented two Case studies of inclined structures in Egypt, with 11 and 13 stories, respectively. A total of 89 micropiles, with 20 m length and axial capacity of 250 kN, were used to restore the 11-story building. For the 13-story building, 36 micropiles, with 13 m length and an axial capacity of 200 kN, were used. Gutierrez[10] reported strengthening the foundations of a Museum by implementing 62 micropiles with a compression capacity of 250 kN.

The first reported case history of micro piling in shallow foundations in China is about an old 3-story building that was required to support additional applied loads resulting from the construction of two more floors [11]. Edens and Fisher [12] discussed three micropiles retrofitting case studies. In the first project, 36 micropiles were used to repair 12 failed column piers of parking in Lake Highland, Texas; in the second project, the basement of a 50 years old building was converted into a parking garage in Dallas, Texas; and in the third project, micropiles, structural bracing, and permanent soil nails were utilized to enlarge a coliseum. In the continuation of this article, the main explorations and activities of the geotechnical group and the results obtained from the analyses performed on the obtained data have been presented.

2. GEOTECHNICAL STUDY

To evaluate the geotechnical conditions of the site, two mechanical boreholes were drilled in the closest possible places to the Minaret, and disturbed and undisturbed samples were taken from the site (Figure 3) to perform the required laboratory tests on them (physical, mechanical and chemical tests). Moreover, field tests (standard SPT penetration, etc.) were also conducted in the mentioned boreholes. It should be noted that the

metal protective structure was an obstacle to access and made the exploration operation difficult. A summary of subsurface soil parameters is presented in Figure 4. One of the most important issues that was evaluated during the study was determining the shape and dimensions of the foundation of the historical Minaret. The various test pit which was digged around the foundation provided appropriate information for the dimensions of the foundation shown in Figure 5.

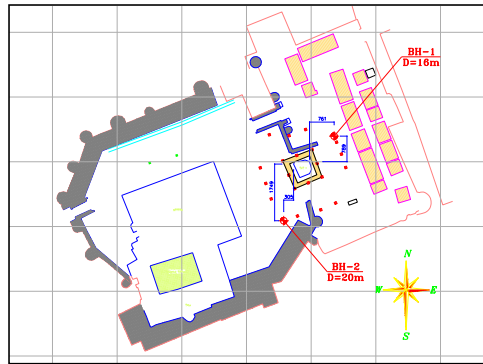


Figure 3: The location of exploratory boreholes in the studied site.

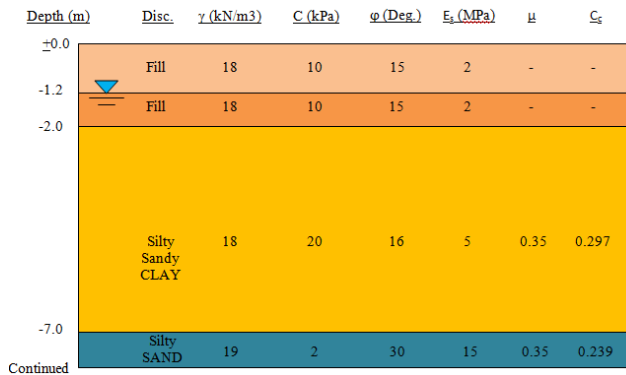


Figure 4: Assessed geotechnical profile of the site.

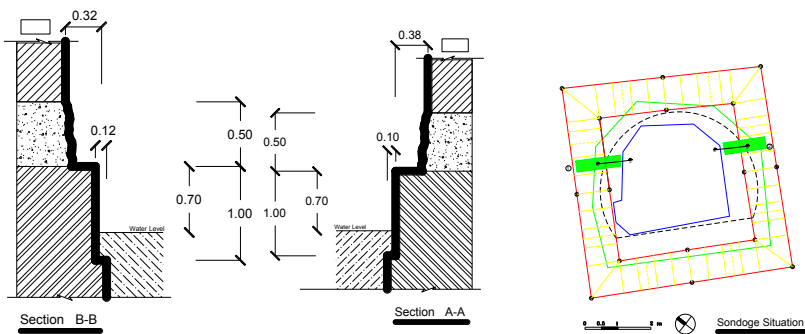


Figure 5: Sections and plans of the minaret foundation.

3. EVALUATION OF DAMAGE AND GEOTECHNICAL DATA

Based on the geotechnical evaluations, it can be observed that the stresses created in the soil before the minaret rotation from the vertical direction are about 1.13 to 1.69 kilograms per square centimeter, which exceeded the limit of the Minaret's foundation bearing capacity (which is about 0.92 kilograms per square

centimeter based on the geotechnical report provided for the failure of a square foundation with a width of 6 meters). This matter was aggravated after the occurrence of rupture in the soil under the foundation by the creation of eccentricity, which, in the state after vertical departure, the created stresses reached about 0.94 to 1.89 kg/cm². One of the reasons for the asymmetric settlement of the Minaret can be found in the weakening of the soil under it (for various reasons, including changes in the underground water level and washing, human manipulations, etc.), which causes the change in the nature of the soil. Also, the following can be mentioned, among other reasons, that have an accelerating role in the current problem of the Minaret:

- The old and historical nature of the Minaret and the existence of weakness in the resistance of the bricks and mortar used in the body of the Minaret.
- The presence of underground water level near the earth's surface and its possible strong seasonal changes.
- Existence of highly corrosive environment in the vicinity of the foundation.
- Manipulating a part of the minaret bed soil by humans and replacing it with filled soil.
- Removal of some structures near the Minaret, which acted as a support for the Minaret.

The above cases and observations indicate that with the current conditions, rupture has probably occurred in the soil, and plastic deformations have continued. If no action is taken to strengthen the foundation, the Minaret will fall and be destroyed without a protective structure. Conceptual proposals for strengthening the foundation and improving subsurface soil as shown in Figure 6. Generally, bearing problems of the minaret ground can be listed according to the following:

- Weakness of the foundation (due to the age and reduction of the contact surface with the soil due to the removal or addition of parts of/to it over time)
- Weakness of bearing capacity of the soil under the foundation (due to washing water and the effect of corrosive factors and an aggressive environment)

Therefore, the following methods were suggested to repair the foundation and increase the bearing capacity of the subsoil:

- Increasing the foundation's bearing capacity by increasing the foundation's dimensions.
- Increasing the bearing capacity of the bed soil by using cement slurry injection.
- Transferring part of the structure's load to the strong layer of the underlying soil using vertical micropiles.

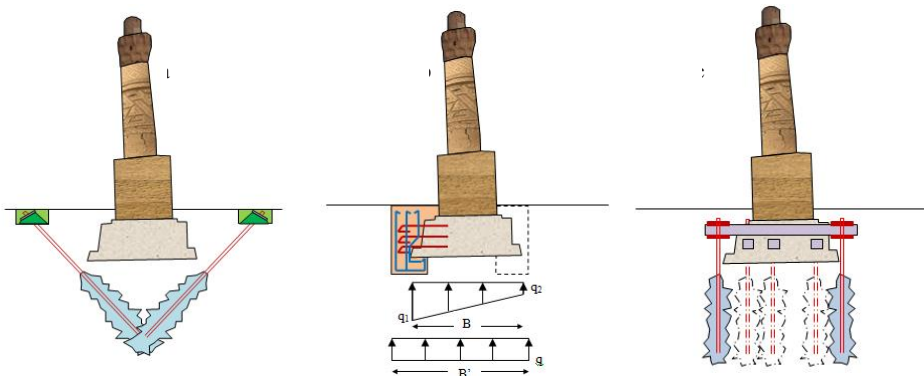


Figure 6: Conceptual proposals for strengthening the foundation and improving subsurface soil a) Injection of slurry in weak soil layers, b) Increasing the dimensions of the foundation, c) Combination of vertical micropile and bearing beam.

4. EVALUATION OF DIFFERENT METHODS FOR SOIL IMPROVEMENTS

To properly assess the appropriateness and efficiency of the mentioned strengthening methods, several functional and executive criteria were taken into consideration, the summary of which is according to Table 1. Each method has been given a score in each criterion so that the number 1 is the lowest score (more unfavorable) and the number 3 is the highest score (desirability). It helps to summarize and comment on choosing the appropriate method so that at the end of the table, the method with more points will have a lower rank and is more suitable. It should be noted that in this table, only the criteria related to soil-structure (foundation) performance have been discussed, but the criteria related to architectural and decorative considerations (including the necessity of minimal damage to the historic structure and the elegance of the improvement elements) has been assessed and evaluated in parallel in specialized working groups and the final results are presented in the next section.

Table 1: Evaluation of different methods to soil improvements.

Final rank	Final score	Evaluation criteria					Method
		Performance		Operational			
		Risk during implementation	Ease of implementation	Reliability	Not changing the previous load transfer system	Functionality integrated with the structure	
2	10	3	2	2	2	1	Inclined micropile method and cement grout injection
1	11	1	2	2	3	3	Increasing the dimensions of the foundation
3	7	1	1	1	1	3	Combination of support beam and vertical micropile

As can be seen in the above-mentioned table, the micropile and injection methods are among the most appropriate methods, which are more suitable than the methods because of the limitations caused by the metal protective structure and the historical nature of the building. It should be noted that after the Second World War, the use of the micropile method in Europe for the restoration of damaged historical structures became popular and gave satisfactory results. For example, it can refer to the project of the Diocesan Museum pointed out in St. Kolumba, Cologne (Figure 7).

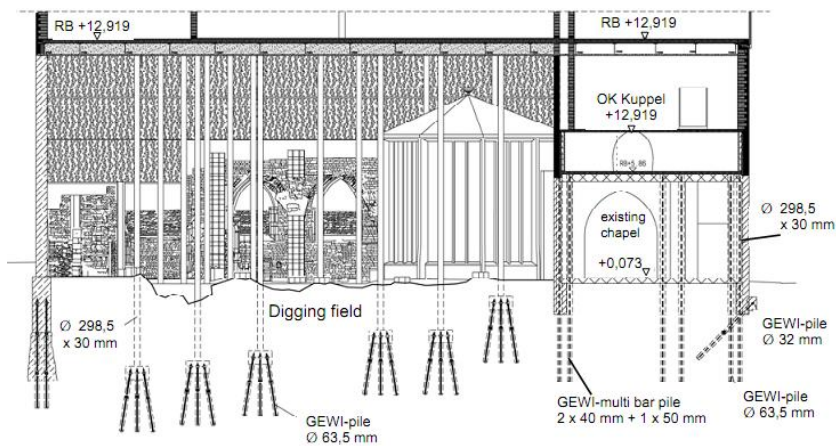


Figure 7: A section of the Diocesan museum building located in Cologne - improving using vertical and inclined micropiles [9].

5. SELECTING THE SUITABLE METHOD TO IMPROVING SOIL

According to the evaluation steps described in Table 1, and regarding the advantages of the above-mentioned methods, the final plan was considered using a combination of the three methods mentioned earlier (Figure 6). In this design, in addition to using vertical micropiles to increase the bearing capacity of the foundation, it was also used to increase the dimensions of the foundation around the brick foundation, which helps to increase the integrity of micropiles in settlement control. Diagonal micropiles were also used to inject limited points under the foundation to improve its geotechnical parameters (Figure 8). In the following, the results of the analyses and evaluations are presented.

6. ANALYSIS RESULTS

As it was mentioned in the previous section, a remote beam (or foundation) was used to strengthen the foot of the Minaret. To strengthen the body of the Minaret, a concrete shell was designed. The task of this concrete shell is to control the twist created in the Minaret because of the deviation from the vertical direction and to create balance in its behavior. After passing over the bottom pedestal, this shell is finally connected to the foot of the bottom pedestal. In the relevant analysis, the structure working group used the powerful finite element program ABAQUS (Figure 9).

In the modeling mentioned above, the staged construction scenario includes the following steps:

- a) Applying the load of the entire minaret structure to the soil.

- b) Strengthening the body of the Minaret, removing the existing metal protective structure, and applying the anchor because of deviation from the vertical direction.
- c) Creating micropiles transfers the load from the reinforcement structure to the lower part and applies deformation, which is likely to happen in the future.

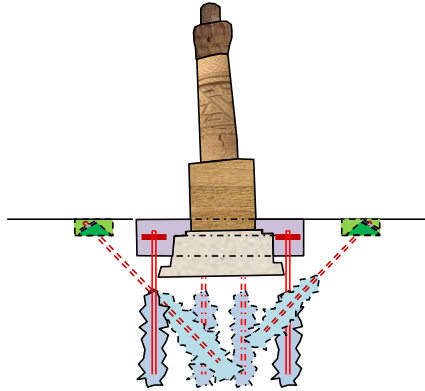


Figure 8: Schematic cross-section of the final design to improve the ground and strengthen the Minaret of Dhu Al-Kifil.

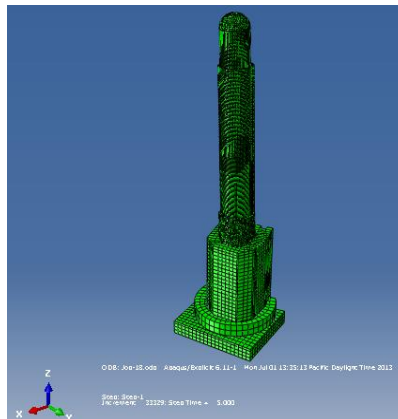


Figure 9: A view of the model made using the ABAQUS software.

To speed up the selection of the right arrangement of vertical micropiles, because of the time-consuming of the three-dimensional analyzes of the ABAQUS program, it was decided that the outputs of this software were transferred to the SAP software at the location of the minaret seat body. Then, by trial and error, choose the right arrangement of vertical micropiles. For this purpose, a model, according to Figure 10, was developed in the SAP software and was subjected to phased construction analysis in the above-mentioned method. After improvement, the amount of deformation in the soil is limited to 1.5 cm. The stress in the soil is also limited to less than 0.6 kg/cm² (Figure 11). It should be noted that the mentioned values have been obtained according to the choice of 1500-2000 kN/m³ for the modulus of the soil bed and the arrangement of vertical micropiles, so the requirement to achieve such a bed modulus is to use the injection method in the soil under the brick foundation.

Vertical micropiles were modeled using spring elements in SAP program, and their vertical stiffness was considered equal to 75-100 tons force/cm. The output of the forces generated in the micropiles at the end of the analysis is according to Figure 12. As it can be seen, the maximum forces generated are around 10 tons with a load factor of 1, and in their design, geotechnical, structural, and punch control considerations were made based on the recommendations of FHWA-SA97-070. The vertical deformation of the mentioned micropiles is limited to 0.1 cm because of the aforementioned hardness value. The final design that was used to improve the foundation of the Minaret is shown in Figure 13. This plan includes the implementation of vertical micropiles with a length of 9 meters and injection through diagonal micropiles with lengths of 6 meters and 9 meters (with an angle of 45 degrees) at the closest distance to the Minaret.

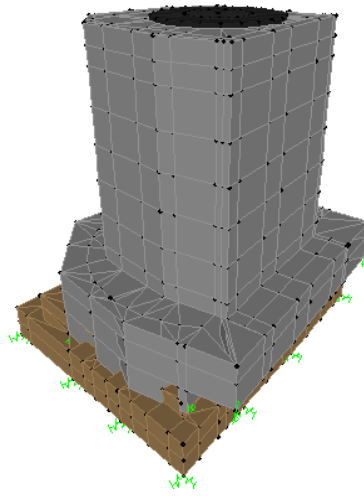


Figure 10: Modeling of the lower part of the Minaret with the SAP finite element software.

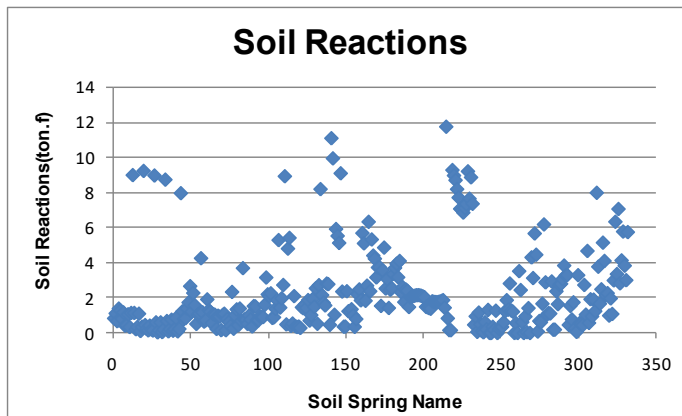


Figure 11: Soil reaction and deformation results based on the SAP finite element software outputs.

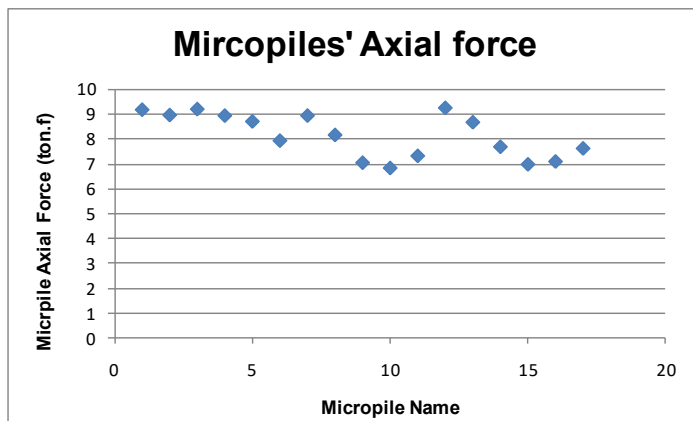


Figure 12: Axial force results in micropiles under stepwise loading without coefficient-program output.

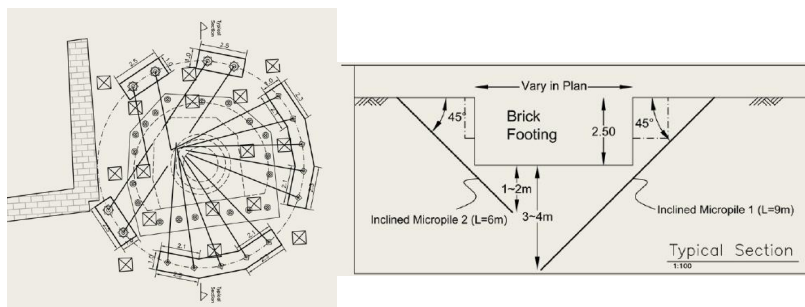


Figure 13: The final design for the improvement and strengthening of Dhu Al-Kifil Nabi minaret
 a) Layout plan of vertical and inclined micropiles, b) Cross section of inclined micropiles.

It should be noted that access and logistic restrictions made it difficult to choose the right place to implement the aforementioned micropiles. To achieve a higher degree of safety and more uniform performance of micropiles, increasing the dimensions of the minaret foundation, which has the role of CAP for micropiles, was also included in the construction plan. Figure 14 presents views of the implementation of vertical micropiles drilled in the vicinity of the Minaret of Dhu Al-Kifil Nabi (PBUH).



Figure 14: Views of the vertical and inclined micropiles implemented near the seat of the Minaret of Dhu Al-Kifil Nabi (PBUH) along with the size of the injected area.

7. CONCLUSIONS

The present article is a report on the various stages of geotechnical design and improvement of the Minaret of Dhu Al-Kifil Nabi (AS) base. The presented plan includes vertical and diagonal micropiles and increasing the dimensions of the Minaret's foundation. The staged construction analysis that was carried out confirms the adequacy of the mentioned plan in controlling the uneven settlement of the Minaret, so that the use of vertical micropiles with a length of 9 meters around the Minaret can control the settlement of the Minaret by 1.5 cm and the soil stress by 2.2 It is 1 kg/cm². Diagonal micropiles are implemented as an additional safety factor and to improve the characteristics of the soil in the area under the foundation, and its arrangement is such that the protective metal structure has the least interference with it. Increasing the dimensions of strip piles at the head of diagonal micropiles also helps integrate the two systems.

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